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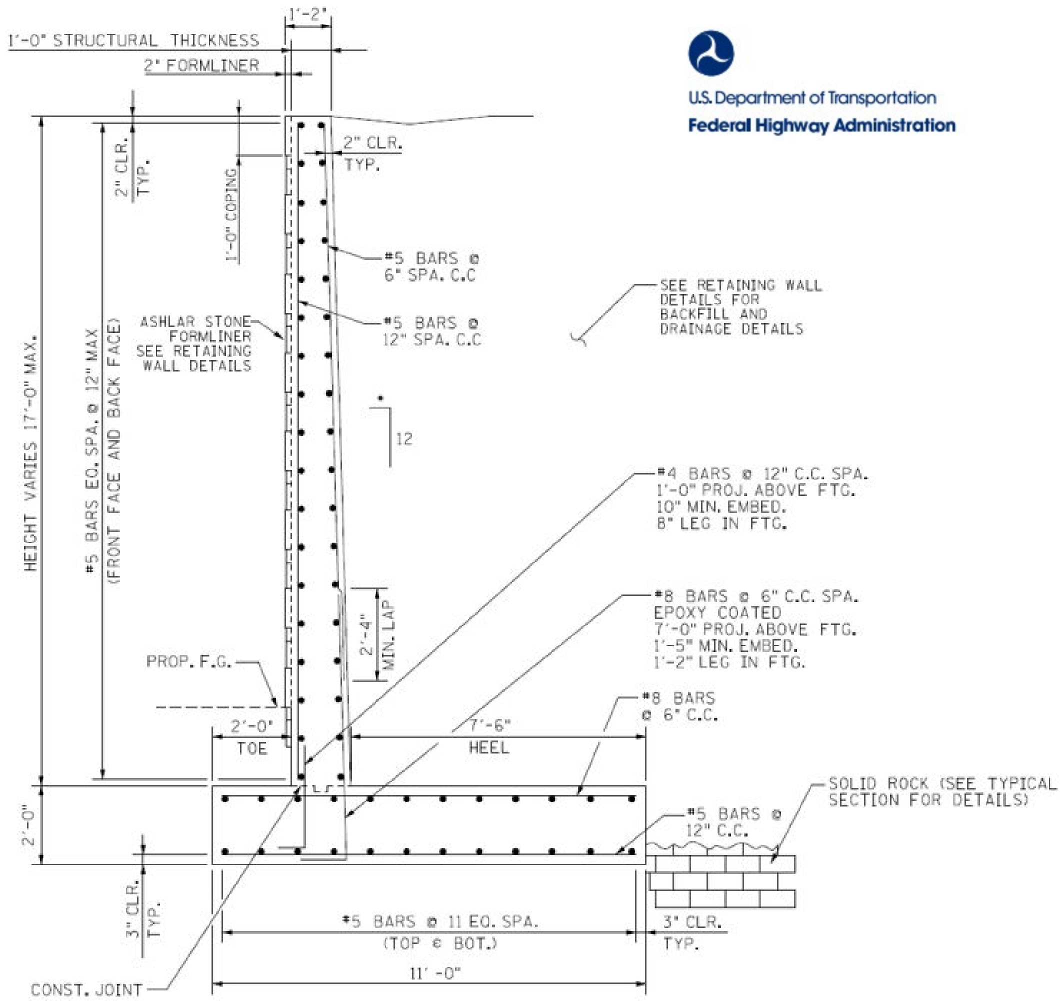

Automatic Tools for Quick and Accurate Construction Cost Estimation for Retaining Walls

Research Final Report from The University of Memphis) | Charles V. Camp, David Arellano, and Leonardo Garcia De La Cruz | May 31, 2024

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16. Abstract

Managing construction costs and budgets remains a top priority of TDOT in allocating resources provided by taxpayers. Estimating project costs accurately is critical to ensuring that projects are delivered in the fiscal year they were planned. This project developed a Retaining Wall Probable Bid Price Estimating Tool to provide accurate estimates of construction costs for diverse retaining wall types quickly. Also, the Cast-in-Place (CIP) Wall Low-Cost Design Tool was developed to optimize the design of economical reinforced concrete cantilever retaining walls. The Retaining Wall Probable Bid Price Estimating Tool was tested with data from the S.R. 115 (US-129, Alcoa) project in Knox County, TN. The Retaining Wall Probable Bid Price Estimating Tool result was 6.3% higher than the actual bid price, within ±10% of the target value. The CIP Wall Low-Cost Design Tool was applied to one of four retaining walls on the I-24 exit ramp at Bell Road in Davidson County, TN. The results of the low-cost design tool, per linear foot of the wall, reduced the cost by 26% compared to the original design. In summary, the primary project deliverables were the Retaining Wall Probable Bid Price Estimating Tool to quickly provide accurate estimates of the construction costs of various retaining walls and a companion user manual. The CIP Wall Low-Cost Design Tool and a companion user's manual were secondary deliverables.

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Executive Summary

According to the American Association of Highway and Transportation Officials' Practical Guide to Cost Estimating (AASHTO, 2013), sound financial decisions are based on the ability to estimate project costs accurately. If estimated costs are too high, the resulting reduction in the benefit-to-cost ratio may cause a project that might otherwise be beneficial to be rejected. Furthermore, if the estimated costs are too low, an inaccurately inflated benefit-to-cost ratio might indicate that a project should be accepted, which could lead to possible cost overruns. Cost increases on current construction put additional demands on Tennessee Department of Transportation (TDOT) budgets and restrict the development and construction of more projects.

The primary objective of this project was to develop an easy-to-use tool to quickly provide TDOT professionals with means to estimate the construction costs of retaining walls accurately. A secondary objective was to develop a cost optimization tool to assist TDOT in developing and evaluating economical cast-in-place (CIP) concrete cantilever retaining wall designs. Interactive, sophisticated spreadsheets were developed to meet the specifications of both project objectives. The Retaining Wall Probable Bid Price Estimating Tool was developed based on data collected from historical TDOT SP624 retaining wall bid prices from 2018 to 2022. The CIP Wall Low-Cost Design Tool integrated the procedures and specifications outlined in the AASHTO guidelines for Load and Resistance Factor Design (LRFD) with a sophisticated optimization algorithm. TDOT personnel were trained using these spreadsheet tools and provided detailed user manuals.

Key Findings

This project developed two tools: the Retaining Wall Probable Bid Price Estimating Tool allows users to accurately estimate construction costs for TDOT retaining walls based on the parameters available at the time of letting, and the CIP Wall Low-Cost Design Tool optimizes the design of CIP reinforced concrete cantilever retaining walls. Both tools are detailed within the user manuals and included as appendices to the report. The user manual for the Retaining Wall Probable Bid Price Estimating Tool is provided in Appendix A, while the CIP Wall Low-Cost Design Tool user manual is provided in Appendix B.

The Retaining Wall Probable Bid Price Estimating Tool was validated by applying it to a test case. The project, chosen randomly, was a series of eight SP624 retaining walls of various sizes and configurations, initially bid in August 2019 on S.R. 115 (US-129, Alcoa Highway) in Knox County, TN. The best result from the Retaining Wall Probable Bid Price Estimating Tool was only 6.3% higher than the actual bid price. All other bid projections were within ±10% of the actual bid results.

The CIP Wall Low-Cost Design Tool was applied to four retaining walls on the I-24 exit ramp at Bell Road in Davidson County, TN. The walls vary from 7 to 16 ft., with a single slope parapet built adjacent to the roadway shoulder. With the cost optimization component of the CIP Wall Low-Cost Design Tool enabled, the overall wall cost of the 16 ft. height wall was reduced by 26%.

- The Retaining Wall Probable Bid Price Estimating Tool allows users to estimate construction costs accurately.
- Retaining Wall Probable Bid Price Estimating Tool projections were within ±10% of the actual bid results.

- The CIP Wall Low-Cost Design Tool optimizes the design of CIP reinforced concrete cantilever retaining walls.
- For an example design, the CIP Wall Low-Cost Design Tool reduced the wall cost of the 16 ft. height wall by 26%.

Key Recommendations

While the Retaining Wall Probable Bid Price Estimating Tool provided estimates with ±10% of the actual bid results for a subset of SP624 retaining walls, applying the tool to other retaining wall systems would significantly enhance its applicability and practicality to TDOT.

- A primary recommendation would be for TDOT’s Cost Estimating Section to utilize the Bid Price Estimating Tool to analyze historical bid data and provide a statistical-based regression model to estimate costs at various project stages.
- A secondary recommendation would be to expand the tool’s database to other wall systems besides mechanically stabilized earth and cast-in-place concrete wall systems.
- Adding other systems will enhance the tool's capabilities and extend its functionality.
- Another recommendation is to consider adding the additional cost of foundation improvements for the retaining walls to the Retaining Wall Probable Bid Price Estimating Tool.

The CIP Wall Low-Cost Design Tool was developed to generate LRFD-complaint designs of reinforced concrete cantilever retaining walls.

- A primary recommendation would be for TDOT’s Structures division to utilize the Low-Cost Design Tool to develop cost-effective internal designs for projects requiring CIP retaining walls.
- Another recommended that this optimization tool be updated to design other retaining wall systems, such as mechanically stabilized earth (MSE) systems.
- MES retaining walls are frequently used in TDOT projects, especially for large-scale transportation systems. Design optimization can reduce material and construction costs significantly while generating efficient designs.
- The design optimization can also be reformulated to include other important design considerations, such as reliability, sustainability, and reducing the carbon footprint.

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Chapter 1 Introduction

> *The primary objective of the research is to develop easy-to-use software modules that will provide TDOT professionals with tools to estimate the construction costs of retaining walls quickly and more accurately.*

The inability to estimate project costs accurately can result in poor financial decisions, as noted by the American Association of Highway and Transportation Officials' Practical Guide to Cost Estimating (AASHTO, 2013). Estimated costs that are too high result in a reduction of the calculated benefit-to-cost ratio, which can lead to the rejection of a project that should be accepted. Estimated costs that are too high can also incorrectly indicate an overrun in Tennessee Department of Transportation (TDOT) budgets that can contribute to fewer projects being developed and constructed. On the other hand, costs that are too low result in an artificially high benefit-to-cost ratio that may lead to accepting a project that should not be constructed and can contribute to underrun TDOT budgets, whereby the non-expended funds could have been used to develop and build more projects.

Earth retaining walls are commonly required in highway construction along cuts and fill where space is inadequate to construct cut slopes or embankment slopes (Tanyu & Sabaatini, 2008). Therefore, accurate construction cost estimates of retaining walls are essential. Through this research effort, TDOT professionals seek automated/semi-automated tools to estimate the construction costs of retaining walls quickly and accurately. TDOT needs accurate estimates as part of the letting process to evaluate construction bids effectively and minimize the risk of change orders to awarded contracts during construction.

The primary objective of the research is to develop easy-to-use software modules that will provide TDOT professionals with automated/semi-automated tools to estimate the construction costs of retaining walls quickly and more accurately. The estimating modules will (1) incorporate existing bid history data for walls, as well as provide data entry for new bid history data ; (2) allow TDOT professionals to adjust the estimate based on relevant factors, such as wall heights, wall lengths, preferred wall; (3) integrate the automated toolset and emerging technologies to help streamline the estimation process of retaining wall construction; and (4) consider the bid environment when estimating costs, including the time of year, number of bidders, project location, and current economic conditions.

The limited amount of TDOT historical bid data for retaining walls is a constraint in developing the software modules to estimate the construction costs. Another limitation is that it is difficult to estimate the cost of any required foundation improvements since they are included in the lump sum cost of the wall.

A secondary objective is to develop software to assist TDOT professionals in developing economical cast-in-place (CIP) concrete cantilever retaining wall designs.

The research methodology consists of several tasks to estimate the costs of retaining wall construction for TDOT accurately. The tasks involved thoroughly reviewing existing cost estimation tools, including software platforms and databases, and gathering and tabulating cost data for retaining wall systems. Subsequent tasks focused on developing a software program structure, incorporating alternative analyses of potential platforms, and considering factors like regional cost differences and the number of bidders. This methodology ensured the development of user-friendly, automated tools to enhance the speed and precision of retaining wall construction cost estimates.

Chapter 2 Literature Review

The current cost estimation tools used by the Departments of Transportation (DOTs) and other available commercial estimating software tools were evaluated. The primary objective of this task was to identify cost estimation tools used by different DOTs. Although this survey of cost estimation tools was done on all 50 state DOTs, there was limited available data. Many DOTs do not have easily accessible information on their cost estimation software. Only 20 state DOT websites had information relating to cost estimating. The survey showed that only nine states (Connecticut, Georgia, Montana, New Jersey, New York, Ohio, Oregon, Vermont, and Wisconsin) use AASHTOWare Project Estimation (2022). AASHTOWare Project Estimation is a web-based "cradle-to-grave" software that provides accurate and reliable project estimates. Of the remaining state DOTs with public cost data, some used Excel spreadsheets with historical bid data, while others did not mention what cost estimation tools were used. One of the interesting spreadsheet layouts was from Texas DOT, which includes the pay item code, description, 3- and 12-month low bid averages for each district, and the low bid average for the state.

In addition to AASHTOWare Project Estimation (2022), other commercial estimating tools were reviewed, such as Sage 300 Construction and Real Estate (2022), HCSS HeavyBid (2022), and RSMeans Database Online (2022) to help provide ideas for the proposed new software structure layout. Sage 300 Construction and Real Estate is an estimating software that calculates quantities and dimensions and counts quickly and accurately using pricing databases and onscreen takeoff tools. This software can use historical estimates to track the probability and profitability of future jobs. HCSS HeavyBid is a cost estimation software that allows users to import bid items directly from DOT websites, allowing the development of quick estimates. Additionally, this software is used by 45 of the Engineering News-Record's top 50 heavy civil contractors.

A secondary objective was to gather and tabulate available cost data for retaining wall systems. After an extensive review, most cost data were found in state DOT bid databases. Only ten states had cost data available to the public. Table I lists retaining wall cost data collected from Arkansas, Connecticut, Florida, North Dakota, Oklahoma, South Dakota, Texas, Washington, West Virginia, and Wisconsin.

After evaluating documents and cost estimation procedures from other states, TDOT's current processes and systems were reviewed. TDOT-related documents contributed information about retaining walls, such as cost-related data to develop the suite of automated/semi-automated software module tools, including TDOT Geotechnical Guidelines (TDOT 2020a), TDOT Special Provision 624 regarding retaining walls: SP624 (TDOT 2021a), TDOT standard drawings (TDOT 2022a), TDOT 2021 Standard Specifications (TDOT, 2021b), TDOT Qualified Products List of Retaining Wall Systems (TDOT 2020b), and the TDOT Construction Division Resources: Price Information (Average Bid Prices) database (2021c).

Available cost data was gathered from multiple sources such as the TDOT Construction Division Resources: Price Information (Average Bid Prices) database (TDOT, 2021c), similar databases from other DOTs, RSMeans online cost database (RSMeans, 2022), The Federal Highway Administration Earth Retaining Structures Reference Manual (Tanyu & Sabatini, 2008), and the web based GeoTechTools (ASCE, 2021). Although outdated, the 1988 report on earth retaining wall costs in the USA was reviewed because it provided some helpful information (Koerner et al., 1988).

TABLE I

RETAINING WALL COST DATA

State DOT	Item	Unit	Price
Arkansas (Bennett, 2017)	MSE wall	sf	$26-$83
	Modular block wall	sf	$20-$76
Connecticut (CTDOT, 2021)	For wall areas<100 sf	sf	$325-$650
	For wall areas 100-500 sf	sf	$160-$325
	For wall areas 500-1000 sf	sf	$135-$200
	For wall areas>1000 sf	sf	$80-$135
Florida (FDOT, 2021)	Concrete class NS, gravity wall	cy	$952.98
	Concrete class II, retaining wall	cy	$766.93
	Concrete class IV, retaining wall	cy	$1,819.68
	Reinforcing steel-retaining wall	lb	$1.90
North Dakota (ND DOT, 2020)	General retaining wall	sf	$253.69
	Concrete modular block	sf	$97.66
Oklahoma (ODOT, 2022)	Block retaining wall with cap	sf	$32.30
	Temporary retaining wall	sy	$300.00
	MSE walls	sy	$595.98
South Dakota (SD DOT, 2020)	Retaining wall excavation	cy	$15.62
	Type C concrete retaining wall	sf	$99.99
	MSE segmental block wall	sf	$132.00
	MSE large panel wall, furnish	sf	$42.10
	MSE large panel wall, install	sf	$26.78
	Gravity large concrete block wall	sf	$70.21
	Granular backfill for MSE large panel wall	cy	$44.60
	Granular backfill for gravity concrete block wall	cy	$31.50
Texas (TxDOT, 2022)	Class C concrete (retaining walls)	cy	$574.50
	Retaining wall (MSE)	sf	$53.97
	Retaining wall (CIP)	sf	$78.82
	Retaining wall (Soil Nail)	sf	$45.98
	Retaining wall (Rock Nail)	sf	$50.00
Washington (WSDOT, 2021)	Gravel backfill for wall	cy	$55.14
	Concrete class 4000 for retaining wall	cy	$788.53
	Reinforcement for retaining wall	lb	$1.82
	Structural earth wall	sf	$45.77
West Virginia (WVDOT, 2022)	CIP reinforced concrete wall	sf	$66.02
	MSE wall	sf	$123.87
	Segmental wall	sf	$90.00
	Modular block wall	sf	$72.75
Wisconsin (WisDOT, 2022a)	MSE block wall	sf	$144.87
	MSE panel wall	sf	$123.02
	Soldier pile wall	sf	$219.22

Initially, the itemized cost of the components of standard wall systems was investigated to provide an option of using a cost-based estimating approach. This included a summary of factors that influence retaining wall costs and compiling a list of standard pay items associated with various types of retaining walls. Several sources, including FHWA manuals and state DOT documents, were used to determine factors influencing costs for each retaining wall type. After reviewing the cost-based approach, the research team decided to use a regression model based on historical bid data.

Reinforced concrete cantilever retaining walls are one of the most utilized retaining structures. In the analysis and design of retaining structures, the interaction between the soil and the structures poses many challenges to the designer; the structure must safely and reliably support the backfill soil, provide stability against the possibility of overturning and sliding, limit stresses in both the soil and the structure and provide acceptable safety from all failure modes. In addition to these design objectives, there are many requirements that a reinforced concrete wall must satisfy: it must have sufficient shear and moment capacities in the stem, toe, heel, and base shear key sections of the wall; the bearing capacity of the foundation cannot be exceeded or allowed to be in tensile stress; and the configuration of the steel reinforcement must meet all building code requirements. In this project, the design of CIP retaining structures followed the procedures and specifications outlined in the AASHTO guidelines for Load and Resistance Factor Design (LRFD) (AASHTO, 2020).

Methods for developing low-cost and low-weight designs of reinforced concrete retaining structures have been the subject of research for many years. Retaining wall optimization has attracted considerable attention within geotechnical engineering. Camp & Akin (2012) utilized a big bang big crunch (BB-BC) algorithm for cost and weight optimization of retaining walls. Gandomi et al. (2015), Gandomi et al. (2017a), and Gandomi et al. (2017b) developed designs for retaining walls using swarm and evolutionary algorithms. Kalemci et al. (2020) solved this problem using Grey Wolf optimization. Kaveh et al. (2020) employed a shuffled shepherd optimization algorithm for retaining wall optimization. Mergos and Mantoglou (2020) applied a flower pollination algorithm to the optimum design of retaining walls. Öztürk et al. (2020) investigated the minimum cost design of counterfort retaining walls using teaching-learning-based optimization and Jaya algorithms. Uray et al. (2020) conducted a sensitivity analysis on optimizing retaining walls on different soils using an artificial bee colony algorithm.

