US Army Corps of Engineers®

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Appendix N - Limestone Cost Investigation

Draft Supplemental Environmental Assessment
Morgan Shoal Revetment Reconstruction (45th - 51st Street)

SMITHGROUP

MEMORANDUM
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PROJECT	Morgan Shoal Revetment Reconstruction	DATE	6/6/2024
PROJECT NO.	PBC: 22703 SmithGroup: 13578.001		
SUBJECT	Conceptual Assessment of Revetment Options Using Cut Limestone		
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File	

Technical Memorandum: Summary of Conceptual Assessment of Revetment Options for the Morgan Shoal Shoreline Incorporating New Cut Limestone Blocks

Executive Summary

This memorandum documents a conceptual investigation into the availability and potential cost impacts of incorporating new cut limestone blocks into revetment configurations for the Morgan Shoal shoreline rehabilitation. The investigation indicates that while suitable material may be available and could be incorporated into revised revetment alternatives, there would be a significant cost premium over the other revetment options which have been considered.

Additional construction costs (as compared with the October 2023 Opinion of Probable Construction Cost) are in the range of $8,000 - $11,000 per linear foot of application outside of the very sheltered portion of the project within the dynamic revetment area. The feasibility and cost premium of using cut limestone varies depending on location within the project, as a result of the differing wave exposure conditions. In general, replacing the concrete portion of the sheet pile / stepped revetment is more expensive than adding limestone on top of a rubblemound foundation. If the entirety of the project outside the dynamic revetment were to be built using cut limestone steps, the additional cost is estimated to be in excess of $40-$50M.

Further investigation, including site visits to the quarries and reliable laboratory test data, of the available quality and dimension of cut limestone is a required next step to validating this material as a feasible alternative, followed by hydraulic laboratory testing of the preferred cross section to confirm site-specific design guidance.

1. Introduction

This memorandum documents a conceptual investigation into the availability, design considerations, and potential cost impacts of incorporating new cut limestone blocks into revetment configurations for the Morgan Shoal shoreline rehabilitation. The project, which is located in Chicago's Burnham Park between 45th Street and 51st Street, includes rehabilitation of approximately 1 mile of deteriorated shoreline. The existing structures, which have been rehabilitated several times over the past decades, were constructed with cut limestone "step stones" supported by rubble-filled timber cribs. The timber piling that was used in the original structures has deteriorated over time, resulting in loss of the supporting fill and subsequent settlement, displacement, and ultimately collapse of the limestone stepped structure. Recent rehabilitation methods used elsewhere along the Chicago shoreline have generally involved steel sheet pile with a concrete stepped revetment. In some locations rubble mound structures using newly quarried armor stone arranged in a sloped revetment have been used.

There has been growing interest in exploring the feasibility of using cut limestone blocks in the revetment rehabilitation and attempting to more closely replicate the original structure design, while improving on the overall system durability by replacing the rubble-filled timber foundation. The investigation comprises three main components:

- Desktop research into the availability and potential cost of suitable cut limestone materials that would meet the size and quality requirements for this application;
- Development of conceptual cross sections applicable to the varying water depths and wave exposure found across the project site, and documentation of the design approach and associated design criteria; and
- Analysis of the potential cost impact of using cut limestone as compared with the steel sheet pile / concrete and armor stone alternatives documented in the October 2023 Engineering Report and associated Opinion of Probable Construction Cost.

2. Stone Availability

a. Quality Requirements

This section describes standard references for dimension limestone and information on the performance of limestone construction within the specific coastal conditions of the Great Lakes.

i. Standard References

ASTM C568/C568M – 22, "Standard Specification for Limestone Dimension Stone" distinguishes 3 distinct classifications of limestone, based primarily on the density of the stone. Other relevant properties of limestone such as absorption and compressive strength – both of which are important indicators of durability in a marine setting – are strongly correlated with density. Parameters from C568 are listed below. For marine applications within the Great Lakes, Type III is strongly preferred based on the increased resistance to freezing/thawing, and wetting/drying.

Table 1: ASTM C568 Standard Limestone Properties

Property	Type II	Type III
Min. Density (lb/cf)	135	160
Absorption by weight (%)	7.5	3
Min. Compressive Strength (psi)	4,000	8,000

ii. Location-Specific References

The US Army Corps of Engineers technical report1, “Monitoring Stone Degradation on Coastal Structures in the Great Lakes – Summary Report”, (USACE) ERDC/CHL TR-05-1, provides insight into the weathering and use of Indiana Cut Limestone in Coastal Structures in the Great Lakes. Stones placed in the coastal environment are exposed to wetting-drying, freezing-thawing cycles, and wave impacts which accelerates stone weathering that give rise to chronic premature deterioration of armor stone on breakwaters and jetties around the Great Lakes.

USACE’s report indicates that over the last century, the Great Lakes and Ohio River Division has experienced chronic and recurring problems with stone durability for structures such as breakwaters and jetties, including significant premature deterioration of armor stone, composed of Silurian and Devonian limestones and dolomites. This deterioration causes the need for maintenance and rehabilitation at a cost of tens of millions of dollars. The study examines the possible causes of deterioration from several quarries, including one from Bloomington, Indiana that produces cut limestone. The report also examines quarry operations and carried out accelerated laboratory weathering tests on stone samples to better understand the causes of the accelerated weathering.