Big Bang–Big Crunch (BB-BC) is an innovative computational heuristic method for optimization problems. At its core, BB-BC optimization takes advantage of a relatively simple concept first proposed by Galton (1907) that states the average or weighted average of a group of estimates can be remarkably accurate. From this simple yet powerful Galtonian principle, Erol and Eksin (2006) conceptualized an abstract model of the universe's evolution and applied it to develop the original BB-BC algorithm. In their algorithm's “big bang” stage, a random set of solutions is generated within the search space; the “big crunch” stage effectively averages the solutions based on their feasibility and quality to produce a new center for the next big bang. Over a series of sequential Big Bang and Big Crunch cycles, the size and shape of the random distribution of newly generated solutions grow smaller than the moving average solution computed during the Big Crunch. Over multiple cycles, as some measure of the averaged solution and the best solution ceases to improve, the optimization is assumed to have converged.

Although the BB-BC algorithm has been shown to outperform many other evolutionary methods in structural optimization, in their original paper, Erol and Eksin (2006) demonstrated that BB-BC outperformed enhanced and classic genetic algorithms (GAs) for many benchmark optimization functions. Camp (2007) and Kaveh and Talatahari (2009, 2010) proposed hybrid forms of the BB-BC algorithm that significantly improved the computational efficiency of the method, as compared with GA and ant colony optimization (ACO) and demonstrated its applicability to solve structural engineering optimization problems.

Chapter 3 Methodology

3.1 Retaining Wall Probable Bid Price Estimating Tool

SP624 Retaining Walls (TDOT, 2021a) are unusual, as they are specified to be designed by the bidder based on conceptual drawings provided by TDOT. Generally, the bidder can price the design and build one of the acceptable wall systems listed in the plans. The most common types of systems specified are the mechanically stabilized earth (MSE) and cast-in-place concrete (CIP) wall systems. At bid time, TDOT needs to know what type of retaining wall system the lowest-bid contractor will choose to price and ultimately design and build. The data known at bid time is basic geometric information for the retaining wall system, which can be determined from the conceptual drawings provided by TDOT. The geometric information includes the total area of the wall face (SF), the total length of the wall (LF), the average height of the wall (AHT), and the maximum height of the wall (MHT). The TDOT region for the project (REG) and the time of the bid opening (BID DATE) are known. Also, a reasonable estimate can be made on how competitive the bidding process will be based on the anticipated number of bidders (BIDS).

Based on what information is known at the time of the bid, the research team and TDOT decided to create a tool based on historical bid information from projects over 5 years with the ability to add to that dataset as needed. To accomplish this, a database of historical TDOT SP624 retaining wall bid price data from the last five years, 2018 to 2022, was developed in collaboration with TDOT. This data was compiled into a sortable and filterable database within the Excel-based price estimating tool.

The Retaining Wall (RW) Probable Bid Price Estimating spreadsheet uses multiple linear regression techniques to predict bid prices. Multiple linear regression is a statistical technique that uses several explanatory variables to predict the outcome of a response variable. Multiple linear regression aims to model the linear relationship between the explanatory (independent) and response (dependent) variables. In the RW Bid Price Estimating spreadsheet, the response variable is the probable low-bid price of the retaining wall (TOTAL COST). The explanatory variables can be a combination of items, including the total area of the wall face (SF), the total length of the wall (LF), the average height of the wall (AHT), the maximum height of the wall (MHT), the TDOT region for the project (REG), the time of the bid opening (DATE), and the anticipated number of bidders (BIDS). All the explanatory variables are considered continuous except for the TDOT region (REG), which is regarded as a discrete (categorial) variable.

The RW Bid Price Estimating spreadsheet is divided into three predefined worksheets: BID ESTIMATE, BID DATABASE, and REGRESSION. The following sections describe these worksheets.

3.1.1 Bid Estimate

The BID ESTIMATE worksheet allows the user to enter the project and retaining wall data and then calculate a prediction of the lowest bid price based on that data. The BID DATABASE worksheet stores and revises historical retaining wall bid pricing data. The REGRESSION worksheet sorts and filters the retaining wall bid price database and, based on the user's preference, runs the LINEST array formula for the different regression equations (Total $Cost_n$). The resulting bid prediction is reported on the BID ESTIMATE worksheet.

The BID ESTIMATE worksheet is where project and wall-specific data is entered. Required data input includes the project number, date, estimator's name, TDOT Region (REG), the time of the bid opening (DATE), the anticipated number of bidders (BIDS), the total number of walls for the project, wall designation (WALL), the area of each wall, currently the TDOT pay unit (SF), the beginning and ending station for each wall (BST and EST), and the bottom and top wall elevations (BOW and TOW) at the maximum wall height.

3.1.2 Bid Database

The BID DATABASE spreadsheet is used to update and store retaining wall information in the database and display a summary of bid price statistics. This statistical information is useful when identifying irregularities and determining general trends in the bid price database.

3.1.3 Regression

The REGRESSION worksheet sorts or filters the historical bid price data stored in the BID DATABASE spreadsheet and runs regression analyses to predict the bid price. The user can also set regression parameters and the model equation. The RW Bid Price Predictor is designed to consider the following regression equations. The first listed regression equation (Total $Cost_1$) is called "ALL" in the spreadsheet.

$$\text{Total Cost}_1 = bb_0 + bb_1SF + bb_2LF + bb_3AHT + bb_4MHT + bb_5DATE + bb_6REG + bb_7BIDS$$

$$\text{Total Cost}_2 = bb_0 + bb_1SF + bb_2LF + bb_3MHT$$

$$\text{Total Cost}_3 = bb_0 + bb_1SF + bb_2LF$$

$$\text{Total Cost}_4 = bb_0 + bb_1SF$$

$$\text{Total Cost}_5 = bb_1SF + bb_2LF + bb_3AHT + bb_4MHT + bb_5DATE + bb_6REG + bb_7BIDS$$

$$\text{Total Cost}_6 = bb_1SF + bb_2LF + bb_3MHT$$

$$\text{Total Cost}_7 = bb_1SF + bb_2LF$$

$$\text{Total Cost}_8 = bb_1SF$$

The RW Bid Price Estimating spreadsheet calculates the coefficients or slopes (bb_1-bb_7) for the explanatory variables using the LINEST statistical array formula. Then, it solves each of the eight regression equations to determine the probable bid price (Total $Cost_n$). Note that bb_0 is the value for the Y-intercept, and the user may set it to zero or not. The LINEST formula also provides a value for the coefficient of determination (R^2). In statistics, R^2 is a measure that assesses the ability of a model to predict or explain an outcome in the linear regression setting. More specifically, R^2 indicates the proportion of the variance in the predicted response or explained by linear regression and the explanatory variables. Generally, the higher the R^2 value, the better the regression equation predicts the probable bid price.

3.2 Cast-in-place (CIP) Wall Low-Cost Design Tool

In addition to the regression tool, a low-cost CIP concrete cantilever retaining wall design tool was developed. This cost-optimization program uses a Big Bang-Big Crunch (BB-BC) algorithm to generate designs and check their feasibility with the AASHTO LRFD Bridge Design Specifications (AASHTO, 2020). This design optimization program will provide TDOT professionals with a tool to assist them in developing economical reinforced concrete retaining wall designs.

The AASHTO LRFD CIP wall design optimization spreadsheet consists of three sections: 1) design parameters, 2) low-cost design, and 3) LRFD design details. The following sections describe each of these worksheets.

3.2.1 Design Parameters

The optimization of the CIP wall design requires values for geometry, retained and base soils, and concrete and steel properties. Required geometric values include the stem height, soil depth in front of the wall, minimum stem thickness, and the minimum thickness of the slab. Required retained soil values include Internal friction angle, unit weight, and backfill slope. Base soil values include internal friction angle and nominal bearing resistance. Required concrete properties include unit weight, yield strength, minimum concrete cover, and the unit cost of installed concrete. Steel properties are yield strength of reinforcement, material cost, and installation cost.

The CIP wall design optimization also includes, if desired, the Colorado Department of Transportation (CDOT) Guardrail Type 7, TL-4 vehicle collision, and live vertical surcharge loads. CDOT Guardrail Type 7 values include the rail height, weight, and center of gravity. Required data to consider vehicle collision (TL-4) include vehicle load, collision load distribution, and the collision point. Live surcharge values include the surcharge height and the distance from the wall backface to the vertical surcharge.

3.2.2 Low-Cost Design

The optimization algorithm computes low-cost CIP wall designs with and without a shear key. The optimization is based on the BB-BC algorithm proposed by Erol and Eksin (2006). The BB-BC method is a two-stage procedure: an initial Big Bang stage where solutions are randomly distributed within the search space and a Big Crunch stage where the center of the next Big Bang is located by considering the weighted average of the feasibility of candidate designs. The initial Big Bang stage is very similar to other evolutionary methods in that an initial population of candidate solutions is generated randomly over the search space. Erol and Eksin (2006) modeled the random nature of the Big Bang stage as the dissipation of energy or the transformation from an ordered state to a disordered or chaotic state. Next, a contraction operation is applied during the Big Crunch stage, which computes the center of mass for the next Big Bang from the penalized objective function values of the candidate solution population. A detailed description of the BB-BC algorithm and its application to the low-cost design of CIP retaining walls is presented in Camp & Akin (2012).

3.2.3 AASHTO LRFD Details

Each potential CIP wall design generated in BB-BC optimization must be checked for feasibility using the AASHTO LRFD Bridge Design Specifications (AASHTO, 2020). This design verification is divided into geotechnical and structural design requirements. More details are provided in Appendix B.

Geotechnical design is divided into the following steps.

Step 1: Establish project requirements, including all geometry, external loading conditions (transient and permanent, seismic, etc.), performance criteria, and construction constraints.
Step 2: Evaluate site subsurface conditions and relevant properties of in situ soil and rock parameters and wall backfill parameters.
Step 3: Evaluate soil and rock parameters for design and establish resistance factors.
Step 4: Select the initial base dimension of the wall for strength limit state (external stability) evaluation.
Step 5: Select lateral earth pressure distribution. Evaluate water, surcharge, compaction, and seismic pressures according to AASHTO 3.11.
Step 6: Evaluate factored loads for all appropriate loading groups and limit states.
Step 7: Evaluate bearing resistance - ASHTO 11.6.3.2
Step 8: Check eccentricity - AASHTO 11.6.3.3
Step 9: Check sliding - AASHTO 11.6.3.6 (10.6.3.4)
Step 10: Check overall stability at the service limit state and revise the wall design if necessary.
Step 11: Estimate maximum lateral wall movement, tilt, and wall settlement at the service limit state. Revise the design if necessary.
Step 12: Design wall drainage systems.

Structural design is divided into the following steps.

Step 1: Define the strength properties of concrete and reinforcement and resistance factors.

Step 2: Design the wall stem.

- Obtain factored loads and moments acting on the stem.
- Design the section for flexure using AASHTO 5.6.3.2.
- Check that the tensile reinforcement meets the minimum requirement using AASHTO 5.6.3.3.
- Check the reinforcement spacing using AASHTO 5.6.7.
- Check to see if shear reinforcement is required using AASHTO 5.7.2.3.
- Check shrinkage and temperature reinforcement using AASHTO 5.10.6

Step 3: Design the footing heel.

- Obtain factored loads and moments acting on the heel.
- The reinforcement design procedure is the same as in Step 2.

Step 4: Design the footing toe.

- Obtain factored loads and moments acting on the heel.
- The reinforcement design procedure is the same as in Step 2.

Step 5: Design the shear key (if one is required).

- Obtain factored loads and moments acting on the heel.
- The reinforcement design procedure is the same as in Step 2.

Chapter 4 Results and Discussion

Managing construction costs and budgets remains a top priority of TDOT in allocating resources provided by taxpayers. Estimating project costs accurately is critical to ensuring that projects are delivered in the fiscal year they were planned. This project developed a comprehensive set of software tools to quickly provide accurate estimates of construction costs for diverse retaining wall types. Also, a user manual for the Retaining Wall Probable Bid Price Estimating Tool is provided in Appendix A. A second software program was also developed to optimize the design of economical cast-in-place concrete cantilever retaining walls. A user manual for the Cast-in-place (CIP) Wall Low-Cost Design Tool is provided in Appendix B.

This project developed a comprehensive set of software tools to quickly provide accurate estimates of construction costs for diverse retaining wall types.

4.1 Retaining Wall Probable Bid Price Estimating Tool

Implementing the Retaining Wall Probable Bid Price Estimating Tool adds a valuable component to TDOT's estimating process. As TDOT collects more data after each letting, the tool's database can be expanded, leading to continuous refinement and enhancement of its bid estimates.

A test project was chosen at random to see how the Retaining Wall Probable Bid Price Estimating Tool would perform. The project chosen was the S.R. 115 (US-129, Alcoa Highway) project in Knox County, TN. The project was bid in August 2019 and contained eight SP624 retaining walls of various sizes and configurations, totaling 52,704 ft^2. Figure 4-1 shows the data used in the regression analysis.

RECORD	ACTUAL DATA										
	Wall Information				Length	Height		Bid Results			
	Job	REG	WALL	SF	LF	AHT	MHT	$/SF	TOTAL COST	BIDS	DATE
20	CNT023	1	1B	3,849	247.19	15.57	23.35	$ 83.69	$ 322,123	4	8/9/2019
21			2B	4,994	572.16	8.73	14.05	$ 78.03	$ 389,682		
22			3	5,660	400.00	14.15	22.39	$ 82.07	$ 464,516		
23			5	3,266	171.53	19.04	28.05	$ 116.17	$ 379,411		
24			6A	2,022	228.51	8.85	10.44	$ 79.17	$ 160,082		
25			7	19,246	975.00	19.74	23.38	$ 108.54	$ 2,088,961		
26			7A	10,626	859.18	12.37	20.53	$ 78.09	$ 829,784		
27			7B	3,041	170.80	17.80	19.07	$ 94.22	$ 286,523		

Figure 4-1 Actual Data for Regression Test.

Based on the data entered, the Retaining Wall Probable Bid Price Estimating Tool was used to run each regression equation (Total Cost$_1$ to Total Cost$_8$). Figure 4-2 shows the best result (all parameters with Y-intercept = 0), just 6.3% higher than the actual bid price of $4,921,082. All bid projections were within ±10% of the actual bid results. Note that the default filter for the database was used (MHT<=40 ft.; $/SF <=$186/SF).

ACTUAL BID RESULTS		PROBABLE BID PRICE ESTIMATE							
		Y INTERCEPT = 0				Y INTERCEPT ≠ 0			
WALL	TOTAL COST	ALL	SF	SF/LF	SF/LF/MHT	ALL	SF	SF/LF	SF/LF/MHT
1B	$ 322,123	$ 381,181	$ 396,520	$ 400,393	$ 374,861	$ 395,299	$ 369,952	$ 382,770	$ 381,679
2B	$ 389,682	$ 438,885	$ 514,477	$ 438,368	$ 434,180	$ 469,602	$ 495,202	$ 442,676	$ 441,903
3	$ 464,516	$ 573,827	$ 583,088	$ 577,003	$ 561,432	$ 590,758	$ 568,055	$ 568,824	$ 567,947
5	$ 379,411	$ 331,304	$ 336,460	$ 352,079	$ 315,325	$ 342,541	$ 306,179	$ 329,565	$ 327,760
6A	$ 160,082	$ 125,270	$ 208,305	$ 178,505	$ 168,017	$ 147,347	$ 170,099	$ 160,824	$ 161,237
7	$ 2,088,961	$ 2,070,935	$ 1,982,705	$ 2,086,292	$ 2,132,932	$ 2,083,452	$ 2,054,207	$ 2,109,027	$ 2,111,799
7A	$ 829,784	$ 1,080,777	$ 1,094,681	$ 1,048,334	$ 1,058,457	$ 1,109,409	$ 1,111,278	$ 1,068,858	$ 1,068,174
7B	$ 286,523	$ 250,017	$ 313,281	$ 324,246	$ 303,036	$ 267,492	$ 281,566	$ 301,835	$ 301,570
ALL	$4,921,082	$5,252,197	$5,429,518	$5,405,220	$5,348,240	$5,405,899	$5,356,539	$5,364,378	$5,362,069
R2		0.950	0.937	0.941	0.942	0.916	0.895	0.899	0.899
+/-		6.30%	9.36%	8.96%	7.99%	8.97%	8.13%	8.26%	8.22%

Figure 4-2 Results of the Regression Test.

4.2 CIP Wall Low-Cost Design Tool

A CIP reinforced concrete retaining wall design spreadsheet was developed using a BB-BC optimization algorithm. The design procedure follows the AASHTO LRFD guidelines. Appendix B provides details on the AASHTO LRFD and provides example calculations. The CIP Wall Low-Cost Design Tool integrates the AASHTO LRFD for CIP walls with a sophisticated BB-BC optimization algorithm to generate low-cost designs. The optimized values for volumes of concrete and steel for the CIP designs are computed per foot linear of the wall.

The CIP Wall Low-Cost Design Tool requires users to input values for geometry, retained and base soils, concrete and steel properties, guardrail type, TL-4 vehicle collision, and live vertical surcharge loads. Also, three cost parameters are user-specified: the cost of installed concrete $/ft^3, the cost of steel $/lb., and the cost of installation for reinforcing steel $/ft.

The CIP Wall Low-Cost Design Tool was applied to one of four retaining walls on the I-24 exit ramp at Bell Road in Davidson County, TN. Figure 4.3 shows a typical cross-section of the walls. The walls vary from 7 to 16 ft., with a single slope parapet built adjacent to the roadway shoulder. Table II lists the dimensions and steel reinforcing of the 16 ft. retaining wall. The backfill for the retaining walls had a unit weight of 110 pcf, with a friction angle of 34°. The strength of the concrete was 3,000 psi, and the reinforcing steel was ASTM A615 Grade 60. The design of these walls did not include bridge railing, live load surcharge, or vehicle collision loads. Since material and construction costs can vary, the following cost values were assumed for comparing the designs: the cost of installed concrete of $1.13/ft^3, the cost of steel of $0.18/lb., and the cost of installation for reinforcing steel of $1.00/ft.

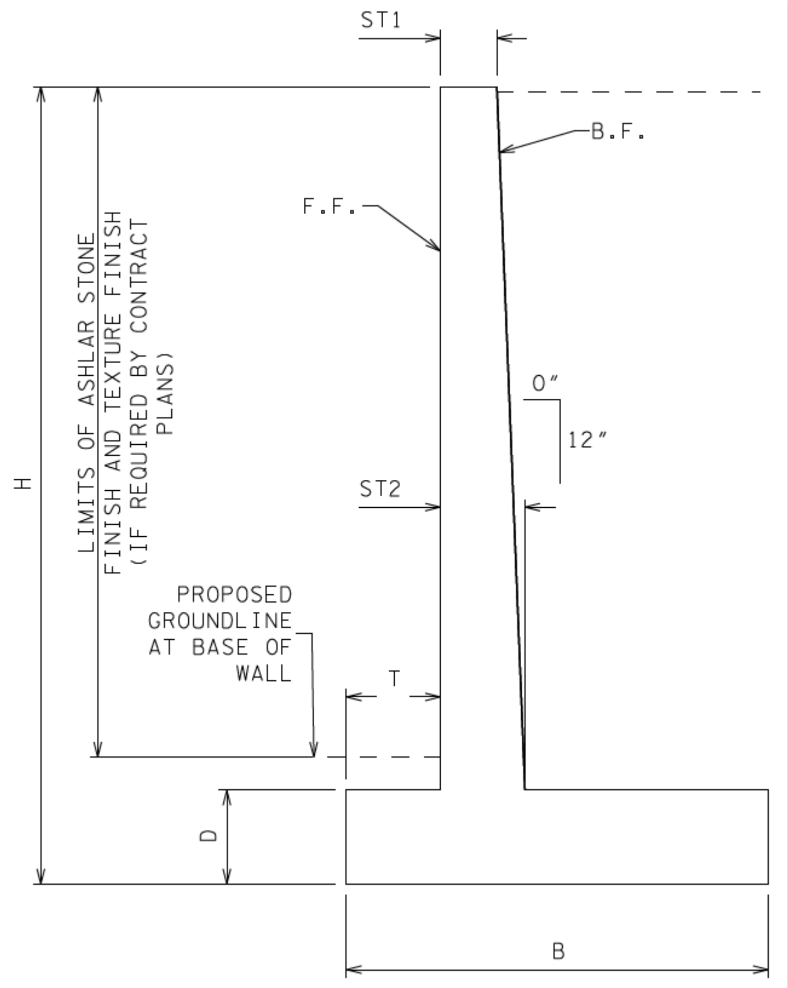

Figure 4-3 Typical Cross Section of I-24 Exit Ramp CIP Walls.

TABLE II

I-24 EXIT RAMP WALL DESIGN

I-24 Wall Geometry		
Base width (B)	12.25	ft.
Toe Projection (S)	1.00	ft.
Stem Thickness at the Bottom (T_{Bot})	1.21	ft.
Stem Thickness at Top (T_{Top})	1.21	ft.
Thickness of Base Slab (T_F)	2.00	ft.

I-24 Wall	**Transverse**	**Longitudinal**
Stem	#6 @ 12"	#4 @ 12"
Heel	#8 @ 9"	#4 @ 12"
Toe	#6 @ 12"	#4 @ 12"

Based on the design details presented in Appendix B, the volume of concrete per linear foot of the wall was 42.94 ft^3, the total weight of steel, including transverse and longitudinal steel, was 72.60 lb., and the length of steel reinforcing was 53.83 ft. The total cost of the retaining wall was $115.42/ft.

The I-24 Exit Ramp retaining wall was redesigned using the CIP Wall Low-Cost Design Tool. All values for the geometry, retained and base soils, and concrete and steel properties were the same. Table III lists the results using the CIP Wall Low-Cost Design Tool.

TABLE III

CIP WALL LOW-COST DESIGN FOR I-24 EXIT RAMP WALL

I-24 Wall Geometry		
Base width (B)	9.00	ft.
Toe Projection (S)	1.70	ft.
Stem Thickness at the Bottom (T_{Bot})	2.10	ft.
Stem Thickness at Top (T_{Top})	1.00	ft.
Thickness of Base Slab (T_F)	1.50	ft.

I-24 Wall	**Transverse**	**Longitudinal**
Stem	#5 @ 12"	#4 @ 21"
Heel	#7 @ 12"	#4 @ 21"
Toe	#3 @ 12"	#4 @ 21"

The low-cost design, per linear foot of the wall, had a volume of concrete of 35.20 ft^3, a total steel weight, including transverse and longitudinal steel, of 42.28 lb., and a length of steel reinforcing of 37.86 ft. The total cost of the CIP retaining wall was $85.25/ft., a 26% reduction over the original design.

In summary, the primary project deliverables were the Retaining Wall Probable Bid Price Estimating Tool to quickly provide accurate estimates of the construction costs of various retaining walls and a companion user manual (see Appendix A). A secondary deliverable was the CIP Wall Low-Cost Design Tool and a companion user's manual (see Appendix B).

The Retaining Wall Probable Bid Price Estimating Tool demonstrated the ability to accurately estimate bid prices based on historical bid information from SP624 Retaining Walls from 2018 to 2020. The CIP Wall Low-Cost Design Tool can be a valuable resource for TDOT's Geotechnical Engineering Section and Structures Division, offering a means to optimize designs and effectively reduce overall project costs.

Chapter 5 Conclusion

The objectives of this project were to develop a set of interactive, easy-to-use software tools to provide TDOT professionals with resources to accurately estimate the construction costs of retaining wall systems and generate low-cost designs for cast-in-place (CIP) reinforced concrete retaining walls. The Retaining Wall Probable Bid Price Estimating Tool was developed to estimate construction costs, and the CIP Wall Low-Cost Design Tool was developed to generate low-cost retaining wall designs.

The Retaining Wall Probable Bid Price Estimating Tool used a database collected from historical TDOT SP624 retaining wall bid prices from 2018 to 2022. The Price Estimating Tool was verified with a project, bid initially in August 2019, along S.R. 115 (US-129, Alcoa Highway) in Knox County, TN, that utilized eight SP624 retaining walls of various sizes and configurations. The results using the Price Estimating Tool were just 6.3% higher than the actual bid price, well within ±10% margin of error of the actual bid results. More details are available in the user manual for the Retaining Wall Probable Bid Price Estimating Tool provided in Appendix A.

The CIP Wall Low-Cost Design Tool combined a sophisticated optimization algorithm with AASHTO LRFD specifications to generate designs that reduce material and construction costs for CIP retaining walls. The Low-Cost Design Tool was applied to a wall design defined in the Colorado Department of Transportation (CDOT) Bridge Design Manual. With the cost optimization component of the Low-Cost Design Tool enabled, the overall wall cost was reduced by 26%. More details on the AASHTO LRFD specifications in the CIP Wall Low-Cost Design Tool are provided in Appendix B.

The CIP Wall Low-Cost Design Tool was applied to a 16-ft. retaining wall on the I-24 exit ramp at Bell Road in Davidson County, TN. With the cost optimization component enabled, the overall wall cost was reduced by 26%.

The Retaining Wall Probable Bid Price Estimating Tool demonstrated the ability to accurately estimate bid prices based on historical bid information from SP624 Retaining Walls from 2018 to 2020. Since the database can be easily updated and expanded, the tool's effectiveness and utility can be maintained over time. For example, bid data can be collected and added to the database after each letting. With the increase in bid information, the database represents a broader set of wall types and can deliver better bid estimates. More importantly, TDOT's Cost Estimating Section can utilize the Bid Price Estimating Tool to analyze historical bid data and provide a statistical-based regression model to estimate costs at various project stages.

While the CIP Wall Low-Cost Design Tool was developed to generate LRFD-compliant reinforced concrete retaining walls, it can be applied to other wall systems. In particular, the design tool can be applied to mechanically stabilized earth (MSE) systems. This tool optimizes retaining wall designs to reduce overall project costs and can provide a valuable resource for TDOT's Geotechnical Engineering Section and Structures Division. For example, the Low-Cost Design Tool can be utilized by the TDOT Structures division to develop cost-effective designs internally that require CIP retaining walls.

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Appendix A

Retaining Wall Probable Bid Price Estimating Tool

User MANUAL

A1. Getting Started

The Retaining Wall Probable Bid Price Estimating Tool uses Visual Basic for Application (VBA) programming and Microsoft Excel macros. The Bid Price Estimating Tool is commonly called a Microsoft Excel template. A template is a predesigned workbook to create one or several worksheets with the same layout, formatting, and formulas. The Bid Price Estimating Tool has been compiled into an executable (.exe) file. It is password-protected. The password is “tdotjwd.” This password can be used to unprotect and unhide the individual worksheets in the workbook.

The program's filename is TDOTRWBID31923.exe. Double-clicking on the file name will run the program. The last five digits represent the data date (March 19, 2023) for the retaining wall bid database information. As the database is updated or the system is used to estimate a bid result, the file should be saved as a .exe file, with the last five digits changed to reflect the current date.

The Bid Price Estimating Tool contains three predefined worksheets accessed through tabs at the bottom of the workbook: BID ESTIMATE, BID DATABASE, and REGRESSION. The BID ESTIMATE worksheet is used to enter a project and retaining wall data, and it calculates a prediction of the lowest bid price based on that data. The BID ESTIMATE worksheet contains a PRINT button, which formats the bid estimate information to be printed on letter-sized (8 ½” x 11”) paper. The BID DATABASE worksheet stores, revises, adds, and saves the historical retaining wall bid pricing database. The REGRESSION worksheet is used to sort and filter the retaining wall bid price data and, based on the user’s preference, run the LINEST array formula for the different regression equations (Total $Cost_n$). This information predicts the bid results in the BID ESTIMATE worksheet.

Figure A1 shows a flowchart of the general process for using the RW Bid Price Predictor.

A2. Worksheet Specifics

All worksheets in the workbook are formatted similarly. Cell (adjacent columns or rows) titles are highlighted in yellow where data entry is required. Titles are highlighted in blue for cells with formulas or VBA code/macros. All cells that do not require input from the user are protected. To remove cell protection (not recommended), use the Review-Protect Sheet commands and enter the password “TDOTBID.”

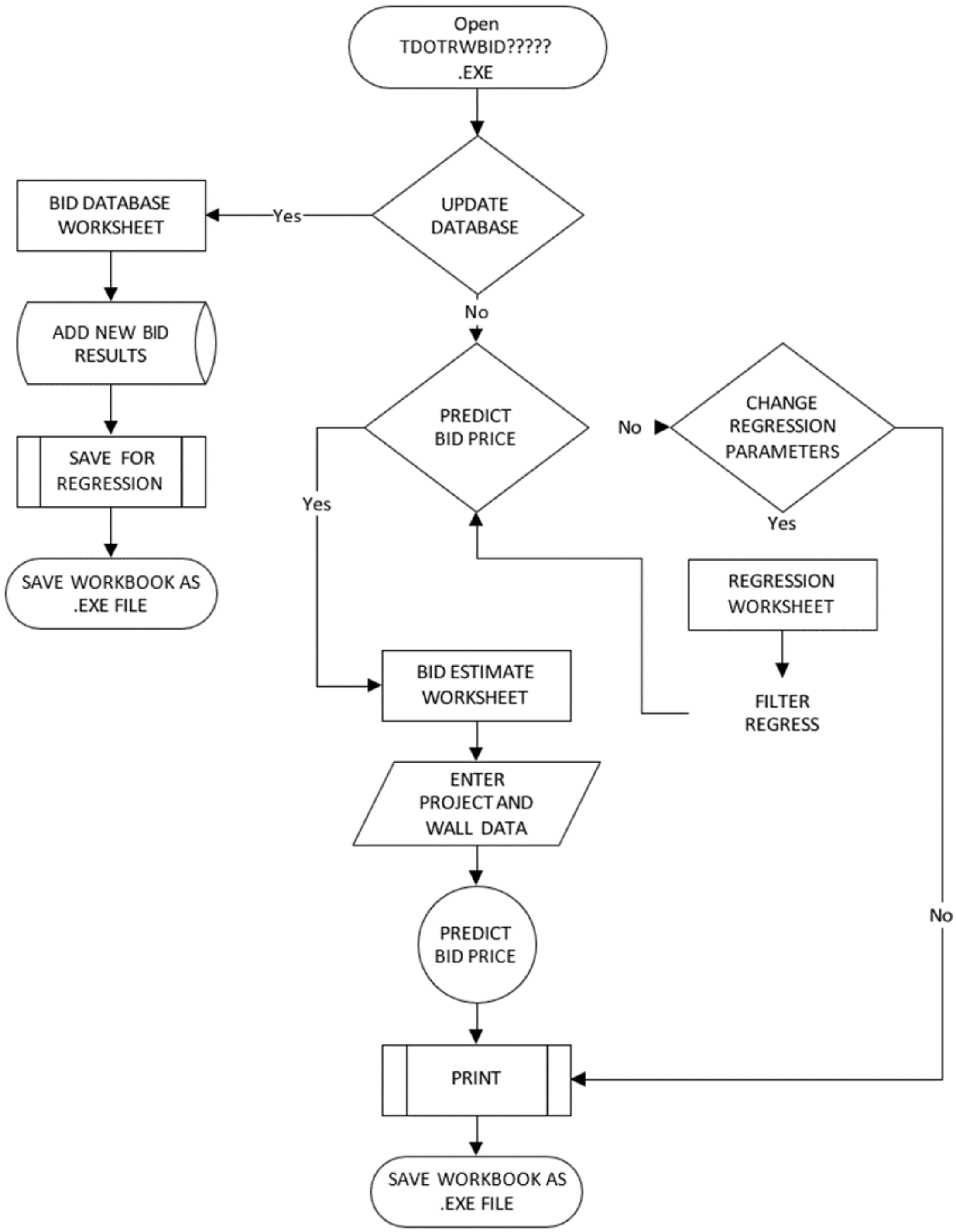
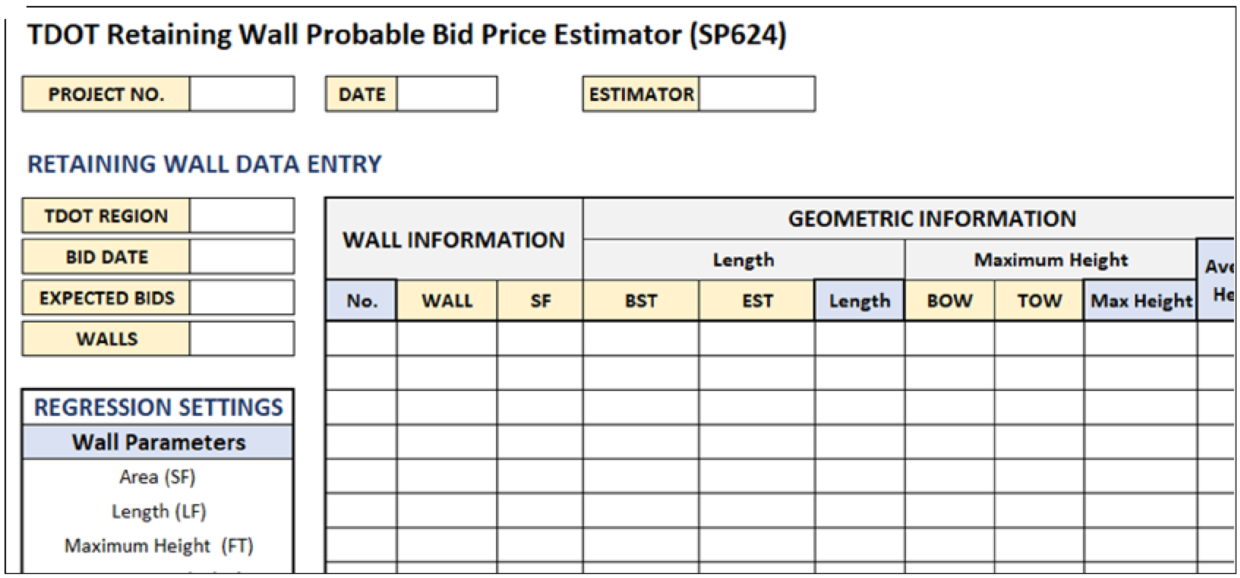


Figure A1 Bid Price Predictor Tool Flow Chart

A2.1 BID ESTIMATE WORKSHEET

The BID ESTIMATE worksheet is the main screen form for the Bid Price Estimating Tool and is where project and wall-specific data is entered. Required data input includes the PROJECT NO., DATE, ESTIMATOR, TDOT REGION, BID DATE, EXPECTED BIDS, WALLS (total number of walls for the project), Wall Designation (WALL), the area of each wall, currently the TDOT pay unit (SF), the beginning and ending station for each wall (BST and EST), and the bottom and top wall elevations (BOW and TOW) at the maximum wall height. Figure A2 shows a partial screenshot of the screen form.



TDOT Retaining Wall Probable Bid Price Estimator (SP624)

PROJECT NO. | DATE | ESTIMATOR

RETAINING WALL DATA ENTRY

TDOT REGION
BID DATE
EXPECTED BIDS
WALLS

REGRESSION SETTINGS
Wall Parameters
Area (SF)
Length (LF)
Maximum Height (FT)

WALL INFORMATION			GEOMETRIC INFORMATION						
			Length			Maximum Height			Ave He
No.	WALL	SF	BST	EST	Length	BOW	TOW	Max Height	

Figure A2 Bid Estimate Partial Screen Form

Once all the required data is entered, the Bid Price Estimating Tool will predict the bid price for each wall based on the data entered and the default regression mode. The Bid Price Estimating Tool can predict bid prices for up to 20 walls per project. The default regression mode is “ALL” parameters with the Y-intercept set to zero. The current default regression mode also includes a filtered bid price database to remove outliers as follows:

- Retaining walls with a maximum height greater than or equal to 40 feet have been excluded.
- Retaining walls with bid prices over $186/SF have been excluded.

Based on the updated database of bid prices, as of 3/19/2023, these exclusions represent approximately 10% of the 127 retaining walls in the current database. To change the default regression mode, see the section in the User Manual regarding the REGRESSION worksheet.

The BID ESTIMATE worksheet displays the information used in the regression analysis in the “REGRESSION SETTINGS” section at the screen's bottom-left corner (see Figure A3). It also shows the coefficient of regression (R2). This information will be automatically updated if the regression parameters change from the default.

EXPECTED BIDS	4
WALLS	8

REGRESSION SETTINGS	
Wall Parameters	
Area (SF)	
Length (LF)	
Maximum Height (FT)	
Average Height (FT)	
Project Parameters	
Bid Date	
Region	
Number of Bidders	
Regression Parameters	
Database Filtered	YES
Y Intercept = 0	YES
R^2 = 0.950	

No.	WALL
1	1B
2	2B
3	3
4	5
5	6A
6	7
7	7A
8	7B

Figure A3. Bid Estimate Regression Settings Form

The predicted bid prices for each wall are displayed in the worksheet's far-right column (TOTAL COST), as shown in the example in Figure A4.

The predicted bid price can be adjusted based on the unique FOUNDATION INFORMATION for the specific wall or other reasons such as complex geometry, working conditions, or economics. The last two revisions are done in the ADJUST column at the user's discretion. The data is entered in the columns beneath the yellow highlighted columns, and the RW Bid Price Predictor automatically updates the TOTAL COST and $/SF fields. There is also an area for comments to the right of the TOTAL COST column. A CLEAR button is also provided to help with "what if" type analysis of different regression parameters and database filters.

	FOUNDATION INFORMATION					ESTIMATED BID PRICE			
	Soil Improvement					$/SF			TOTAL COST
Average Height	Y/N	TYPE	QTY	$/QTY	Total Cost	Forecast	ADJUST	Revised	
15.57						$ 99.03		$ 99.03	$ 381,181
8.73						$ 87.88		$ 87.88	$ 438,885
14.15						$ 101.38		$ 101.38	$ 573,827
19.04						$ 101.44		$ 101.44	$ 331,304
8.85						$ 61.95		$ 61.95	$ 125,270
19.74						$ 107.60		$ 107.60	$ 2,070,935

Figure A4. Bid Estimate Partial Screen Form

A2.2 BID DATABASE WORKSHEET

The purpose of the BID DATABASE worksheet is to store and update the historical bid pricing data. The Bid Price Estimating Tool will be used in the regression analysis and to display summary information. Figure A5 is a screenshot of a portion of the current bid price database.