The report indicates that the worst stone degradation is seen in the areas where wet/dry and freeze/thaw cycles are at a maximum, which are at the water level and at the splash zone. The study monitored the Chicago Harbor, IL, breakwater; Calumet Harbor, IL and IN, breakwater; Calumet Harbor, IL, CDF; Burns Harbor, IN, breakwater all of which were composed of stones from the Salem formation cut limestone, from Bloomington, IN. The breakwater monitoring showed that gaps in the breakwater were created by weathering of the Salem formation Indiana limestone blocks, and over badly weathered sections of the limestone blocks. The documented causes of the weathering were:

[1] https://erdc-library.erdc.dren.mil/jspui/handle/11681/7590

- Mechanical fractures due to waves pounding against the flexible steel sheet pile immediately adjacent to the armor blocks;
- Parting along a stylolite; and
- Exfoliation or delamination zones associated with highly porous fossiliferous grain stone zones adjacent to large stylolites in the cut limestone blocks.

  Laboratory testing indicated that the freeze/thaw percent loss was 42%, and the specific gravity was 2.43. Absorption was 3.80 for the cut limestone blocks. These values are considered outside the preferred ranges for use in Great Lakes applications susceptible to weathering.

b. Stone Availability Inquiries

To understand the availability of cut limestone, at the dimensions and quality required for design, a total of twelve (12) quarries were contacted:

- Five (5) quarries were unresponsive;
- Four (4) quarries responded that they did not produce large cut stone; and
- Three (3) quarries provided varying levels of detail regarding their ability to produce suitable stone and some indication of the potential cost of cut stone.

The three quarries which reported the ability to produce suitable stone are:

- Independent Limestone located in Bloomington, IN; Independent Limestone reported that the density of the stone is 137 lbs/cf which is less than the density required for Type III based on ASTM C-568. However, further investigation and testing may demonstrate that the source could offer stone that is suitably durable
- Reed Quarries Inc. located in Bloomington, IN; Reed Quarries reported that the density of the stone is 141 lbs/cf which is less than the density required for Type III based on ASTM C-568. However, further investigation and testing may demonstrate that the source could offer stone that is suitably durable; and
- Indian Creek Stone located in Mitchell, IN; Indian Creek Stone was unable to report density of stone.

Further investigation, additional laboratory tests, and quarry site visits would be essential next steps to verify that these quarries would be able to produce stone that met the required standards.

c. Stone Material Costs

i. Independent Limestone, located approximately 230 miles from the project site, reported that it would be able to produce cut stone of the desired dimension range at a cost of $70/cf, which equates to approximately $1,000 per ton at their stated specific gravity. Independent Limestone estimated that producing 1,000 pieces may take approximately six to ten months.

ii. Reed Quarries, located approximately 230 miles from the project site, reported that it would be able to produce cut stone of the desired dimension range at a cost of about $550 per ton. They reported completing a similar waterfront project a few years ago. They are only able to transport 5-8 trucks per day.

iii. Indian Creek Stone, located approximately 275 miles from the project site, reported that it would be able to produce cut stone of the desired dimension range at a cost of about $650 per ton. They were unable to quote deliveries.

Figure 1: Quarry Operations at Independent Limestone, IN (2001)

3. Conceptual Design Approach

a. Design Parameters

The Morgan Shoal shoreline protection structures design conditions are summarized in the Engineering Design Report, October 2023, which details the bathymetric, water levels, winds, wave, and all other environmental conditions that govern the design of all the structures. The cut limestone alternative design is based on these same conditions and are not repeated in this technical memorandum.

Based on the environmental conditions, the project area was divided into three zones for the purposes of this investigation:

- "North Revetment" which starts at the project's northern boundary and ends at the north headland of the dynamic revetment / pebble beach. This area is characterized by deep nearshore water, and since there is no protection from the shoal is exposed to the largest waves. The existing design for this area is a rubblemound sloped stone revetment, with armor stone in the range 6 – 10 tons;
- The "Pebble Beach" area, or Dynamic Revetment, between the north and south headland. The existing design for this area is a sloped cobble revetment with a stepped revetment (comprised of salvaged existing on-site limestone blocks) at the landward side of the dynamic zone; and
- The third considered area was the "South Revetment" area, south of the dynamic revetment to the southern project limits at 51st Street. This area is characterized by somewhat shallower nearshore water than the north area and has some natural protection from the northeast waves due to the presence of the shoal.

Figure 2-5 in the October 2023 Engineering Report shows the wave conditions along the project's extents and illustrates the shoal's sheltering effect along the coast.

The October 2023 Engineering Report documents several combinations of water level and storm conditions, along with the frequency of exceedance. For this investigation the following parameters were selected to evaluate feasibility of cut limestone alternative cross sections:

- Design Water Level: the 1% monthly mean water level (+4.7 Feet LWD), in combination with a 10-year return period storm surge (+2.1 Feet), for a total design water level of +6.8 Feet LWD[2];
- Design Wave Conditions: 10-year return period wave conditions were selected, which have a 99.5% probability of exceedance over a 50-year design life.
  - The North Revetment area is exposed to 11.2 feet significant wave heights with a wave period of 12 seconds;
  - The Pebble Beach sheltered areas are exposed to 6.2 feet significant waves and a wave period of 6.3 seconds; and
  - The South Revetment area is exposed to 8.9 feet significant wave heights with a wave period of 8.1 seconds.

The table below summarizes the design parameters used for the three areas:

[2] See Table 2-1 Total Static Water Levels for Design, Morgan Shoal Engineering Report, October 2023.