RETAINING WALL BID PRICE DATABASE (SP624)

Use Add Button to Enter New Data, then Save

ADD SAVE

Wall Information				Length			Maximum Height			Bid Results			
Job	Reg.	Wall	SF	BST	EST	Distance	BOW	TOW	Height	$/SF	Total Cost	Bids	DATE
CNS202	3	2	5,642	17767.28	18200.00	432.72	562.00	578.75	16.75	$ 60.00	$ 338,520	5	8/17/2018
CNS202	3	3	9,510	9600.00	10234.81	634.81	580.00	599.75	19.75	$ 59.00	$ 561,090	5	8/17/2018
CNS289	4	6	6,125	0.00	257.28	257.28	330.00	357.00	27.00	$ 165.00	$ 1,010,625	3	10/5/2018
CNS289	4	3	8,017	0.00	556.37	556.37	337.11	357.71	20.60	$ 110.00	$ 881,870	3	10/5/2018
CNS289	4	1	10,293	0.00	843.85	843.85	355.96	374.96	19.00	$ 145.00	$ 1,492,485	3	10/5/2018
CNS060	3	2	2,838	1000.00	1330.97	330.97	631.50	643.59	12.09	$ 100.00	$ 283,800	5	12/7/2018

Figure A5. Bid Database Partial Screen Form

The Retaining Wall Bid Price Database is a Microsoft Excel Table named “TABLE 1.” The ADD button at the top right of the table inserts a row for input to add data to the database. This action is done discretely by Wall (not Job). When the data is correctly entered, the “SAVE” button stores it and makes it available for the REGRESSION worksheet to use in the regression analysis.

In addition to storing and updating the database, the BID DATABASE worksheet displays summary information in three Pivot Tables and a Histogram Plot. This information is useful when determining anomalies in the data and general trends. Figure A6 shows the Pivot Tables and the Histogram Plot.

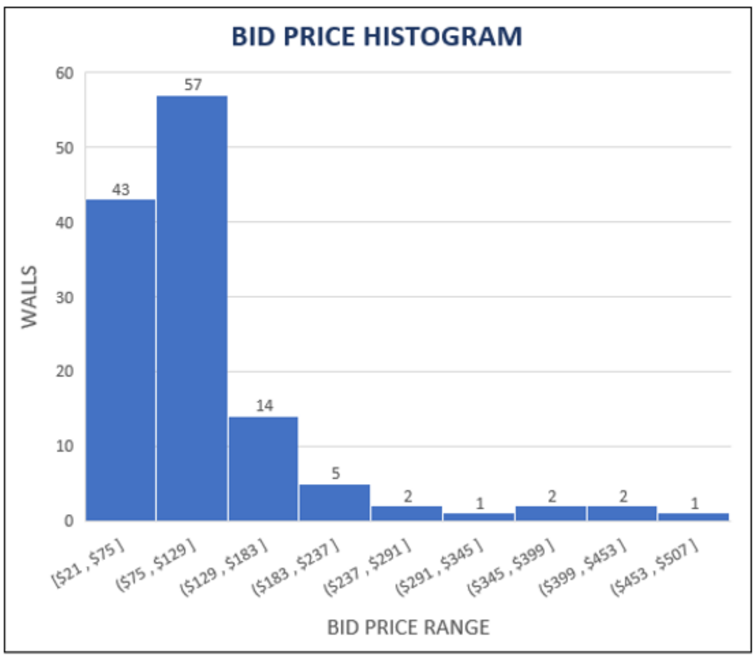
BID PRICE DATABASE STATISTICS

Use Filter and +/- Tabs to Expand/Shrink

Region	Avg. Bids	Avg. $/SF
⊞1	2.6	$ 157.99
⊞2	3.9	$ 96.56
⊞3	3.4	$ 97.32
⊞4	3.1	$ 83.65
TOTALS	3.3	$ 113.97

DATE	Avg. $/SF	Walls
⊞2020	$ 125.06	22
⊞2021	$ 76.33	35
⊞2022	$ 171.44	25
⊞2019	$ 101.50	30
⊞2018	$ 114.69	15
TOTAL	$ 113.97	127

BIDS	Avg. $/SF
1	$ 276.33
2	$ 134.37
3	$ 97.91
4	$ 84.76
5	$ 100.66
TOTAL	$ 113.97



RECORDS	127

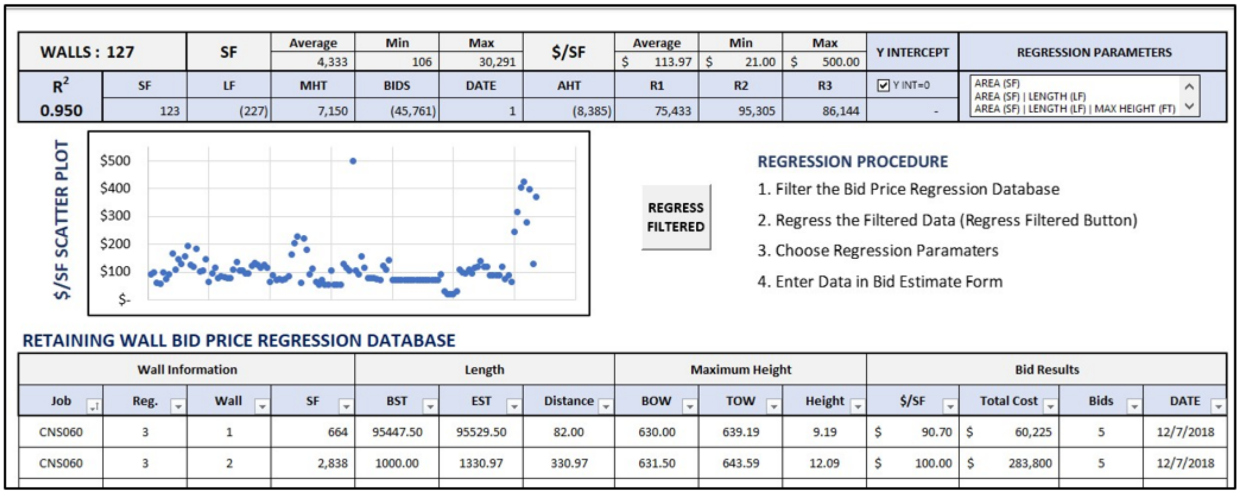
Figure A6. Bid Database Pivot Tables and Histogram

Microsoft Excel's Pivot Table and graphing functions are available to modify the displays.

A2.3 REGRESSION worksheet

When updated and saved in the BID DATABASE worksheet, the REGRESSION worksheet retrieves the historical retaining wall bid price information. The data may then be sorted or filtered, and regression parameters are set to feed the algorithm, determining the predicted bid price.

Figure A7 shows a partial screen form for the REGRESSION worksheet. It should be noted that no data entry is permitted in the REGRESSION worksheet.



WALLS : 127		SF	Average 4,333	Min 106	Max 30,291	$/SF	Average $ 113.97	Min $ 21.00	Max $ 500.00	Y INTERCEPT	REGRESSION PARAMETERS
R^2	SF	LF	MHT	BIDS	DATE	AHT	R1	R2	R3	☑ Y INT=0	AREA (SF) AREA (SF) | LENGTH (LF) AREA (SF) | LENGTH (LF) | MAX HEIGHT (FT)
0.950	123	(227)	7,150	(45,761)	1	(8,385)	75,433	95,305	86,144	-	

REGRESSION PROCEDURE

1. Filter the Bid Price Regression Database
2. Regress the Filtered Data (Regress Filtered Button)
3. Choose Regression Paramaters
4. Enter Data in Bid Estimate Form

RETAINING WALL BID PRICE REGRESSION DATABASE

Wall Information				Length			Maximum Height			Bid Results			
Job	Reg.	Wall	SF	BST	EST	Distance	BOW	TOW	Height	$/SF	Total Cost	Bids	DATE
CNS060	3	1	664	95447.50	95529.50	82.00	630.00	639.19	9.19	$ 90.70	$ 60,225	5	12/7/2018
CNS060	3	2	2,838	1000.00	1330.97	330.97	631.50	643.59	12.09	$ 100.00	$ 283,800	5	12/7/2018

Figure A7. Regression Worksheet Partial Screen Form

The Retaining Wall Bid Price Regression Database is named Microsoft Excel Table: "TABLE 16". It has been formatted to permit the user to sort or filter the data for any of the table's columns. This sorting is done using the built-in Microsoft Excel sort and filter commands. The sort and filter commands are accessed using the filter buttons adjacent to the column titles. Figure A8 shows how a user would filter the bid price database to include all walls with unit bid prices equal to or less than $186/SF.

If the database is filtered, the REGRESS FILTERED button must be pressed so the pricing algorithm can be set up to run the regression based on the newly filtered data. When this is done, an updated Scatter Plot and various updated statistical data (in the grey highlighted cells) related to the newly filtered data are displayed at the top of the screen. This action also updates the formulas in the BID ESTIMATE worksheet to predict the bid prices.

The user can filter the Retaining Wall Bid Price Regression Database and set the parameters to be regressed. The current regression options are reviewed in the INTRODUCTION section of the User Manual.

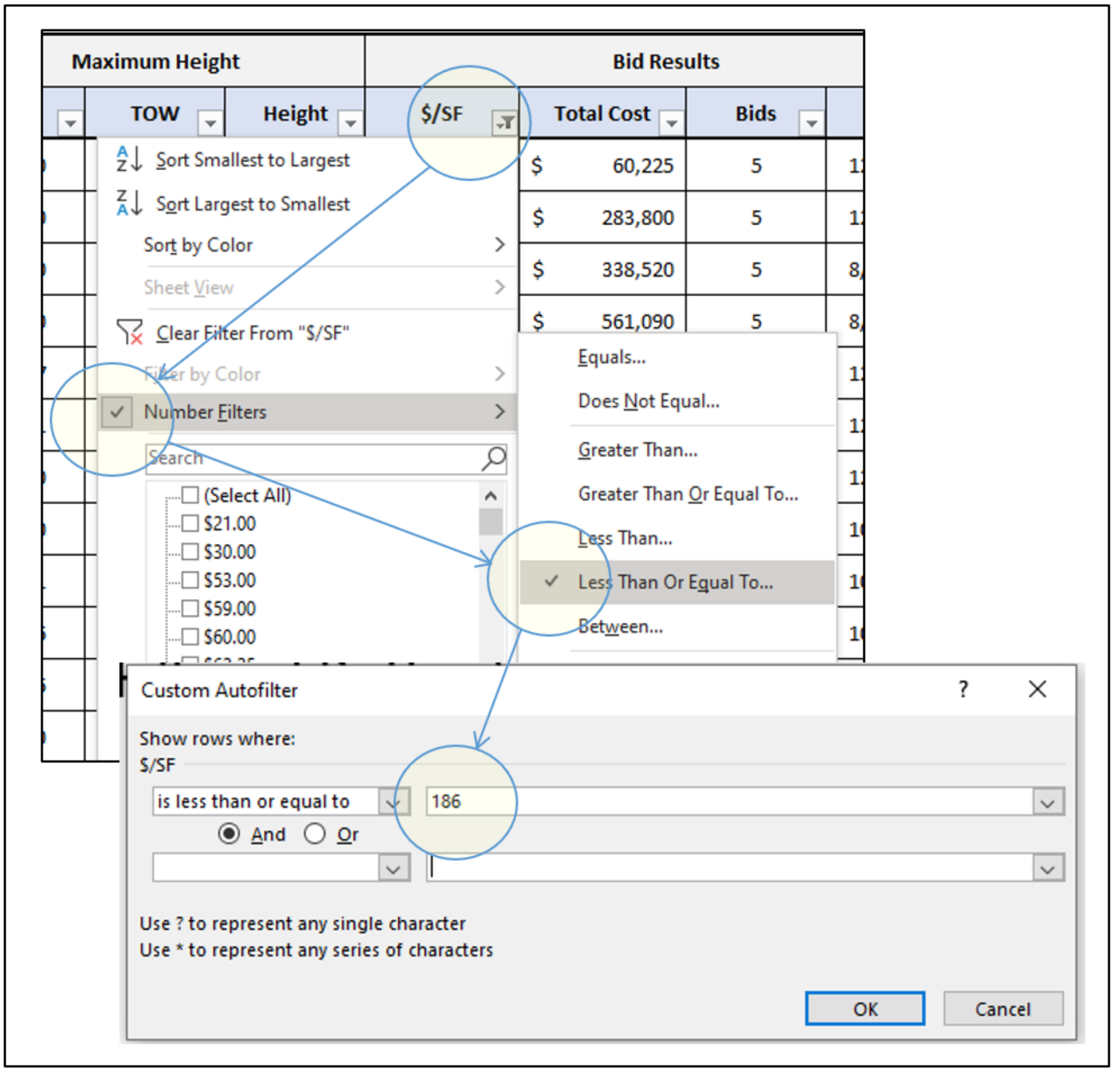


Figure A8. Regression Worksheet Filter ($/SF <= $186)

The regression parameters are selected using the buttons on the top-right corner of the REGRESSION worksheet. This action allows the user to specify the Y-intercept as 0 and choose one of the four combinations of the explanatory variables. Figure A9 shows the user interface for selecting the regression parameters.

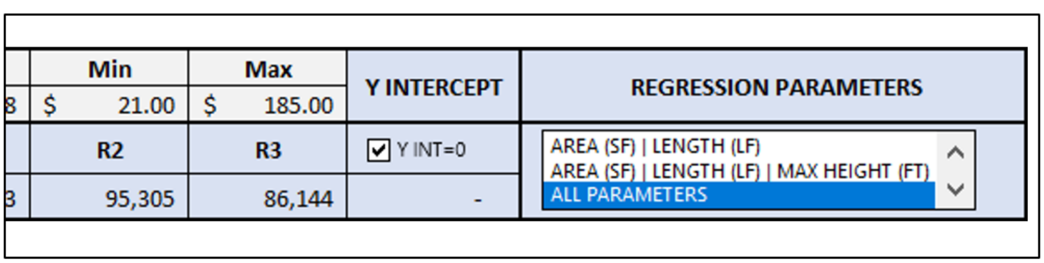


Figure A9. Regression Worksheet Parameter Selection

A3. Test Project

A test project was chosen at random to see how the Bid Price Estimating Tool would perform in predicting bid pricing using the various regression equations. The project chosen was the S.R. 115 (US-129, Alcoa Highway) project in Knox County, TN. The project was bid in August 2019 and contained 8 SP624 Retaining Walls of various sizes and configurations, totaling 52,704 sq. ft. Figure A10 shows the data used in the regression analysis.

RECORD	ACTUAL DATA										
	Wall Information				Length	Height		Bid Results			
	Job	REG	WALL	SF	LF	AHT	MHT	$/SF	TOTAL COST	BIDS	DATE
20	CNT023	1	1B	3,849	247.19	15.57	23.35	$ 83.69	$ 322,123	4	8/9/2019
21			2B	4,994	572.16	8.73	14.05	$ 78.03	$ 389,682		
22			3	5,660	400.00	14.15	22.39	$ 82.07	$ 464,516		
23			5	3,266	171.53	19.04	28.05	$ 116.17	$ 379,411		
24			6A	2,022	228.51	8.85	10.44	$ 79.17	$ 160,082		
25			7	19,246	975.00	19.74	23.38	$ 108.54	$ 2,088,961		
26			7A	10,626	859.18	12.37	20.53	$ 78.09	$ 829,784		
27			7B	3,041	170.80	17.80	19.07	$ 94.22	$ 286,523		

Figure A10. Actual Data for Regression Test

Based on the data entered, the Bid Price Estimating Tool was used to run each regression equation (Total $Cost_1$ to Total $Cost_8$) and obtained the following results for predicted bid pricing. Note that the default filter for the database was used (MHT<=40 ft.; $/SF <=$186/SF). Figure A11 shows the results, with the best result (All parameters with Y-Intercept = 0) just 6.3% higher than the actual bid price of $4,921,082. All bid projections were within ±10% of the actual bid results.

ACTUAL BID RESULTS		PROBABLE BID PRICE ESTIMATE							
		Y INTERCEPT = 0				Y INTERCEPT ≠ 0			
WALL	TOTAL COST	ALL	SF	SF/LF	SF/LF/MHT	ALL	SF	SF/LF	SF/LF/MHT
1B	$ 322,123	$ 381,181	$ 396,520	$ 400,393	$ 374,861	$ 395,299	$ 369,952	$ 382,770	$ 381,679
2B	$ 389,682	$ 438,885	$ 514,477	$ 438,368	$ 434,180	$ 469,602	$ 495,202	$ 442,676	$ 441,903
3	$ 464,516	$ 573,827	$ 583,088	$ 577,003	$ 561,432	$ 590,758	$ 568,055	$ 568,824	$ 567,947
5	$ 379,411	$ 331,304	$ 336,460	$ 352,079	$ 315,325	$ 342,541	$ 306,179	$ 329,565	$ 327,760
6A	$ 160,082	$ 125,270	$ 208,305	$ 178,505	$ 168,017	$ 147,347	$ 170,099	$ 160,824	$ 161,237
7	$ 2,088,961	$ 2,070,935	$ 1,982,705	$ 2,086,292	$ 2,132,932	$ 2,083,452	$ 2,054,207	$ 2,109,027	$ 2,111,799
7A	$ 829,784	$ 1,080,777	$ 1,094,681	$ 1,048,334	$ 1,058,457	$ 1,109,409	$ 1,111,278	$ 1,068,858	$ 1,068,174
7B	$ 286,523	$ 250,017	$ 313,281	$ 324,246	$ 303,036	$ 267,492	$ 281,566	$ 301,835	$ 301,570
ALL	$4,921,082	$5,252,197	$5,429,518	$5,405,220	$5,348,240	$5,405,899	$5,356,539	$5,364,378	$5,362,069
R2		0.950	0.937	0.941	0.942	0.916	0.895	0.899	0.899
+/-		6.30%	9.36%	8.96%	7.99%	8.97%	8.13%	8.26%	8.22%

Figure A11. Results of the Regression Test

Appendix B

Cast-in-place (CIP) Wall Low-Cost Design Spreadsheet Manual

B-1. Introduction

This document gives a step-by-step introduction and guide to using the Excel cast-in-place (CIP) design spreadsheet to generate low-cost designs. The design procedure follows the American Association of Highway and Transportation Officials (AASHTO) guidelines for Load and Resistance Factor Design (LRFD). The Appendix gives more details on the AASHTO LRFD and provides example calculations. The CIP wall design spreadsheet integrates the AASHTO LRFD for CIP walls with a sophisticated optimization algorithm to generate low-cost designs. The volumes of concrete and steel for the CIP designs are computed per foot linear of the wall.

The CIP wall design spreadsheet consists of three sheets: 1) *Design parameters*, 2) *Low-cost design*, and 3) *LRFD design details*. The following step-by-step instructions detail inputting design parameters and information, viewing the low-cost designs, and reviewing the AASHTO LRFD guidelines.

Step 1. Most of the information and design parameters for the CIP wall are inputted into the *Design parameters* worksheet (see Figure B-1). The yellow boxes are unlocked, and a user can input parameter values for geometry, retained and base soils, concrete and steel properties, Colorado Department of Transportation (CDOT) Guardrail Type 7, TL-4 vehicle collision, and live vertical surcharge loads. Also, three cost parameters are user-specified: cost of installed concrete \$/ft^3, cost of steel \$/lb., and cost of installation for reinforcing steel \$/ft.