Table 2: Cross Section Concept Design Parameters

Section	Significant Wave Height Hs (ft)	Wave Period Tp(s)	Water Level (ft, LWD)
North Section	11.2	12.0	+6.8'
Sheltered Area	6.2	6.3	+6.8'
South Section	8.9	8.1	+6.8'

b. Proposed Cross Sections

Two general cross section types were developed. These included a “rubblemound foundation” approach suitable for all of the project areas, and a “sheet pile foundation” approach suitable for areas without high bedrock. All of the sections are illustrated in Appendix A – Proposed Cross Sections For Initial Cut Limestone Investigation.

i. Rubblemound Foundation. In this approach the cut limestone blocks would be supported on a core stone base, with large filter and armor stone on the lakeside of the structure. The arrangement that was evaluated incorporated a 12-foot wide lower level comprising 3 cut limestones, and 3 steps taking the overall elevation to +15 ft LWD. This alternative does not require concrete or steel and only uses stone.

ii. Sheet Pile Foundation. In this approach the cut limestone blocks would be supported on a core stone base supported within a sheet pile bulkhead wall. The sheet pile structure could either be an anchored wall, or could be constructed as a double sheet pile cellular structure. For this preliminary investigation, a double sheet pile cellular structure has been assumed. As with other vertical bulkheads, scour protection on the lakebed would also be required on the lakeside of the structure. The arrangement that was evaluated incorporated a 12-foot wide lower level comprising 3 cut limestones, and 3 steps taking the overall elevation to +15 ft LWD. Two versions of this alternative were considered – one using the minimum scour protection, and another where additional armor stone is placed in front of the sheet pile to help reduce the wave pressure.

c. Design Approach

Specific design guidance for cut limestone block stepped revetments is scarce. Established methods for determining wave pressure distributions were obtained for each of the proposed structures, using formulae presented in USACE’s Coastal Engineering Manual[3].

[3] Engineer Manual 1110-2-1100 (Part VI)

- For the rubblemound foundation, Table VI-5-58 Wave Loads on Vertical Walls Protected by a Rubble-Mound Structure (Takahashi, Tanimoto, and Shimosako 1990) was used for estimating the wave pressure on the cut limestone blocks.

- For the sheet pile foundation, Table VI-5-53 Goda Formula for Irregular Waves (Goda 1974; Tanimoto et al. 1976), modified for breaking waves, was used for estimating the horizontal and uplift pressure distributions for each row of blocks.

Required block size to resist the design pressures was iterated using an initial assumed block size / density and a factor of safety of 1.25, and then adjusting the block size up, if the overall system did not meet stability requirements. This iterative process was applied until a stable arrangement of blocks was found that could be resist the computed pressure distributions. Where the section included a sheet pile wall, a factor of 0.2 was applied to significantly reduce the uplift forces on the blocks placed behind the sheet pile, as the sheet pile is assumed to significantly diminish the wave uplift force on the recessed blocks.

Figure 2, below, illustrates the issues associated with constructing coastal structures with large, regularly shaped unit blocks. This photograph shows very large concrete blocks had been placed in a regular, uniform manner that were then subjected to unexpected wave forces, which displaced the blocks and the underlying fill material, resulting in displacement and rotation.

Figure 2: Unit Block Construction Subjected to Wave Forces and Uplift

The calculations are included as Appendix B to this technical memorandum.

4. Cost Impact Analysis

a. Methodology

In order to compare the potential costs of each proposed alternative the following approach was adopted:

- Costs are compared to the most recent Morgan Shoal OPCC, October 2023.
- For each arrangement, a typical section was developed, and costs evaluated on a per linear foot basis.
- For the cut limestone materials, unit production costs obtained from the quarries were combined with assumed transportation costs and placement costs to develop an in-place unit cost for cut limestone.

b. Cut Limestone In-Place Unit Costs

The following items are included in the estimated Cut Limestone In-Place Unit Costs:

- Unit production costs (obtained from the quarries) ranged from $38.50/cf to $70/cf with an average reported stone density of about 140 lbs/cf. Combining these to generate an average cost at the quarry results in an estimated unit cost of about $740/ton.
- Transportation costs from the quarry to the job site were estimated based on about $180/hr for trucking, and about a 10-hour round trip, with each load bringing about 18 tons of stone, resulting in a trucking cost of about $100/ton.
- Placement costs at the job site were estimated as being similar to the October 2023 cost for placement of the salvaged limestone blocks, which was about $200/ton.
- Total estimated in place costs for cut limestone blocks is sum of items listed above and is approximately $1,000 per ton[4].

c. Cost Comparison of Alternatives

The table below summarizes the ***additional costs*** associated with the use of cut limestone blocks to create a stepped revetment, compared with the estimated per linear foot costs of the originally proposed project.

[4] For this initial comparative cost analysis this value seems reasonable, but will need to be verified with additional data regarding limestone quality.