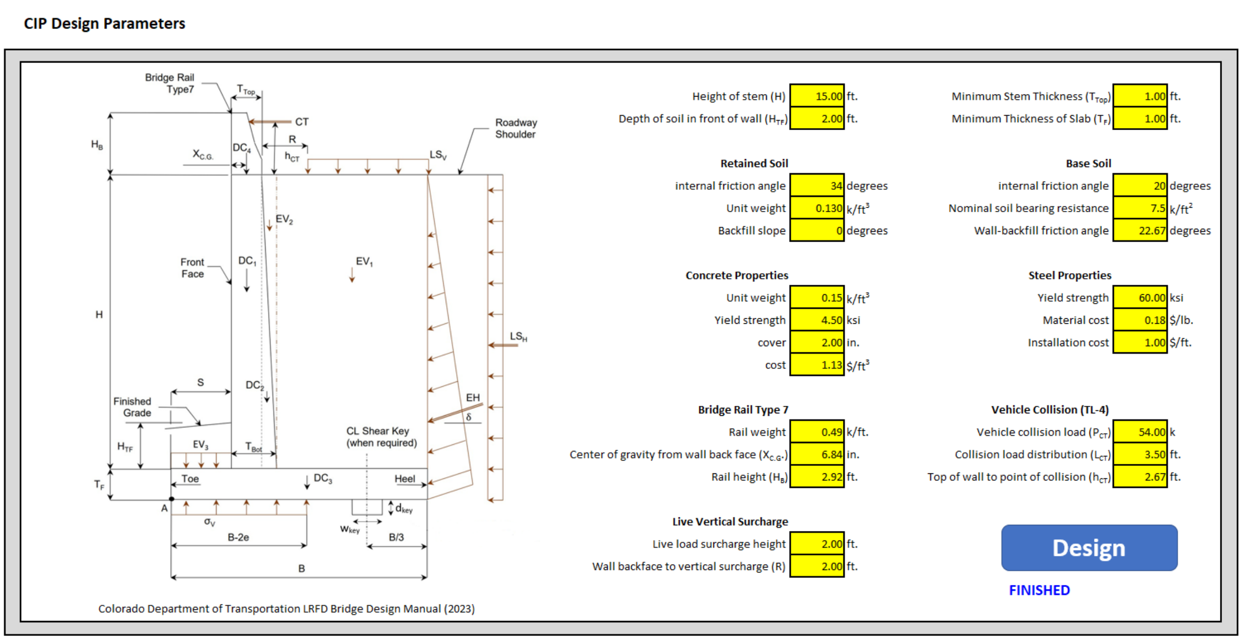


Figure B-1. Screenshot of the *Design parameters* worksheet

Values for geometry, retained and base soils, and concrete and steel properties are required. Required geometric values include:

- Height of stem (H)
- Depth of soil in front of the wall (HTF)
- Minimum stem thickness (T_{Top})
- Minimum thickness of slab (T_F)

Required retained soil values include:

- Internal friction angle
- Unit weight (k/ft^3)
- Backfill slope

Required base soil values include:

- Internal friction angle
- Nominal bearing resistance (k/ft^2)

Required concrete properties include:

- Unit weight (k/ft^3)
- Yield strength (ksi)
- Cover (in.)
- Concrete cost ($/ft^3)

Required steel properties include:

- Yield strength (ksi)
- Material cost ($/lb.)
- Installation cost ($/ft.)

The spreadsheet can generate designs without CDOT Guardrail Type 7 values, TL-4 vehicle collision, or live vertical surcharge loads.

CDOT Guardrail Type 7 values include:

- Rail weight (k/ft.)
- Center of gravity (in.)
- Rail height (ft.)
- Concrete cost ($/ft^3)

Vehicle collision (TL-4) values include:

- Vehicle collision load (k)
- Collision load distribution (ft.)
- Point of collision (ft.)

Live vertical surcharge load values include:

- Live load surcharge height (ft.)
- Wall backface to vertical surcharge (ft.)

Step 2. Low-cost design can be generated once the design parameter values are entered and verified. The design optimization algorithm is initiated by clicking the **Design** button in the lower-right-hand corner of the *Design parameters* worksheet (see Figure B-1). The optimization algorithm designs a CIP wall using the design parameter values entered in the *Design parameters* worksheet. It computes the low-cost CIP walls with and without a shear key. The details of the overall lowest-cost design are reported in the *Low-cost design* worksheet (automatically activated upon successful completion of the optimization algorithm). Figure B-2 shows a screenshot of the *Low-cost design* worksheet displaying the dimensions of the CIP wall and the steel reinforcing.

Low-Cost CIP Design

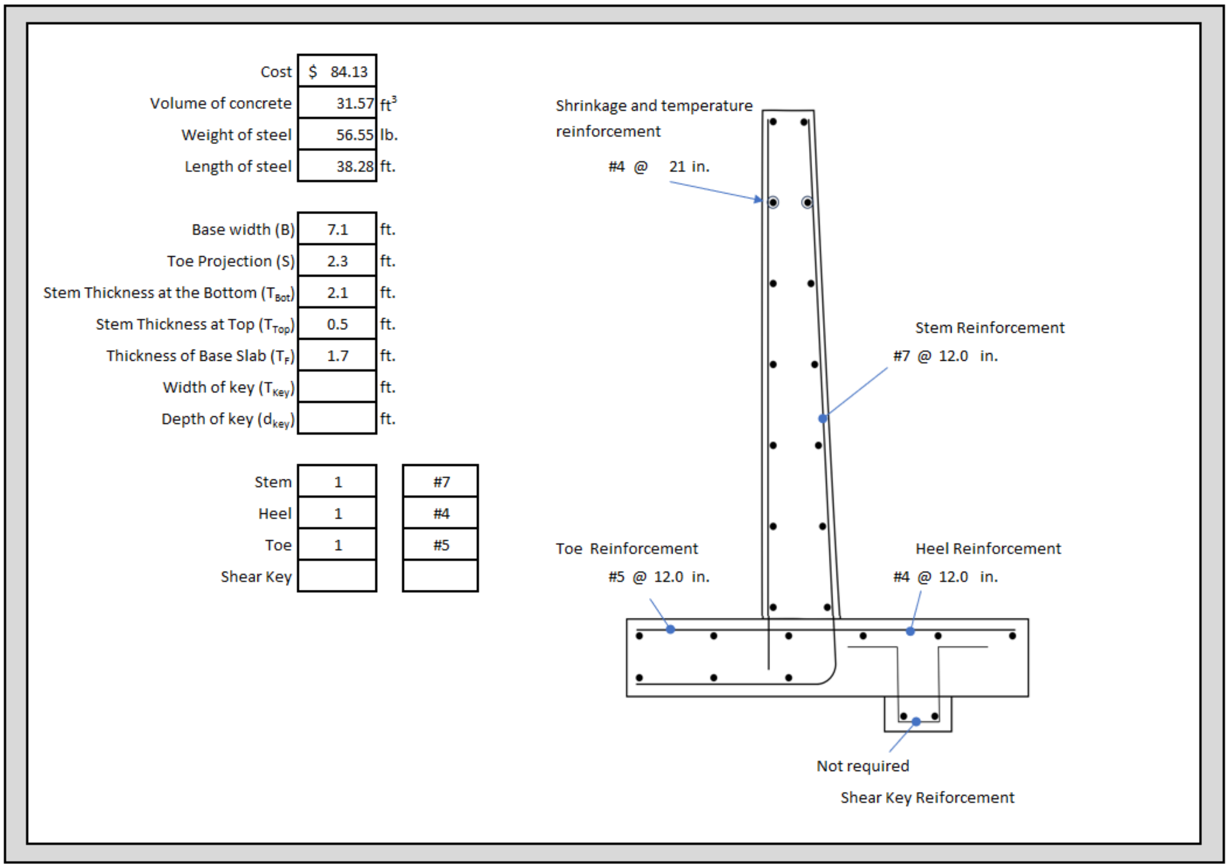


Figure B-2. Screenshot of the *Design parameters* worksheet

Step 3. The *LRFD design details* worksheet presents a comprehensive list of all the AASHTO LRFD calculations for the optimization design. The users adjust all values in the yellow boxes. In contrast, values in the green boxes are either transferred from the *Design parameters* worksheet or computed using equations prescribed in the AASHTO guidelines. Calculations are based on assumed values for LRFD resistance factors and load combinations. Table B-1 lists the default LRFD resistance factors.

Table B-1. AASHTO LRFD resistance factors

Bearing	φ_b =	0.55	AASHTO T.11.5.7-1
Sliding (concrete on soil)	φ_T =	1.00	AASHTO T.11.5.7-1
Sliding (soil on soil)	$\varphi_{Ts\text{-}s}$ =	1.00	AASHTO T.11.5.7-1
Passive pressure	φ_{ep} =	0.50	AASHTO T.10.5.5.2.2-1
Extreme event	φ_{EE} =	1.00	AASHTO 11.5.8

Table B-2 lists the default LRFD load factors and load combinations.

Table B-2. AASHTO LRFD load factors and load combinations

Load Combination	γ_{DC}	γ_{EV}	γ_{LS_V}	γ_{LS_H}	γ_{EH}	γ_{CT}	Application
Strength Ia	0.90	1.00	1.75	1.75	1.50	0.00	Sliding, Eccentricity
Strength Ib	1.25	1.35	1.75	1.75	1.50	0.00	Bearing, Strength
Strength IV	1.50	1.35	0.00	0.00	1.50	0.00	Bearing
Extreme IIa	1.00	1.00	0.50	0.50	0.00	1.00	Sliding, Eccentricity
Extreme IIb	1.00	1.00	0.00	0.00	0.00	1.00	Bearing
Service I	1.00	1.00	1.00	1.00	1.00	0.00	Wall Crack Control

Other user-adjustable factors include the exposure condition class and exposure factor for determining steel reinforcing spacing. Factors for flexural cracking variability, prestress, and the ratio of minimum yield strength to ultimate tensile strength for checking minimum steel reinforcement. Also, the concrete density modification factor and maximum aggregate size (in.) are used to check the shear in the concrete.

A #4 steel reinforcement bar is assumed for shrinkage and temperature control calculations.

B-2. Design of Cast-in-Place Retaining Walls using AASHTO LRFD 2020

This document outlines the steps to design cast-in-place (CIP) concrete retaining walls using the AASHTO LRFD Bridge Design Specifications (2020). The steps are divided into two sections: geotechnical design steps and structural design steps. Most of the required information for design is included in this document. However, there are a few sections in which the reader needs to read the appropriate AASHTO sections to see which equations are applicable.

Geotechnical Design

- **Step 1:** Establish project requirements, including all geometry, external loading conditions (transient and permanent, seismic, etc.), performance criteria, and construction constraints.
- **Step 2:** Evaluate site subsurface conditions and relevant properties of in situ soil, rock, and wall backfill parameters.
- **Step 3:** Evaluate soil and rock parameters for design and establish resistance factors.
- **Step 4:** Select the initial base dimension of the wall for strength limit state (external stability) evaluation. Figure B-3 shows the typical wall proportions (FHWA 2008).

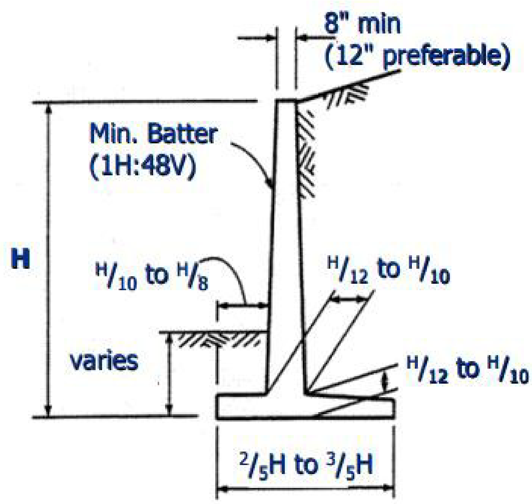


Figure B-3. Typical wall proportions (FHWA 2008)

- **Step 5:** Select lateral earth pressure distribution. Evaluate water, surcharge, compaction, and seismic pressures according to AASHTO 3.11.
  - Lateral earth pressure is computed using AASHTO Equation 3.11.5.1-1

$$p = k\gamma_z z$$

where:

p	= lateral earth pressure
k	= coefficient of lateral earth pressure
γ_z	= unit weight of soil
z	= depth below the surface

  - For normally consolidated soils, the at-rest lateral earth pressure coefficient is computed using AASHTO Equation 3.11.5.2-1

$$k_o = 1 - \sin\varphi'_f$$

where:

φ'_f	= effective friction angle of soil
k_o	= coefficient of at-rest lateral earth pressure

  - For overconsolidated soils, the at-rest lateral earth pressure coefficient is computed using AASHTO Equation 3.11.5.2-2

$$k_o = (1 - \sin\varphi'_f)(\mathrm{OCR})^{\sin\varphi'_f}$$

where OCR is the overconsolidation ratio

- The active lateral earth pressure coefficient is computed using AASHTO Equation 3.11.5.3-1

$$k_a = \frac{\sin^2(\theta + \varphi_f')}{\Gamma\left[\sin^2\theta \sin(\theta - \delta)\right]}$$

in which:

$$\Gamma = \left[1 + \sqrt{\frac{\sin(\varphi_f' + \delta)\sin(\varphi_f' - \beta)}{\sin(\theta - \delta)\sin(\theta + \beta)}}\right]^2$$

where:

δ = friction angle between fill and wall (degrees)
β = angle of fill to the horizontal (degrees)
θ = angle of the back face of the wall to the horizontal (degrees)

- The passive lateral earth pressure coefficient is obtained from AASHTO Figures 3.11.5.4-1 and 3.33.5.4-2 for flat and sloped backfills, respectively (Figures B-4 and B-5).

- **Step 6:** Evaluate factored loads for all appropriate loading groups and limit states.

  See Table B-3 (AASHTO Table 3.4.1-2) for load factors and Table B-4 (AASHTO Table 11.5.7-1) for resistance factors.

REDUCTION FACTOR (R) OF k_p
FOR VARIOUS RATIOS OF $-\delta/\phi_f$

ϕ_f \ δ/ϕ_f	−0.7	−0.6	−0.5	−0.4	−0.3	−0.2	−0.1	0.0
10	.978	.962	.946	.929	.912	.898	.881	.864
15	.961	.934	.907	.881	.854	.830	.803	.775
20	.939	.901	.862	.824	.787	.752	.716	.678
25	.912	.860	.808	.759	.711	.666	.620	.574
30	.878	.811	.746	.686	.627	.574	.520	.467
35	.836	.752	.674	.603	.536	.475	.417	.362
40	.783	.682	.592	.512	.439	.375	.316	.262
45	.718	.600	.500	.414	.339	.339	.221	.174

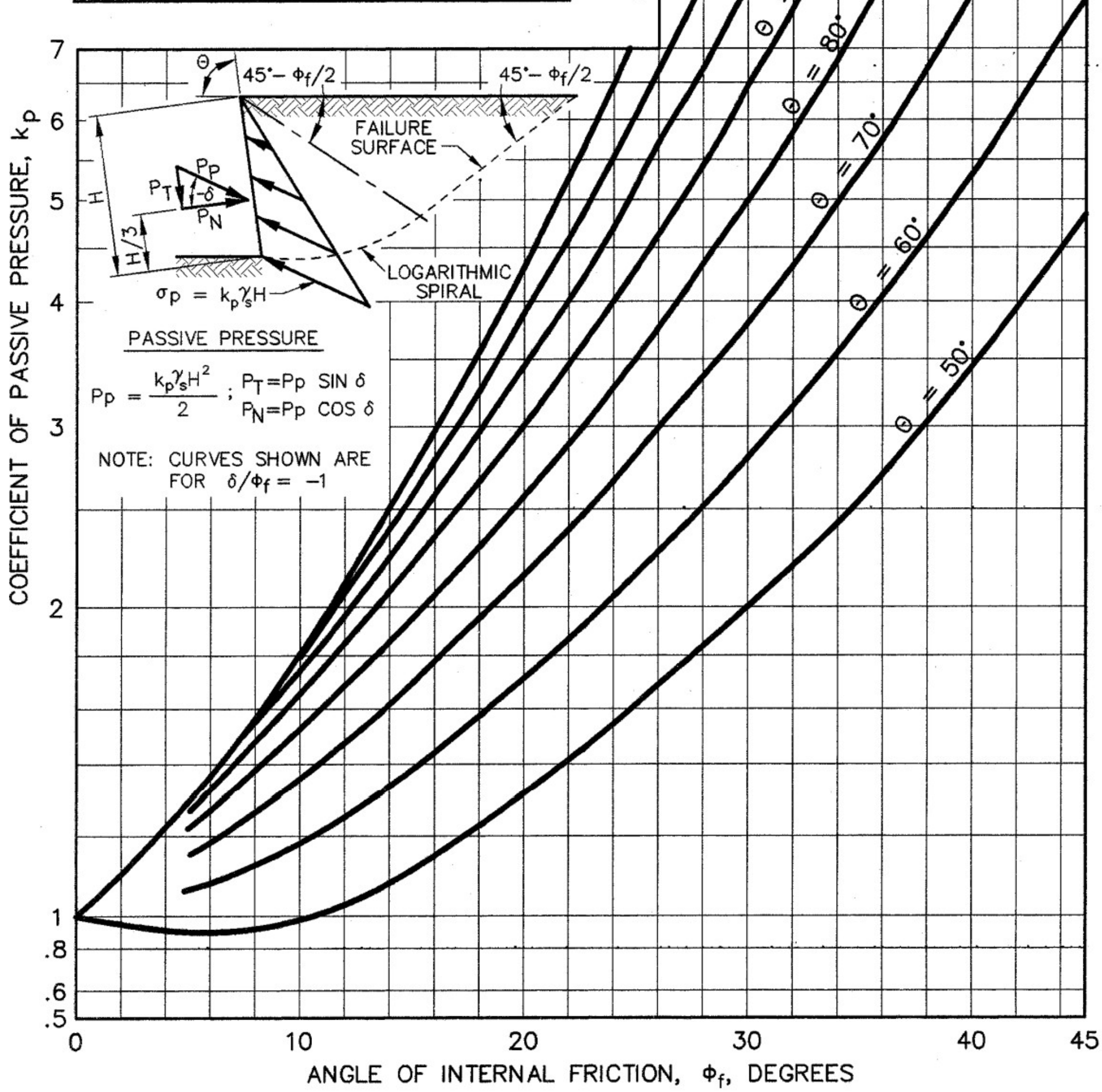
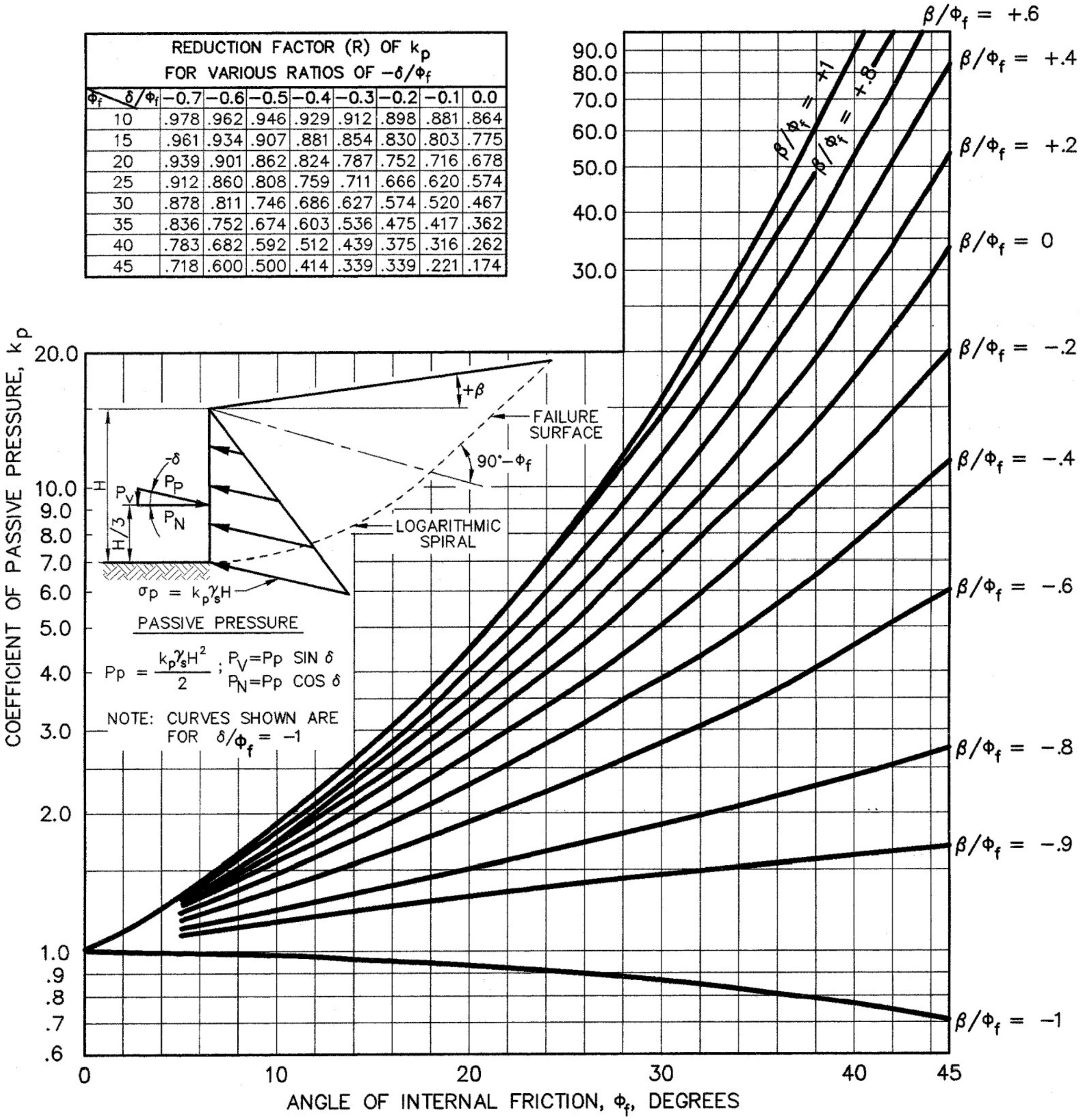