Table 3: Summary of Additional Costs Associated with Use of Cut Limestone

Item	Description	**Additional Cost**, Construction Only ($/LF)	**Additional Cost**, w/Indirects ($/LF)
R1	Rubblemound Foundation, North Project Area	$6,900	$9,300
R2	Rubblemound Foundation, South Project Area	$6,500	$8,900
R3	Rubblemound Foundation, Sheltered Project Area (Headlands)	$3,400	$5,800
SP1-S	Sheet Pile Foundation, Standard Scour Protection, North	$7,500	$10,000
SP2-S	Sheet Pile Foundation, Standard Scour Protection, South	$5,800	$8,400
SP1-R	Sheet Pile Foundation, Rubblemound Scour Protection, North	$8,000	$10,900
SP2-R	Sheet Pile Foundation, Rubblemound Scour Protection, South	$7,500	$10,300

The investigation indicates there would be a significant cost premium over the other revetment options which have been considered. Additional construction costs (as compared with the October 2023 Opinion of Probable Construction Cost) are in the range of $8,000 - $11,000 per linear foot of application outside of the very sheltered portion of the project within the dynamic revetment area. The feasibility and cost premium of using cut limestone varies depending on location within the project, as a result of the differing wave exposure conditions. In general, replacing the concrete portion of the sheet pile / stepped revetment is more expensive than adding limestone on top of a rubblemound foundation. If the entirety of the project outside the dynamic revetment were to be built using cut limestone steps, the additional cost is estimated to be in excess of $40-$50M.

d. Additional Cost Considerations

If cut limestone is to be used for a portion of the Morgan Shoal revetment, some further analysis will be required to confirm the likely construction costs. Specifically, if further testing indicates that individual limestone blocks would need to be doweled together to resist differential movement, then the placement costs per block may increase significantly. Likewise there is a trade-off between initial construction cost and long-term maintenance associated with the quality (and specifically the density) of the stone that is procured.

Further optimization of a preferred section would be expected to result in the opportunity for some refinement in the additional cost associated with cut limestone.

One such optimization that was briefly examined for the rubblemound foundation approach involves placing a concrete caisson below the lowest row of cut limestone blocks to help provide stability without the need of very large blocks which might be difficult to procure.

An additional option that might prove to be cost effective, would be to only use limestone for the upper stepped levels, which would place the blocks in areas subjected to smaller wave forces and uplift pressures, and as a result, comparatively smaller blocks can be used. While not explicitly examined in this study, replacing the upper two steps in the concrete stepped revetment with limestone blocks may result in a cost premium of approximately $1,000/LF.

5. Conclusions

This investigation examines the feasibility, and potential associated costs, of adding cut limestone blocks into the proposed Morgan Shoal revetment rehabilitation. A number of different approaches have been examined to explore the likely range of options that may be available. Based on the desktop analysis the following conclusions are offered:

- Correspondence with several quarries in Indiana have confirmed that there are potential sources of cut limestone blocks that may be interested and capable of sourcing material of the required size;
- Further investigation into the available stone quality must be performed, with specific attention to the availability of large blocks meeting ASTM C568 Type III specifications;
- Initial desktop analysis indicates that satisfactory arrangements of cut limestone blocks can be developed that would meet the estimated wave forces and associated uplift pressures. However, specific design guidance for cut limestone block stepped revetments is scarce, and physical modeling of the preferred cross sections is recommended before design finalization;
- Total unit cost for in-place cut limestone blocks is estimated at approximately $1,000 per ton. There is significant uncertainty regarding this value, and it would need to be further investigated to develop a higher class of cost opinion;
- The investigation indicates that while suitable material may be available and could be incorporated into revised revetment alternatives, there would be a significant cost premium over the other revetment options which have been considered;
- Additional construction costs (as compared with the October 2023 Opinion of Probable Construction Cost) are in the range of $8,000 - $11,000 per linear foot of application outside of the very sheltered portion of the project within the dynamic revetment area; and
- The feasibility and cost premium of using cut limestone varies depending on location within the project, as a result of the differing wave exposure conditions. In general, replacing the concrete portion of the sheet pile / stepped revetment appears to be more expensive than adding limestone on top of a rubblemound foundation.

LIST OF APPENDICES:

Appendix A – Proposed Cross Sections For Initial Cut Limestone Investigation

Appendix B - Coastal Calculations For Initial Cut Limestone Investigation

LIST OF REFERENCES:

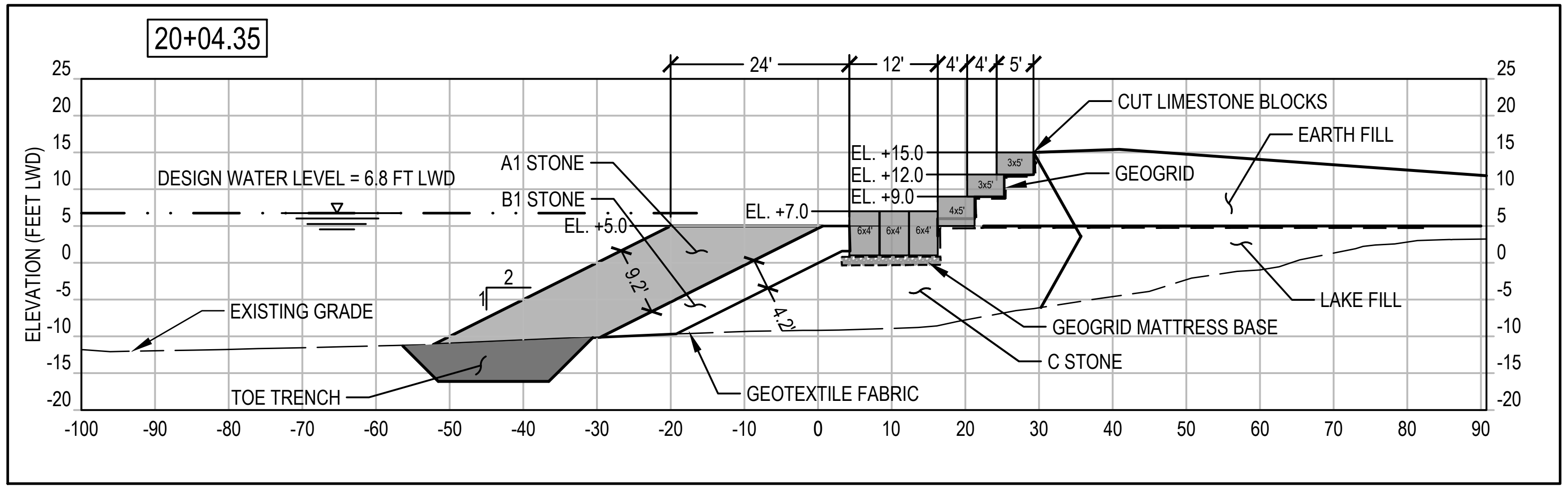
United States Army Corp of Engineers USACE, "*Monitoring Stone Degradation on Coastal Structures in the Great Lakes – Summary Rep*ort", (USACE) ERDC/CHL TR-05-1 https://erdc-library.erdc.dren.mil/jspui/handle/11681/7590