Figure B-4. AASHTO Figure 3.11.5.4-1



REDUCTION FACTOR (R) OF k_p FOR VARIOUS RATIOS OF $-\delta/\phi_f$

ϕ_f \ δ/ϕ_f	−0.7	−0.6	−0.5	−0.4	−0.3	−0.2	−0.1	0.0
10	.978	.962	.946	.929	.912	.898	.881	.864
15	.961	.934	.907	.881	.854	.830	.803	.775
20	.939	.901	.862	.824	.787	.752	.716	.678
25	.912	.860	.808	.759	.711	.666	.620	.574
30	.878	.811	.746	.686	.627	.574	.520	.467
35	.836	.752	.674	.603	.536	.475	.417	.362
40	.783	.682	.592	.512	.439	.375	.316	.262
45	.718	.600	.500	.414	.339	.339	.221	.174

Figure B-5. AASHTO Figure 3.11.5.4-2

Table B-3. AASHTO Table 3.4.1-2.

Table 3.4.1-2—Load Factors for Permanent Loads, γ_p

Type of Load, Foundation Type, and Method Used to Calculate Downdrag		Load Factor	
		Maximum	Minimum
DC: Component and Attachments		1.25	0.90
DC: Strength IV only		1.50	0.90
DD: Downdrag	Piles, α Tomlinson Method	1.40	0.25
	Piles, λ Method	1.05	0.30
	Drilled shafts, O'Neill and Reese (2010) Method	1.25	0.35
DW: Wearing Surfaces and Utilities		1.50	0.65
EH: Horizontal Earth Pressure			
• Active		1.50	0.90
• At-Rest		1.35	0.90
• *AEP* for anchored walls		1.35	N/A
EL: Locked-in Construction Stresses		1.00	1.00
EV: Vertical Earth Pressure			
• Overall and Compound Stability		1.00	N/A
• Retaining Walls and Abutments		1.35	1.00
• MSE wall internal stability soil reinforcement loads			
○ Stiffness Method			
▪ Reinforcement and connection rupture		1.35	N/A
▪ Soil failure – geosynthetics (Service I)		1.20	N/A
○ Coherent Gravity Method		1.35	N/A
• Rigid Buried Structure		1.30	0.90
• Rigid Frames		1.35	0.90
• Flexible Buried Structures			
○ Metal Box Culverts, Structural Plate Culverts with Deep Corrugations, and Fiberglass Culverts		1.50	0.90
○ Thermoplastic Culverts		1.30	0.90
○ All others		1.95	0.90
• Internal and Compound Stability for Soil Failure in Soil Nail Walls		1.00	N/A
ES: Earth Surcharge		1.50	0.75

Table B-4. AASHTO Table 11.5.7-1

Table 11.5.7-1—Strength Limit State Resistance Factors for Permanent Retaining Walls

Wall-Type and Condition		Resistance Factor
Nongravity Cantilevered and Anchored Walls		
Axial compressive resistance of vertical elements		Article 10.5 applies
Passive resistance of vertical elements		0.75
Pullout resistance of anchors (1)	• Cohesionless (granular) soils • Cohesive soils • Rock	0.65 (1) 0.70 (1) 0.50 (1)
Pullout resistance of anchors (2)	• Where proof tests are conducted	1.0 (2)
Tensile resistance of anchor tendon	• Mild steel (e.g., ASTM A615 bars) • High-strength steel (e.g., ASTM A722 bars)	0.90 (3) 0.80 (3)
Overall stability, soil failure		Article 11.6.3.7 applies
Flexural capacity of vertical elements		0.90
Mechanically Stabilized Earth Walls, Gravity Walls, and Semigravity Walls		
Bearing resistance	• Gravity and semigravity walls • MSE walls	0.55 0.65
Sliding		1.0
Tensile resistance of metallic reinforcement and connectors	Strip reinforcements (4) Grid reinforcements (4) (5)	0.75 0.65
Tensile resistance of geosynthetic reinforcement and connectors	• Geotextile and geogrid reinforcements • Geostrip reinforcements	0.80 0.55
Pullout resistance of metallic reinforcement Pullout resistance of geosynthetic reinforcement	• Steel strip reinforcements • Steel grid reinforcements • Geotextiles and geogrids • Geostrip reinforcements	0.90 0.90 0.70 0.70
Service Limit, for soil failure using stiffness method		1.0
Overall and compound stability, soil failure		Article 11.6.3.7 applies
Prefabricated Modular Walls		
Bearing		Article 10.5 applies
Sliding		Article 10.5 applies
Passive resistance		Article 10.5 applies
Overall stability, soil failure		Article 11.6.3.7 applies
Soil Nail Walls (6)		
Lateral sliding		1.00
Overall and Compound stability, soil failure		Article 11.6.3.7 applies
Tensile resistance of nail tendon	Mild steel bars (Grade 75) High resistance bars (Grades 95 and 150)	0.75 0.65
Pullout resistance of nail		0.65
Facing flexure	Initial and final facing	0.90
Facing punching shear	Initial and final facing	0.90
Tensile resistance of headed stud	A307 steel bolt (7) A325 steel bolt	0.70 0.80

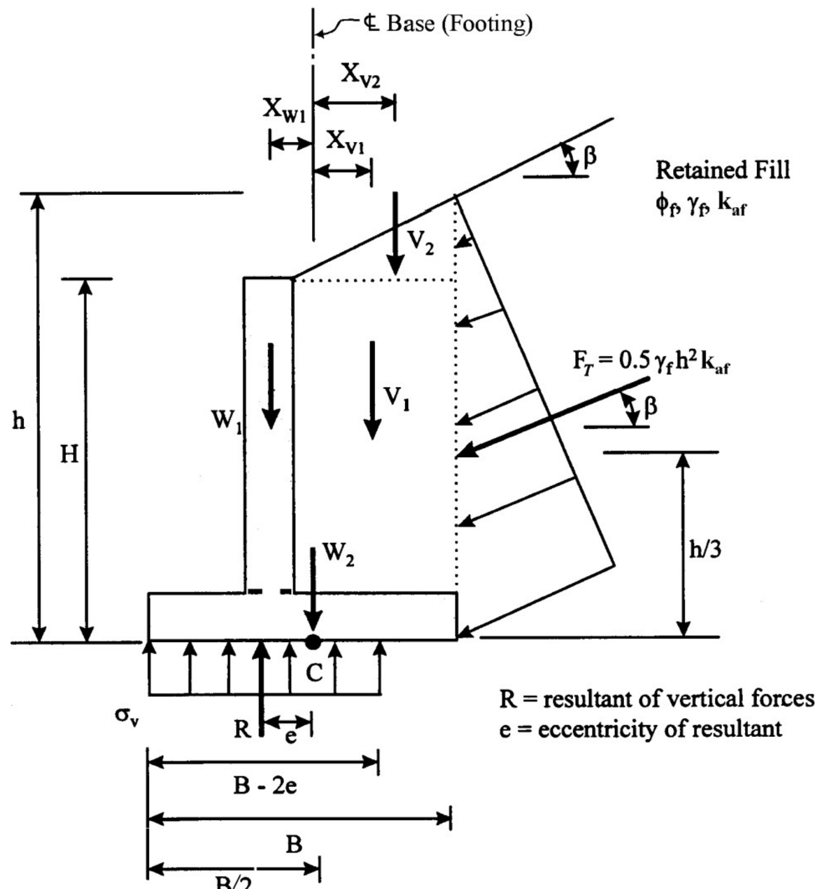
- **Step 7:** Evaluate bearing resistance - ASHTO 11.6.3.2

  - For walls supported by soil foundation, the vertical stress shall be calculated using AASHTO Equation 11.6.3.2-1.

$$\sigma_v = \frac{\sum V}{B - 2e}$$

where:

ΣV = summation of vertical forces defined in Figure B-6 (AASHTO Figure 11.6.3.2-1); the remaining variables are described in Figure B-6



Summing moments about Point C:

$$e = \frac{(F_T Cos\beta)h/3 - (F_T \sin\beta)B/2 - V_1 X_{V_1} - V_2 X_{V2} + W_1 X_{W1}}{V_1 + V_2 + W_1 + W_2 + F_T \sin\beta}$$

Figure B-6. AASHTO Figure 11.6.3.2-1

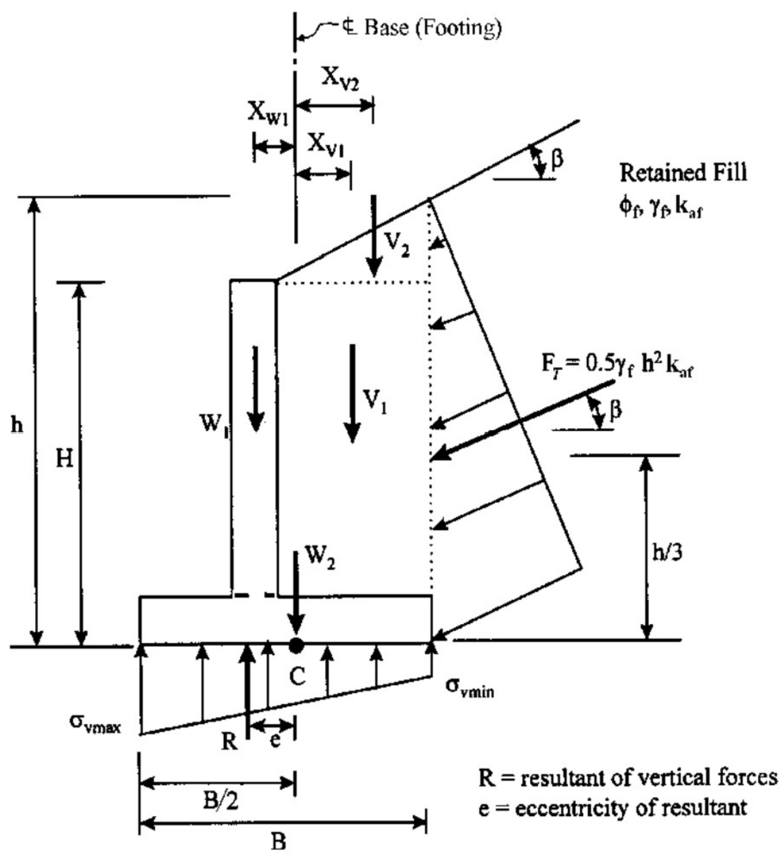
  - For walls supported by rock foundation, the vertical stress shall be calculated using AASHTO Equations 11.6.3.2-2 and 11.6.3.2-3 (if the resultant is within the middle one-third of the base).

$$\sigma_{V_{max}} = \frac{\sum V}{B}\left(1 + 6\frac{e}{B}\right)$$

$$\sigma_{V_{min}} = \frac{\sum V}{B}\left(1 - 6\frac{e}{B}\right)$$

where:

ΣV = summation of vertical forces defined in Figure B-7 (AASHTO Figure 11.6.3.2-2); the remaining variables are described in Figure B-7



If e > B/6, σ_{vmin} will drop to zero, and as "e" increases, the portion of the heel of the footing which has zero vertical stress increases.

Summing moments about Point C:

$$e = \frac{\left(F_T Cos\beta\right)h/3 - \left(F_T \sin\beta\right)B/2 - V_1 X_{V_1} - V_2 X_{V2} + W_1 X_{W1}}{V_1 + V_2 + W_1 + W_2 + F_T \sin\beta}$$

Figure B-7. AASHTO Figure 11.6.3.2-2

- For walls supported by rock foundation, the vertical stress shall be calculated using AASHTO Equations 11.6.3.2-4 and 11.6.3.2-5 (if the resultant is outside the middle one-third of the base).

$$\sigma_{v_{max}} = \frac{2\sum V}{3\left(\frac{B}{2} - e\right)}$$

$$\sigma_{v_{min}} = 0$$

where:

ΣV = summation of vertical forces defined in Figure B-7 (AASHTO Figure 11.6.3.2-2); the remaining variables are described in Figure B-7

- Revise the design if necessary.

- **Step 8:** Check eccentricity - AASHTO 11.6.3.3
  - This section states that the location of the resultant of the reaction forces shall be within the middle two-thirds of the base width (foundations on soil) and the middle nine-tenths of the base width (foundations on rock).
  - Revise if necessary.

- **Step 9**: Check sliding - AASHTO 11.6.3.6 (10.6.3.4)
  - The factored resistance against failure by sliding (in kips) is computed as

$$R_R = \varphi R_n = \varphi_\tau R_\tau + \varphi_{ep} R_{ep}$$

where:

φ = resistance factor
R_n = nominal sliding resistance against failure by sliding (kips)
φ_τ = resistance factor for shear resistance between soil and foundation specified in Table B-6 (AASHTO Table 10.5.5.2.2-1)
R_τ = nominal sliding resistance between soil and foundation (kips)
φ_{ep} = resistance factor for passive resistance specified in Table B-3
R_{ep} = nominal passive resistance of soil available throughout the design life of the structure (kips)

Table B-6. AASHTO Table 10.5.5.2.2-1.

Method/Soil/Condition			Resistance Factor
Bearing Resistance	φ_b	Theoretical method (Munfakh et al., 2001), in clay	0.50
		Theoretical method (Munfakh et al., 2001), in sand, using *CPT*	0.50
		Theoretical method (Munfakh et al., 2001), in sand, using *SPT*	0.45
		Semi-empirical methods (Meyerhof, 1957), all soils	0.45
		Footings on rock	0.45
		Plate Load Test	0.55
Sliding	φ_τ	Precast concrete placed on sand	0.90
		Cast-in-Place Concrete on sand	0.80
		Cast-in-Place or precast Concrete on Clay	0.85
		Soil on soil	0.90
	φ_{ep}	Passive earth pressure component of sliding resistance	0.50

- If the wall sits on cohesionless soil, the nominal sliding resistance between soil and foundation is computed using AASHTO Equation 10.6.3.4-2.

$$R_\tau = CV \tan\varphi_f$$

where:

C	=	1.0 for concrete cast against soil 0.8 for precast concrete footing
φ_f	=	internal friction angle of drained soil (degrees)
V	=	total vertical force (kips)

- If the wall sits on clay, the nominal sliding resistance between soil and foundation is taken as the lesser of
    - the cohesion of the clay or
    - one-half of the normal stress on the interface between the footing and soil, as shown in Figure B-8 (AASHTO Figure 10.6.3.4-1).
- Add key or revise design if necessary.

- **Step 10:** Check overall stability at the service limit state and revise the wall design if necessary.

  AASHTO 11.6.3.7 states that the overall stability should be analyzed using limit equilibrium methods. This section also says that the overall stability of earth slopes should be investigated at the strength I load combination with resistance factor, φ, of 0.75 for well subsurface stratigraphy and 0.65 for highly variable subsurface stratigraphy.

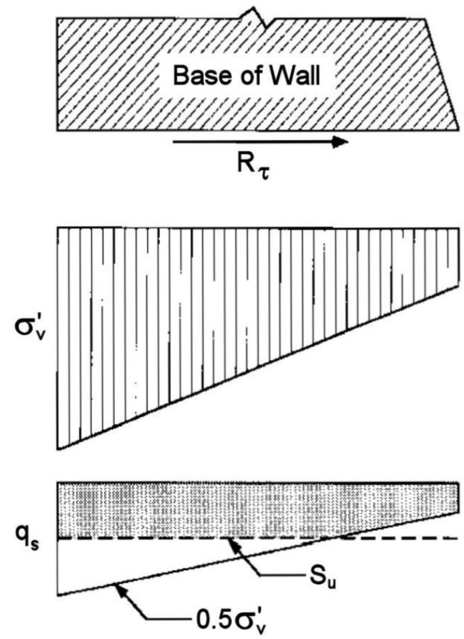


Figure B-8. AASHTO Figure 10.6.3.4-1

- **Step 11:** Estimate maximum lateral wall movement, tilt, and wall settlement at the service limit state. Revise the design if necessary.

  The following sections provide guidance regarding tolerable movements: AASHTO 10.6.2.2 (10.5.2.1), 10.7.2.2 (10.5.2.1), and 10.8.2.1 (10.5.2.1).

  Sections AASHTO 10.6.2.4, 10.7.2.3-10.7.2.5 (piles), and 10.8.2.2-10.8.2.4 (shafts) provide guidance for estimating settlement.

- **Step 12:** Design wall drainage systems.

  AASHTO 11.6.6 says that backfills shall be drained. If drainage cannot be provided, the wall must be designed for loads due to earth pressure plus full hydrostatic pressure due to water in the backfill.

Structure Design

- **Step 1:** Define the strength properties of concrete and reinforcement and resistance factors.
  - AASHTO 5.4.2.4 defines the modulus of elasticity E_c of normal-weight concrete with design compressive strengths up to 15.0 ksi and lightweight concrete up to 10.0 ksi, with unit weights between 0.090 and 0.155 kcf as

$$E_c = 120{,}000 K_1 w_c^2 f_c'^{0.33} \qquad \text{Eq. 5.4.2.4-1}$$

where:

K_1 = correction factor for the source of aggregate to be taken as 1.00 unless determined by physical tests and as approved by the owner
w_c = unit weight of concrete (kcf)
f'_c = compressive strength of concrete (ksi)

- AASHTO 5.4.3.2 says that the modulus of elasticity of steel shall be assumed as 29,000 ksi for specified minimum yield strengths up to 100 ksi.
- AASHTO 5.5.4.2 gives the resistance factors for flexural-tension control and shear-torsion control.
- AASHTO 5.6.1 defines the modular ratio as $n = E_s/E_c$ for reinforcing bars where:

  E_s = modulus of elasticity of reinforcement (ksi)
  E_c = modulus of elasticity of concrete (ksi)

- AASHTO 5.6.2.2 gives information regarding the rectangular stress distribution.

- **Step 2:** Design the wall stem.
  - Obtain factored loads and moments acting on the stem.
  - Design the stem for flexure using AASHTO 5.6.3.2.
  - The factored flexural resistance, M_R, is computed as

$$M_R = \varphi M_n \qquad \text{Eq. 5.6.3.2.1-1}$$

where:

φ = resistance factor from Article 5.5.4.2
M_n = nominal flexural resistance

  - The nominal flexural resistance for rectangular sections is computed as

$$M_n = A_{ps} f_{ps}\left(d_p - \frac{a}{2}\right) + A_s f_s\left(d_s - \frac{a}{2}\right) - A'_s f'_s\left(d'_p - \frac{a}{2}\right) \qquad \text{Eq. 5.6.3.2.2-1}$$

where

A_{ps} = area of prestressing steel (in^2)
f_{ps} = compressive average stress in prestressing steel at nominal bending resistance (ksi) specified in Eq. 5.6.3.1.1-1
d_p = distance from extreme compression fiber to the centroid of the prestressing tendons (in)
A_s = area of nonprestressed tension reinforcement (in^2)
f_s = stress in the nonprestressed tension reinforcement at nominal

flexural resistance (ksi)

d_s = distance from extreme compression fiber to the centroid of nonprestressed tensile reinforcement (in)

A'_s = area of compression reinforcement (in^2)

f'_s = stress in the nonprestressed compression reinforcement at nominal flexural resistance (ksi) as specified in Article 5.6.2.1

d'_s = distance from extreme compression fiber to the centroid of compression reinforcement (in)

a = $c\beta_1$ depth of the equivalent stress block (in)

$$c = \frac{A_{ps}f_{ps} + A_s f_s - A'_s f'}{\alpha_1 f'_c \beta_1 b} \qquad \text{Eq. 5.6.3.1.2-4}$$

(for rectangular sections)

β_1 = stress block factor specified in Article 5.6.2.2

α_1 = stress block factor specified in Article 5.6.2.2

- Check that the tensile reinforcement meets the minimum requirement using AASHTO 5.6.3.3.
- The factored flexural resistance, M_R, must be greater than or equal to the lesser of 1.33 times the factored moment (required by the applicable Strength Load combination specified in Table 3.4.1-1) and the cracking moment, M_{cr}.
- The cracking moment is computed using AASHTO equation 5.6.3.3-1.

$$M_{cr} = \gamma_3\left[\left(\gamma_1 f_r + \gamma_2 f_{cpe}\right)S_c - M_{dnc}\left(\frac{S_c}{S_{nc}} - 1\right)\right]$$

where

f_r = modulus of rupture of concrete specified in Article 5.4.2.6

f_{cpe} = compressive stress in concrete due to effective prestress forces only at the extreme fiber of section where tensile stress is caused by externally applied loads (ksi)

S_c = section modulus for the extreme fiber of the composite section where tensile stress is caused by externally applied loads (in^3)

M_{dnc} = total unfactored dead load moment acting on the monolithic or non-composite section (kip-in)

S_{nc} = section modulus for the extreme fiber of the monolithic or non-composite section where tensile stress is caused by externally applied loads (in^3)

γ_1 = flexural cracking variability factor (see section 5.6.3.3) = 1.6 for CIP retaining walls

γ_2 = prestress variability factor (see section 5.6.3.3). It does not apply to typical TDOT retaining walls.

γ_3 = ratio of specified minimum yield strength to ultimate tensile strength of the nonprestressed reinforcement (see section 5.6.3.3)

- Check the reinforcement spacing using AASHTO 5.6.7.

  This section requires the spacing, *s*, of nonprestressed reinforcement in the layer closest to the tension face to satisfy the following:

$$s \leq \frac{700\gamma_e}{\beta_s f_{ss}} - 2d_c \qquad \text{Eq. 5.6.7-1}$$

in which:

$$\beta_s = 1 + \frac{d_c}{0.7(h - d_c)} \qquad \text{Eq. 5.6.7-2}$$

where:

γ_e = exposure factor (see section 5.6.7)

β_s = ratio of flexural strain at the extreme tension face to the strain at the centroid of the reinforcement layer nearest the tension face

f_{ss} = calculated tensile stress in nonprestressed reinforcement at the service limit state not to exceed $0.60 f_y$ (ksi)

d_c = thickness of concrete cover measured from extreme tension fiber to center of the flexural reinforcement closest to it (in.)

h = overall thickness or depth of the component (in.)

- Revise reinforcement selection if necessary.
- Check to see if shear reinforcement is required using AASHTO 5.7.2.3.
- This section states that except for slabs, footings, and culverts, shear reinforcement is required if

$$V_u = 0.5\varphi(V_c + V_p) \qquad \text{Eq. 5.7.2.3-1}$$

where:

V_u = factored shear force (kip)

φ = resistance factor specified in Article 5.5.4.2

V_c = nominal shear resistance of the concrete (kip)

V_p = component of prestressing force in the direction of the shear force

- The nominal shear resistance of concrete V_c is computed as

$$V_c = 0.0316\beta\lambda\sqrt{f'_c}\,b_v d_v \qquad \text{Eq. 5.7.3.3-3}$$

where:

β = factor indicating the ability of diagonally cracked concrete to transmit tension and shear as specified in Article 5.7.3.4

λ = concrete density modification factor as specified in Article 5.4.2.8

b_v = effective web width is taken as the minimum web width within the depth

d_v = effective shear depth as determined in Article 5.7.2.8 (in)

- The parameter β is computed for sections with at least the minimum amount of transverse reinforcement specified in Article 5.7.2.5 as

$$\beta = \frac{4.8}{(1+750\varepsilon_s)}$$

For sections not containing the minimum amount of transverse reinforcement specified in Article 5.7.2.5 as

$$\beta = \frac{4.8}{(1+750\varepsilon_s)}\frac{51}{(39+s_{xe})}$$

where

$$\varepsilon_s = \frac{\dfrac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{ps}f_{po}}{E_sA_s + E_pA_{ps}}$$

in which:

M_u = absolute value of the factored moment at the section, not taken less than $|V_u\text{-}V_p|\,d_v$ (kip-in)

N_u = factored axial force, taken as positive if tensile and negative if compressive (kip)

V_u = factored shear force for the girder in Eq. 5.7.3.4.2-5 and for the web under consideration in Eq. 5.7.3.4.2-6 (kip)

A_{ps} = area of prestressing steel on the flexural tension side of the member, as shown in Figure 5.7.3.4.2-1 (in^2)

f_{po} = a parameter taken as the modulus of elasticity of prestressing steel multiplied by the locked-in difference in strain between the prestressing steel and the surrounding concrete (ksi). For the usual levels of prestressing, a value of 0.7 f_{pu} is appropriate for pre-tensioned and post-tensioned members.

E_s = modulus of elasticity of reinforcement (ksi)
A_s = area of nonprestressed tension reinforcement (in^2)
E_p = modulus of elasticity of prestressing steel (ksi)
A_{ps} = area of prestressing steel (in^2)
s_x = crack spacing parameter, taken as the lesser of either d_v or the maximum distance between layers of longitudinal crack control reinforcement, where the area of the reinforcement in each layer is not less than $0.003 b_v s_x$, as shown in Figure 5.7.3.4.2-3 (in)
a_g = maximum aggregate size (in)

- Design shrinkage and temperature reinforcement using AASHTO 5.10.6
- The area of shrinkage/temperature, A_S, shall satisfy the following:

$$A_s \geq \frac{1.3bh}{2(b+h)f_y} \quad \text{Eq. 5.10.6-1}$$

$$0.11 \leq A_s \leq 0.60 \quad \text{Eq. 5.10.6-2}$$

where:

A_S = area of reinforcement in each direction and each face (in^2/ft.)
b = least width of the component section (in)
h = least thickness of component section (in)
f_y = specified minimum yield strength of reinforcement ≤ 75.0 ksi

- **Step 3**: Design the footing heel.
  - Obtain factored loads and moments acting on the heel.
  - The reinforcement design procedure is the same as in Step 2. Applicability of Article 5.7.2.3 to footings to be established.

- **Step 4:** Design the footing toe.
  - Obtain factored loads and moments acting on the heel.
  - The reinforcement design procedure is the same as in Step 2. Applicability of Article 5.7.2.3 to footings to be established.

- **Step 5:** Design the shear key (if one is required).
  - Obtain factored loads and moments acting on the heel.

- The reinforcement design procedure is the same as in Step 2. Applicability of Article 5.7.2.3 to footings to be established.

Design Example

The following is an example of a CIP concrete cantilever retaining wall design from the Colorado Department of Transportation Bridge Design Manual. This design example supports a 15-foot-level roadway embankment measured from the top of the wall to the top of the footing. This wall will be built adjacent to the roadway shoulder, where the traffic is 2 ft. from the barrier face. The wall stem is 1.5 ft. wide to accommodate mounting a Type 7 Bridge Rail to the top of the wall (see Figure B-9).

The solution to this example is given below (the highlighted values are input values).

Soil: CDOT Class 1 Backfill-Drained				
Soil unit weight	γ_s =	0.130	kcf	
Friction angle (backfill)	ϕ =	34	deg	
Wall-backfill friction angle	δ =	22.67	deg	
	Γ =	2.94		
Coefficient of active earth pressure	K_a =	0.261		AASHTO Eq. 3.11.5.3-1
Coefficient of passive earth pressure	K_p =	3.54		AASHTO Fig. 3.11.5.4-1
Active equivalent fluid weight	EFW (a) = $K_a\gamma_s$ =	0.036		CDOT BDM 11.5
Passive equivalent fluid weight	EFW (p) = $K_p\gamma_s$ =	0.459		
Angle of fill to the horizontal	β =	0	deg	
Subgrade: for bearing and sliding				
Nominal soil bearing resistance	q_n =	7.5	ksf	
Friction angle (subgrade)	ϕ_{sub} =	20	deg	
Wall-subgrade friction angle	$\delta_{sub} = 2/3\phi_{sub}$ =	13.33	deg	
Nominal soil sliding coefficient	$\mu_n = \tan(\phi_{sub})$ =	0.36		AASHTO C.10.6.3.4
Concrete: CDOT Concrete Class D				
Concrete compressive strength	f'_c =	4.50	ksi	
Concrete unit weight	γ_c =	0.150	kcf	
Bridge Rail Type 7				
Type 7 bridge rail weight	w_{rail} =	0.486	klf	
Center of gravity from wall back face	XC.G. =	6.84	in.	
Rail height	H_B =	2.92	ft.	

Wall Geometry Information

Stem height	H =	15.00	ft.	
Top of wall thickness	T_{top} =	1.50	ft.	
Bottom of wall thickness	T_{bot} =	1.75	ft.	
Width of footing	B =	10.00	ft.	
Thickness of footing	T_F =	1.25	ft.	
Toe distance	S =	2.75	ft.	
Height of fill over the toe	H_{TF} =	2.00	ft.	
Minimum footing embedment ≥ 3 ft.	$H_{TF} + T_F$ =	3.50	ft.	
Bridge rail type 7 height	H_B =	2.92	ft.	
Wall backface to vertical surcharge	R =	2.00	ft.	
Live load surcharge height	h_{sur} =	2.00	ft.	AASHTO Table 3.11.6.4-2
Vehicle collision load (TL-4)	P_{CT} =	54.00	kip	AASHTO Table A13.2-1
Collision load distribution	L_t =	3.50	ft.	AASHTO Table A13.2-1
Top of wall to point of collision impact on rail	h_{CT} =	2.67	ft.	

Resistance Factors

Bearing	ϕ_b =	0.55		AASHTO T.11.5.7-1
Sliding (concrete on soil)	ϕ_T =	1.00		AASHTO T.11.5.7-1
Sliding (soil on soil)	$\phi_{T\,s\text{-}s}$ =	1.00		AASHTO T.11.5.7-1
Passive pressure	ϕ_{ep} =	0.50		AASHTO T.10.5.5.2.2-1
Extreme event	ϕ_{EE} =	1.00		AASHTO 11.5.8
Angle of back face of wall to the horizontal	θ =	89.05	deg	

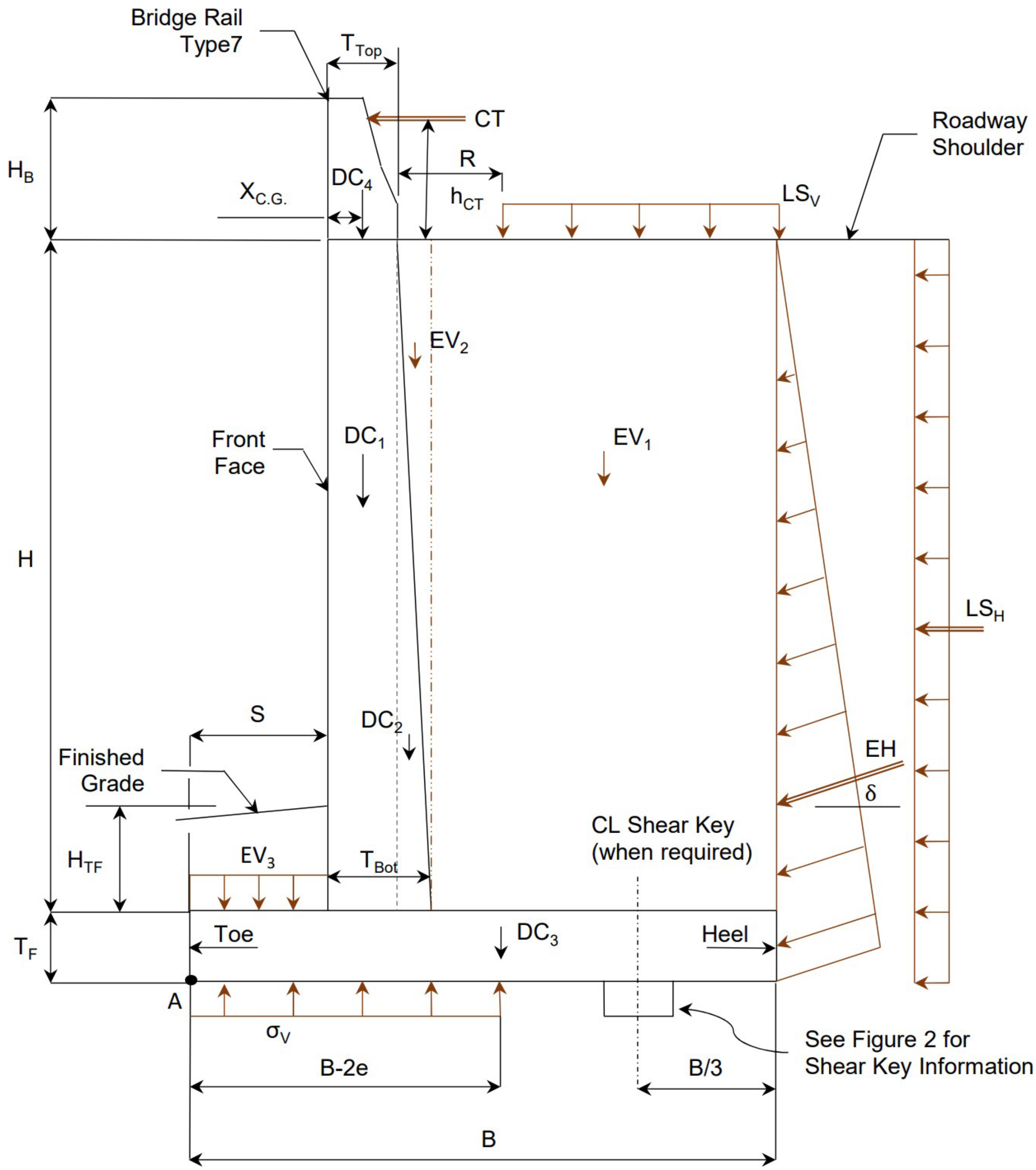


Figure B-9. Wall geometry and loading.

The unfactored loads are computed as the following:

Unfactored Loads & Moments

Vertical Loads & Moments				
Load Type	Description	*V* (kip/ft.)	Moment Arm (ft.)	*MV* (kip-ft.)/ft.
DC_1	Stem dead load	3.38	3.50	11.81
DC_2	Stem dead load	0.28	4.33	1.22
DC_3	Footing dead load	1.88	5.00	9.38
DC_4	Barrier dead load	0.49	3.32	1.61
EV_1	Vertical pressure from dead load of fill on heel	10.73	7.25	77.76
EV_2	Vertical pressure from dead load of fill on heel	0.24	4.42	1.08
EV_3	Vertical pressure from dead load of fill on toe	0.72	1.38	0.98
EH_V	Vertical component of horizontal earth pressure	1.83	10.00	18.32
LS_V	Vertical component of live load surcharge	0.98	8.13	7.92

Vertical Loads & Moments				
Load Type	Description	*H* (kip/ft.)	Moment Arm (ft.)	*MH* (kip-ft.)/ft.
EH_V	Vertical component of horizontal earth pressure	4.39	5.42	23.76
LS_H	Horizontal component of live load surcharge	1.17	8.13	9.51
CT	Vehicular collision load	2.61	18.92	49.43

The load factors and load combinations for each application are listed below.

Load Combinations

Load Factors

Load Cases	γ_{DC}	γ_{EV}	γ_{LS_V}	γ_{LS_H}	γ_{EH}	γ_{CT}	Application
Strength Ia	0.90	1.00	1.75	1.75	1.50	0.00	Sliding, Eccentricity
Strength Ib	1.25	1.35	1.75	1.75	1.50	0.00	Bearing, Strength
Strength IV	1.50	1.35	0.00	0.00	1.50	0.00	Bearing
Extreme IIa	1.00	1.00	0.50	0.50	0.00	1.00	Sliding, Eccentricity
Extreme IIb	1.00	1.00	0.00	0.00	0.00	1.00	Bearing
Service I	1.00	1.00	1.00	1.00	1.00	0.00	Wall Crack Control

Load Groups				
Load Combination	Vertical Load & Moment		Horizontal Load & Moment	
	ΣV (kip/ft.)	ΣMV (kip-ft.)/ft.	ΣH (kip/ft.)	ΣMH (kip-ft.)/ft.
Strength Ia	21.55	142.77	8.63	52.27
Strength Ib	27.75	179.12	8.63	52.27
Strength IV	27.55	171.26	6.58	35.64
Extreme IIa	18.19	107.80	3.20	54.18
Extreme IIb	17.70	103.84	2.61	49.43
Service I	20.51	130.07	5.56	33.26

After obtaining the appropriate loads, the wall must be evaluated for overturning, bearing capacity, and sliding. These analyses are below. Overturning failure is not a problem.