SmithGroup, "*Final Engineering Design Report Morgan Shoal Revetment Reconstruction", *PUBLIC BUILDING COMMISSION PBC PROJECT #22703, October 2023

United States Army Corp of Engineers USACE*, " EM 1110-2-1100 (Part VI) Coastal Engineering Manual (CEM)".* Version 2006, Revision 2010.

Stantec, "*Opinion of Probable Construction Cost MORGAN SHOAL CHICAGO SHORELINE PROTECTION PROJECT 45th St to 51st St Revetment Construction*", PUBLIC BUILDING COMMISSION PBC PROJECT #22703, October 2023

CIRIA/CUR, "*The Rock Manual. The use of rock in hydraulic engineering (second* edition)", June 2007



1 NORTH - OPTION R1 RUBBLEMOUND FOUNDATION

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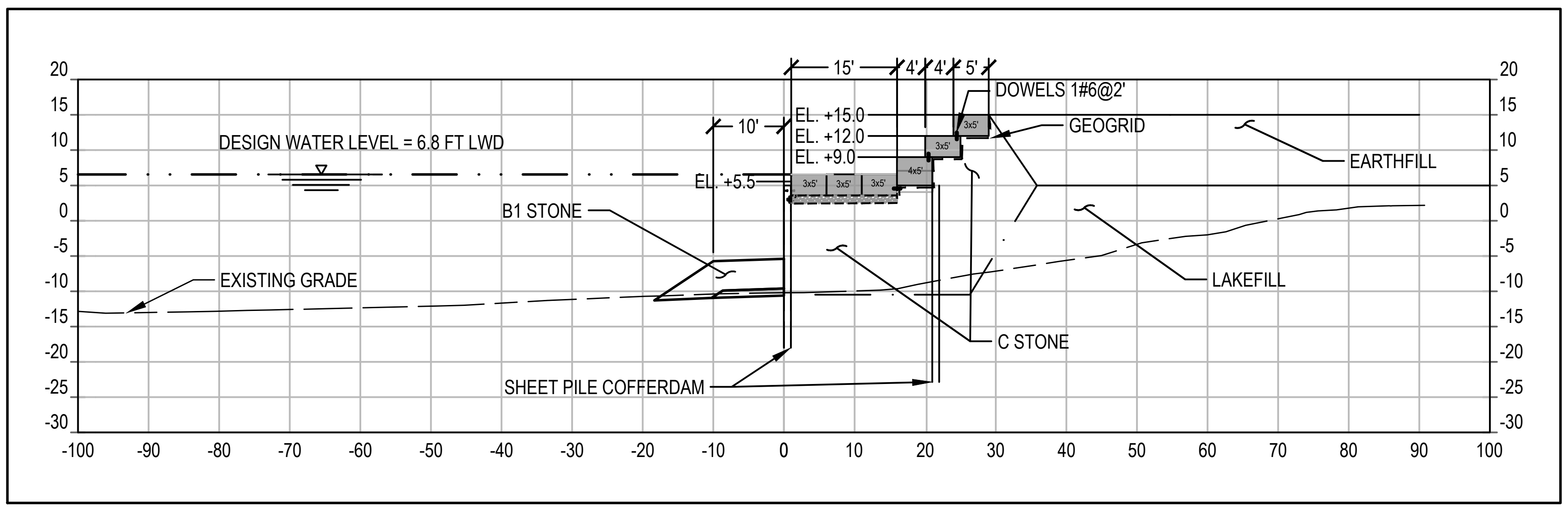

2 NORTH - OPTION SP1-S SHEETPILE FOUNDATION, STANDARD SCOUR PROTECTION

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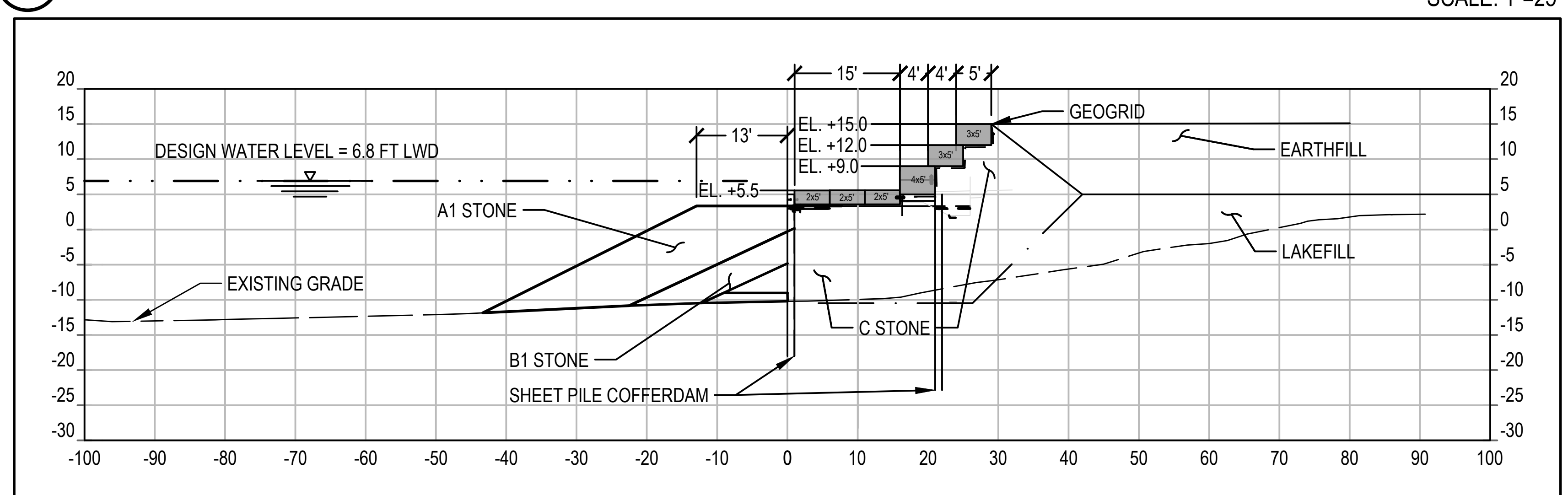

3 NORTH - OPTION SP1-R SHEETPILE FOUNDATION, RUBBLEMOUND SCOUR PROTECTION

SCALE: 1"=25'

NOTES:

OPTION R1: REPLACE UPPER ELEVATION OF RUBBLEMOUND WITH CUT LIMESTONE BLOCKS IN STEPPED ARRANGEMENT. BLOCKS MUST BE SIZED TO RESIST WAVE LOADS INCLUDING UPLIFT PRESSURES.

OPTION SP1-S: INSTALL DOUBLE SHEET PILE COFFERDAM CAPPED WITH CUT LIMESTONE BLOCKS IN STEPPED ARRANGEMENT. LOWER LEVEL BLOCKS MAY BE SMALLER THAN OPTION R1 BECAUSE SHEET PILE REDUCES UPLIFT PRESSURES.

OPTION SP1-R: INSTALL DOUBLE SHEET PILE COFFERDAM CAPPED WITH CUT LIMESTONE BLOCKS IN STEPPED ARRANGEMENT. ADD RUBBLEMOUND SCOUR PROTECTION. LOWER LEVEL BLOCKS MAY BE SMALLER THAN OPTIONS R1 AND SP1-S BECAUSE RUBBLEMOUND AND SHEET PILE REDUCE UPLIFT PRESSURES.

NOT FOR CONSTRUCTION

CHICAGO SHORELINE PROTECTION PROJECT
MORGAN SHOAL REVETMENT RECONSTRUCTION
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CCJM Engineers
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MEP Consultant

Thornton Tomasetti
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Structural Consultant