Eccentricity Check (Overturning)				
Eccentricity	$e = \frac{B}{2} - \frac{\sum MV - \sum MH}{\sum V}$		AASHTO 10.6.3.3	
e_{max} = B(2/3) =	6.67	ft.		
Strength Ia e =	0.80	ft.	Is $e < e_{max}$?	OK
Extreme IIa e =	2.05	ft.	Is $e < e_{max}$?	OK

Bearing Resistance Check					
Vertical stress	$\sigma_v = \frac{\sum V}{B - 2e}$			AASHTO 11.6.3.2-1	
Factored bearing resistance	$q_R = \phi_b q_n$ =	4.13	ksf		
Extreme limit state	$q_{R\_EE} = \phi_{EE} q_n$ =	7.50	ksf		
Strength Ib	e =	0.43	ft.		
	σ_V =	3.04	ksf	Is $\sigma_V < q_R$?	OK
Strength IV	e =	0.08	ft.		
	σ_V =	2.80	ksf	Is $\sigma_V < q_R$?	OK
Extreme IIb	e =	1.93	ft.		
	σ_V =	2.88	ksf	Is $\sigma_V < q_{R\_EE}$?	OK
Service I	e =	0.28	ft.		
	σ_V =	2.17	ksf	For toe reinforcement	

Bearing capacity is not an issue.

Sliding Check					
Factored sliding resistance	$R_R = \varphi R_n = \varphi_\tau R_\tau + \varphi_{ep} R_{ep}$ $R_\tau = CV \tan\varphi_f = CV\mu_n$ AASHTO 10.6.3.4				
	C =	1.00			
	Nominal soil sliding coefficient μ_n =	0.36			
	Nominal passive Resistance (neglected) R_{ep} =	0.00			
Strength Ia	R_R =	7.84	kip/ft.		
	ΣH =	8.63	kip/ft.	Is $\Sigma H < R_R$?	Not OK
Extreme IIa	R_R =	6.62	kip/ft.		
	ΣH =	3.20	kip/ft.	Is $\Sigma H < R_R$?	OK

Strength Ia fails the sliding check. Therefore, a shear key is required. The shear key uses an inert block, as shown in Figure B-10.

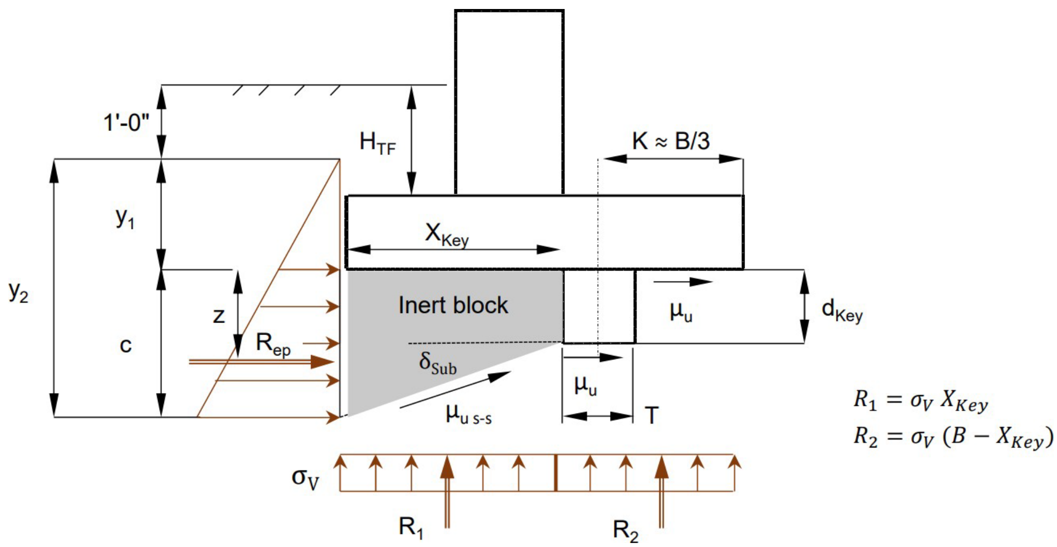


Figure B-10. Shear key dimensions and loading

Shear Key Design Parameters			
Shear key depth	d_{key} =	1.00	ft.
Shear key width	T_{key} =	1.50	ft.
Heel of footing to centerline shear key	K =	3.50	ft.
Toe of footing to front face shear key	X_{key} =	5.75	ft.
Soil cover above the footing toe	H_{TF} =	2.00	ft.
Shear friction angle of subgrade	δ_{sub} =	13.33	deg
Inert block depth	$c = d_{key} + X_{key}\tan(\delta_{sub})$ =	2.36	ft.
Top of fill to top of shear key	y_1 =	2.50	ft.
Top of fill to top bottom of the inert block	y_2 =	4.86	ft.
Equivalent passive pressure	EFW (p) =	0.460	kcf
Nominal soil sliding coefficient	μ_n =	0.36	
Coefficients of friction (factored)	$\mu_u = \phi_T \mu_n$ =	0.36	
	$\mu_{u\ s\text{-}s} = \phi_{T\ s\text{-}s}\ \mu_n$ =	0.36	
	$\mu_{u\ EE} = \phi_{T\ EE}\ \mu_n$ =	0.36	

Once the above parameters were determined, the shear key needed to be checked for sliding failure.

Check the Shear Key for Sliding					
Load Combination	e (ft.)	σ_V (ksf)	R_1 (kip/ft.)	R_2 (kip/ft.)	ϕ_{RT} (kip/ft.)
Strength Ia	0.80	2.57	14.76	10.91	9.20
Extreme IIa	2.05	3.09	17.74	13.11	11.05
Nominal passive resistance	R_{ep} =	4.00	kip/ft.		
Strength Ia	R_R =	11.20	kip/ft.		
	ΣH =	8.63	kip/ft.	Is $\Sigma H < R_R$?	OK
Extreme IIa	R_R =	13.05	kip/ft.		
	ΣH =	3.20	kip/ft.	Is $\Sigma H < R_R$?	OK

The shear key prevents sliding.

The wall is adequate for geotechnical design. Now, the structural design must be completed. The strength parameters are shown below.

Strength Design			
Concrete compressive strength f'_c =	4.50	ksi	
Yield strength of reinforcement f_y =	60.00	ksi	
Concrete unit weight γ_c =	0.15	kcf	
Correction factor for source aggregate K_1 =	1.00		AASHTO 5.4.2.4
Modulus of elasticity of reinforcement E_S =	29,000	ksi	AASHTO 5.4.3.2
Modulus of elasticity of concrete $E_c = 120{,}000 K_1 \gamma_c^2 f'^{\,2}_c$ =	4,435.3	ksi	AASHTO 5.4.2.4
Modular ratio $n = E_S / E_C$ =	6.54		AASHTO 5.6.1
Compression zone factor $\beta_1 = 0.85 - (f'_c - 4.0)0.05$ =	0.83		AASHTO 5.6.2.2
Resistance factor for flexural-tension control ϕ_f =	0.90		AASHTO 5.5.4.2
Resistance factor for shear-tension control ϕ_v =	0.90		AASHTO 5.5.4.2
Design width b =	12.00	in	

After identifying these parameters, the wall stem can be designed. Vertical reinforcement bars at the back face of the stem need to be designed to address flexure in the stem. This design is below.

Stem Design

Unfactored horizontal loads and moments at the bottom of the stem

Horizontal Loads & Moments				
Load Type	Description	H (kip/ft.)	Moment Arm (ft.)	MH (kip-ft.)/ft.
EH_H	Soil	3.74	5.00	18.69
LS_H	Surcharge	1.08	7.50	8.10

Load Groups		
Load Combination	Horizontal Load & Moment	
	V_U (kip/ft.)	M_U (kip-ft.)/ft.
Strength Ib	7.50	42.20
Service I	4.82	26.79

Flexure Design Assumed bar size #5 AASHTO 5.6.3.2		
Factored applied Moment $M_{u\ str}$ =	42.20	kip-ft./ft.
Concrete clear cover r =	2.00	in.
Bar diameter d_b =	0.63	in.
Bar area A_b =	0.31	in^2
Effective depth $d_e = T_{bot} - r - d_b/2$ =	18.69	in.
Assumed spacing	6.00	in.
Design steel area $A_s = A_b b/\text{spacing}$ =	0.61	in^2/ft.
Distance from compression fiber to neutral axis $C_b = A_s f_y / (\beta_1 0.85 f_c' b)$ =	0.97	in.
Equivalent stress block $a = \beta_1 C_b$ =	0.80	in.
Nominal flexural resistance $M_n = A_s f_y (d_e - a/2)$ =	56.10	kip-ft./ft.
Factored flexural resistance $M_R = \phi_f M_n$ =	50.49	kip-ft./ft.
Is $M_R > M_{u\ str}$?	OK	

Check that the minimum reinforcement criteria are met.

Check Minimum Reinforcement AASHTO 5.6.3.3		
Member width b =	12.00	in.
Member depth $d = T_{bot}$ =	21.00	in.
Distance to the neutral axis $y_t = T_{bot}/2$ =	10.50	in.
Stem moment of inertia $I_g = bd^3/12$ =	9,261	in^4
Section modulus $S_{nc} = S_c = I_g/y_t$ =	882.0	in^3
Concrete modulus of rupture $f_r = 0.24\sqrt{f_c'}$ =	0.51	ksi
Flexural cracking variability factor γ_1 =	1.60	
Prestress variable factor γ_2 =	0.00	
Ratio of minimum yield strength to ultimate tensile strength γ_3 =	0.67	
Compressive stress due to prestress force f_{cpe} =	0.00	ksi
Total unfactored dead load moment M_{dnc} =	0.00	kip-ft./ft.
Cracking moment $M_{cr} = \gamma_3\left[\left(\gamma_1 f_r + \gamma_2 f_{cpe}\right)S_c - M_{dnc}\left(\frac{S_c}{S_{nc}} - 1\right)\right]$ =	40.11	kip-ft./ft.
Factored applied moment $1.33M_{u\ str}$ =	56.13	kip-ft./ft.
Factored flexural resistance M_R =	50.49	kip-ft./ft.
Is $M_R > \min(M_{cr}, M_{u\ str})$?	OK	

The minimum reinforcement criteria are met. Now, check the reinforcement spacing.

Check Bar Spacing AASHTO 5.6.7			
Exposure condition class		2.00	
Exposure factor	γ_e =	0.75	
Thickness of concrete cover	d_c = 2" + $d_b/2$ =	2.31	in.
Reinforcement ratio	$\rho = A_s/bd_e$ =	0.003	
Modular ratio	n =	6.54	
	$k = \sqrt{2np + (np)^2} - np$ =	0.17	
	$j = 1 - k/3$ =	0.94	
Service applied moment	$M_{u\ serv}$ =	26.79	kip-ft./ft.
Tensile stress in steel	$f_{ss} = M_{u\ serv}/(A_s j d_e)$ =	29.74	ksi
	$\beta_s = 1 + [d_c/(0.7(T_{bot} - d_c))]$ =	1.18	
Maximum spacing	$s_{max} = [(700\gamma_e)/(\beta_s f_{ss})] - 2d_c$ =	10.38	in.
Spacing provided	s_{prov} =	6.00	in.
	Is $s_{prov} < s_{max}$?	OK	

Reinforcement spacing is adequate. Next, check if shear reinforcement is needed.

Shear Design ASHTO 5.7.3.3		
Factored shear load $V_{u\ str}$ =	7.50	kip/ft.
d_e - $C_b/2$ =	18.20	in.
$0.9d_e$ =	16.82	in.
$0.72T_{bot}$ =	15.12	in.
Effective depth $d_v = \max(d_e - C_b/2, 0.9d_e, 0.72T_{bot})$ =	18.20	in.
$M_{u\ str}$ =	42.20	kip-ft./ft.
$V_{u\ str}d_v$ =	11.37	kip-ft./ft.
Factored moment $M_u = \max(M_{u\ str}, V_{u\ str}d_v)$ =	42.20	kip-ft./ft.
Factored axial force $N_u = 1.25(DC_1 + DC_2 + DC_4)$ =	5.18	kip/ft.
Area of steel on the flexural tension side A_s =	0.61	in^2/ft.
Modulus of elasticity of reinforcement E_s =	29,000	ksi
Longitudinal tensile strain in the section $\varepsilon_s = \dfrac{\dfrac{\lvert M_u \rvert}{d_v} + 0.5N_u + \lvert V_u - V_p \rvert - A_{ps}f_{po}}{E_sA_s + E_pA_{ps}}$ =	0.00184	in./in.
Distance b/w layers of longitudinal crack control reinforcement s_{cr} =	21.00	in.
$\min(d_v, s_{cr})$ =	18.20	in.
$0.003bd_v$ =	0.66	in^2
Crack spacing parameter (1) If A_s>$0.003bd_v$, $s_x = \min(d_v, s_{cr})$, else $s_x = s_{cr}$ s_x =	18.20	in.
Max aggregate size a_g =	0.75	in.
Crack spacing parameter (2) $s_{xe} = s_x \dfrac{1.38}{a_g + 0.63}$ =	18.20	in.
Shear resistance parameter $\beta = \dfrac{4.8}{(1+750\varepsilon_s)} \dfrac{51}{(39+s_{xe})}$ =	1.80	
Concrete density modification factor λ =	1.00	
Nominal shear resistance $V_c = 0.031\beta\lambda\sqrt{f'_c}\,bd_v$ =	26.33	kip/ft.
Factored shear resistance $V_R = \phi_v V_c$ =	23.70	kip/ft.
$0.5V_R$ =	11.85	kip/ft.
$0.5V_R > V_{u\ str}$?	OK	

No shear reinforcement is required. Next, check the design for shrinkage and temperature reinforcement (horizontal at each stem face and vertical at the front stem face).

Shrinkage and Temperature Reinforcement Design - AASHTO 5.10.6				
Assumed bar size Bar #4				
Assumed spacing =	12.00	in.		
Bar diameter d_b =	0.50	in.		
Design steel area A_s =	0.20	in^2	Is $0.11 \le A_s \le 0.60$?	OK
$\dfrac{1.30\ bT_{bot}}{2(b+T_{bot})f_y}$ =	0.083	in^2	Is $A_s \ge \dfrac{1.30\ bT_{bot}}{2(b+T_{bot})f_y}$?	OK

The selected temperature reinforcement is adequate. The reinforcement for the footing toe, footing heel, and shear key follows the same procedure used for the stem design. The toe, heel, and shear key loads are given below, and the reinforcement for each is also tabulated below.

Heel Design

Unfactored loads

Vertical Loads & Moments				
Load Type	Description	*V* (kip/ft.)	Moment Arm (ft.)	*M* (kip-ft.)/ft.
DC	Heel dead load	1.03	2.75	2.84
EV_1	Vertical pressure from dead load of fill on heel	10.73	2.75	29.49

Toe Design

Unfactored loads

Vertical Loads & Moments				
Load Combination	σ_V (ksf)	*V* (kip/ft.)	Moment Arm (ft.)	*M* (kip-ft.)/ft.
Strength Ib	3.04	8.35	1.38	11.48
Strength IV	2.80	7.69	1.38	10.58
Service I	2.17	5.97	1.38	8.21

Shear Key Design

Unfactored loads

Vertical Loads & Moments Acting on the Inert Block			
Pressure distribution acting on the inert block	*H* (kip/ft.)	Moment Arm (ft.)	*M* (kip- ft.)/ft.
Rectangular distribution (passive)	2.44	1.18	2.89
Triangular distribution (passive)	1.28	1.58	2.02
Total passive	3.73	1.32	4.91

Final Design

The results of the heel, toe, and shear key reinforcement design are:

CIP Wall	**Transverse**	**Longitudinal**
Stem	#5 @ 6"	#4 @ 12"
Heel	#6 @ 6"	#4 @ 12"
Toe	#5 @ 6"	#4 @ 12"
Shear key	#4 @ 6"	#4 @ 12"

The final wall design is shown in Figure B-11.

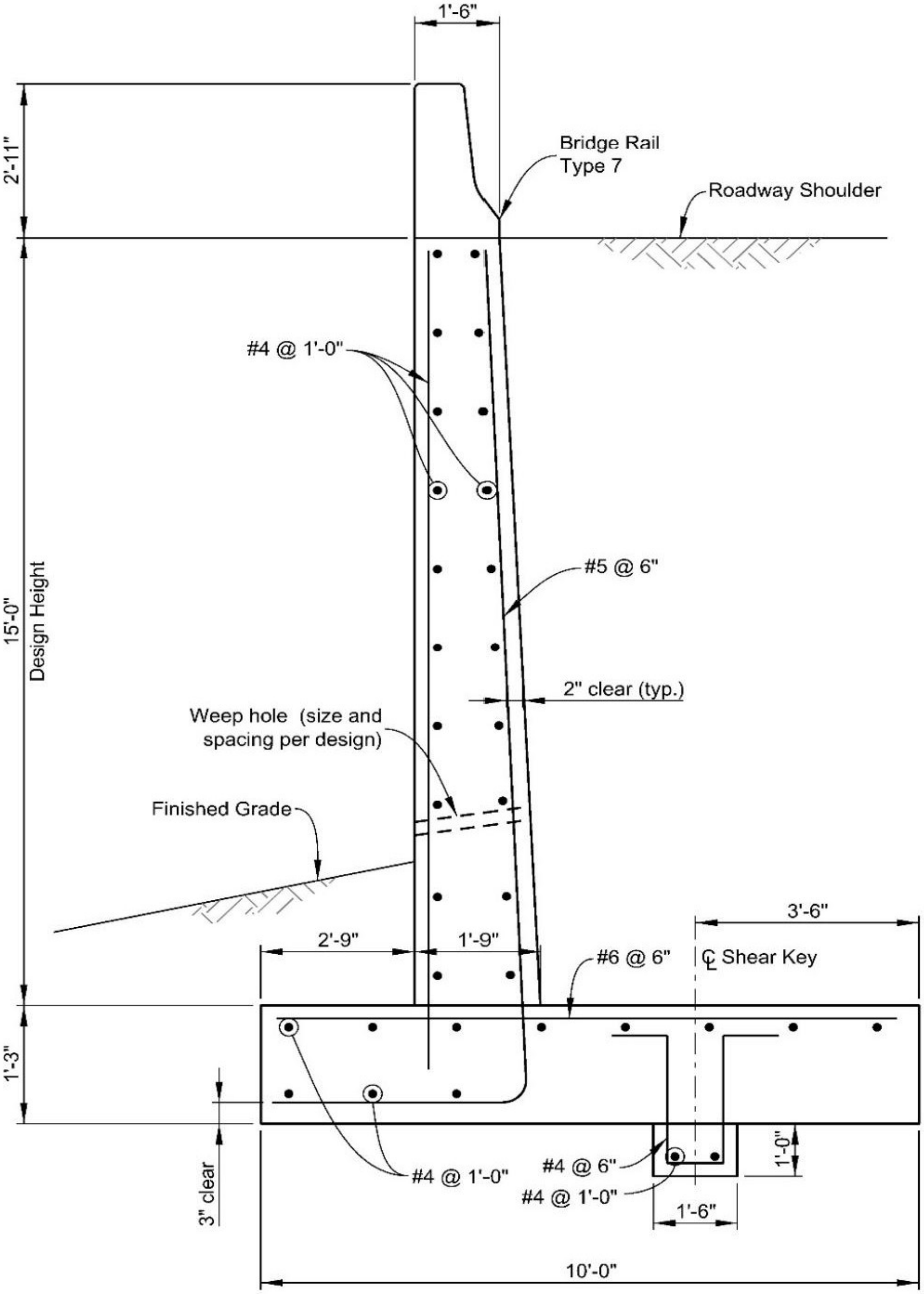


Figure B-11. Final wall design