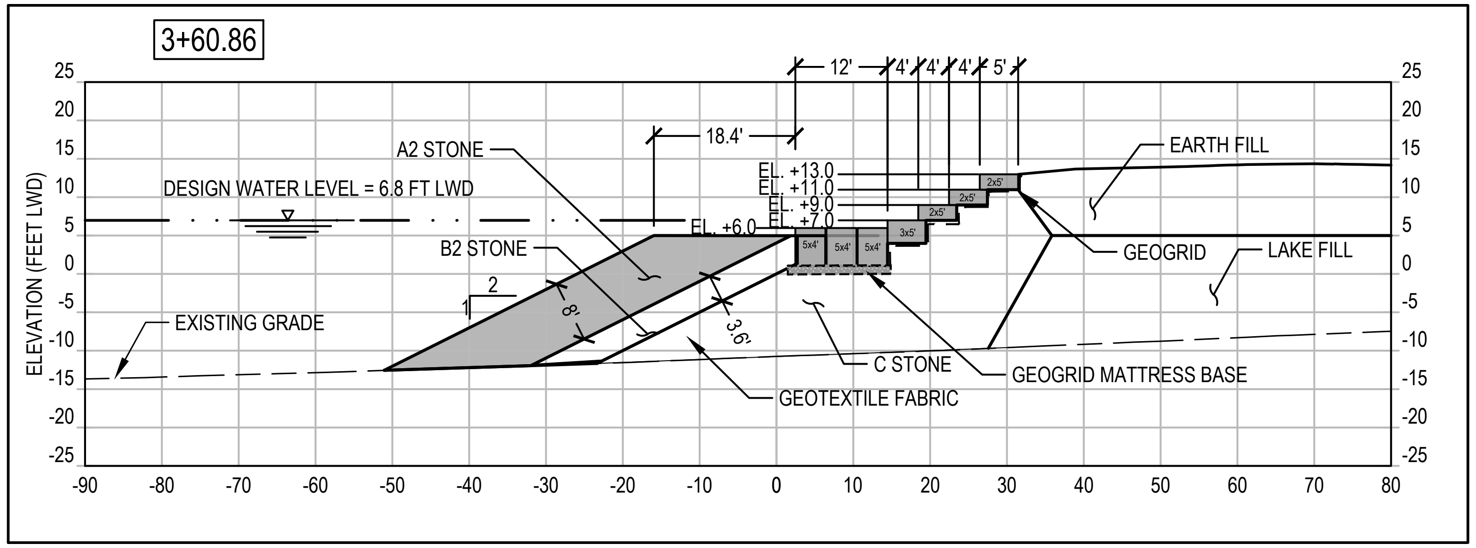
Issuance

Mark	Description	Date

PBC Project Name: Chicago Shoreline Protection Project
PBC Contract No.: 22703
Project No.: 13578

Title
PROPOSED CROSS SECTIONS FOR INITIAL CUT LIMESTONE INVESTIGATION

Sheet
APPENDIX A



1 SOUTH - OPTION R2 RUBBLEMOUND FOUNDATION

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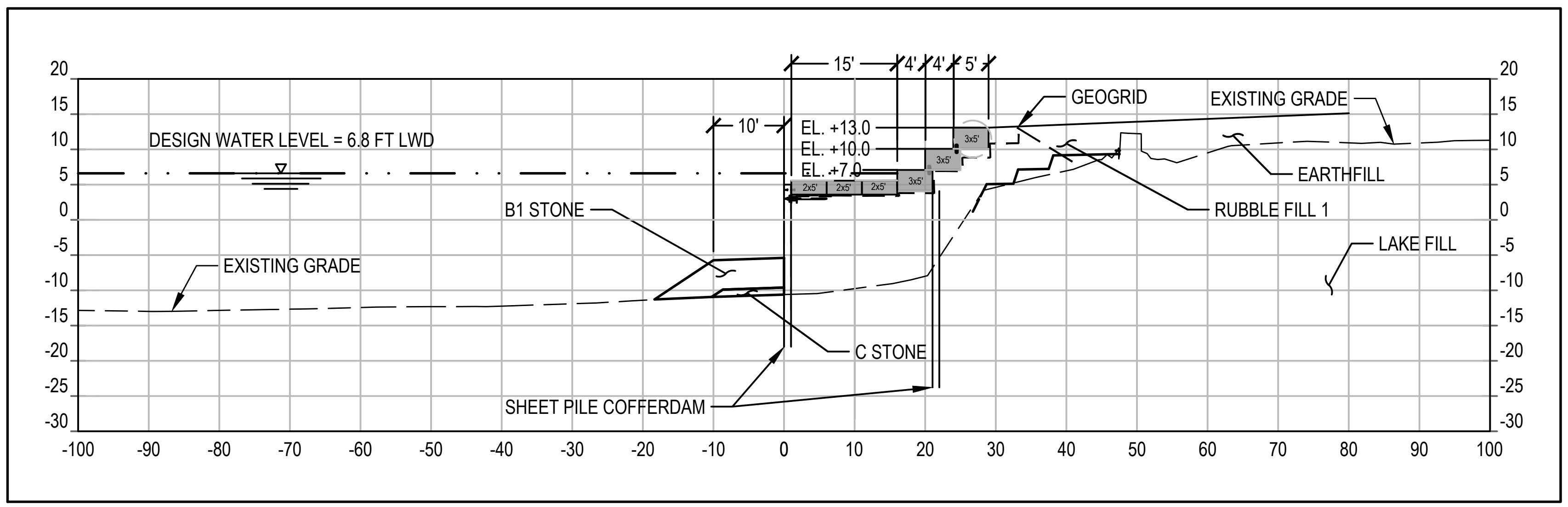

2 SOUTH - OPTION SP2-S SHEETPILE FOUNDATION, STANDARD SCOUR PROTECTION

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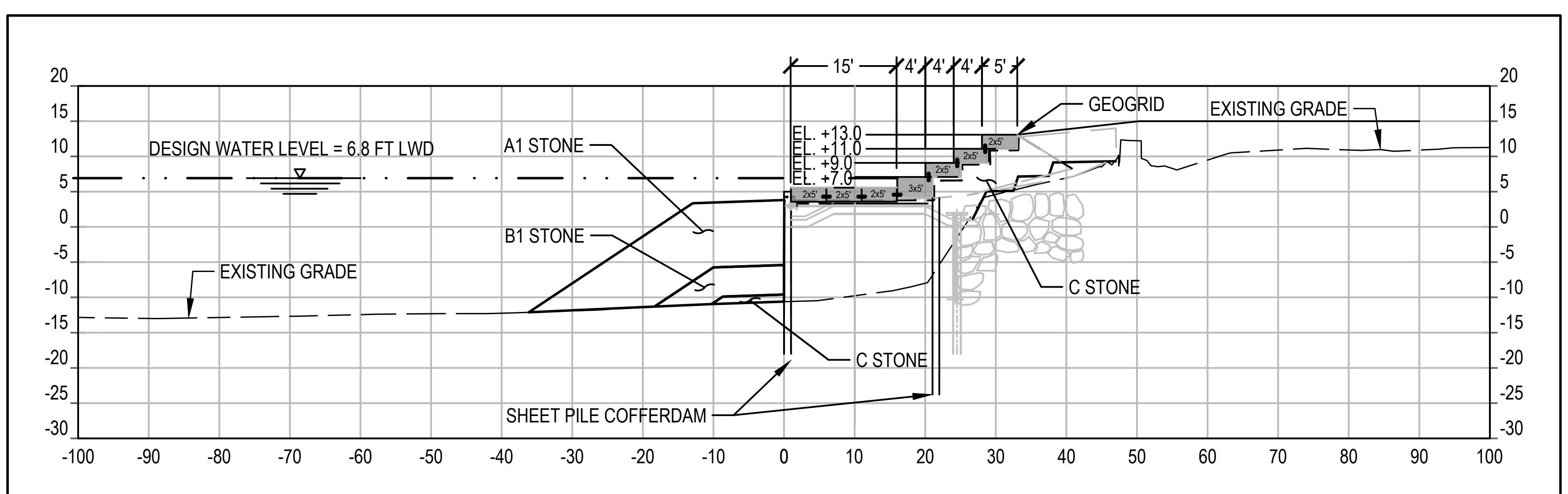

3 SOUTH - OPTION SP2-R SHEETPILE FOUNDATION, RUBBLEMOUND SCOUR PROTECTION

SCALE: 1"=25'

NOTES:

OPTION R2: REPLACE UPPER ELEVATION OF RUBBLEMOUND WITH CUT LIMESTONE BLOCKS IN STEPPED ARRANGEMENT. BLOCKS MUST BE SIZED TO RESIST WAVE LOADS INCLUDING UPLIFT PRESSURES.

OPTION SP2-S: INSTALL DOUBLE SHEET PILE COFFERDAM CAPPED WITH CUT LIMESTONE BLOCKS IN STEPPED ARRANGEMENT. LOWER LEVEL BLOCKS MAY BE SMALLER THAN OPTION R2 BECAUSE SHEET PILE REDUCES UPLIFT PRESSURES.

OPTION SP2-R: INSTALL DOUBLE SHEET PILE COFFERDAM CAPPED WITH CUT LIMESTONE BLOCKS IN STEPPED ARRANGEMENT. ADD RUBBLEMOUND SCOUR PROTECTION. LOWER LEVEL BLOCKS MAY BE SMALLER THAN OPTIONS R2 AND SP2-S BECAUSE RUBBLEMOUND AND SHEET PILE REDUCE UPLIFT PRESSURES.

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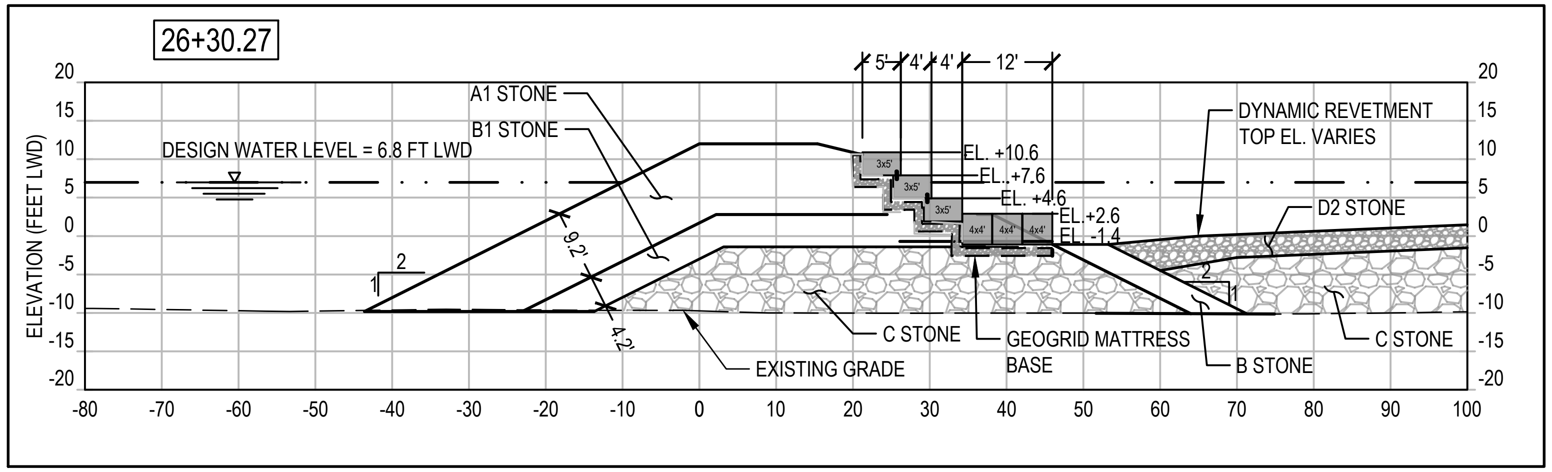
Title: PROPOSED CROSS SECTIONS FOR INITIAL CUT LIMESTONE INVESTIGATION
Sheet: APPENDIX A



1 CENTER - OPTION R3

SCALE: 1"=25'

NOTES:

OPTION R3: REPLACE LEE SIDE OF HEADLAND ARMOR STONE WITH STEPPED LIMESTONE. BLOCKS MUST BE SIZED TO RESIST WAVE LOADS AND UPLIFT PRESSURES, WHICH ARE REDUCED IN THIS SHELTERED LOCATION.

NOT FOR CONSTRUCTION

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CHICAGO SHORELINE PROTECTION PROJECT

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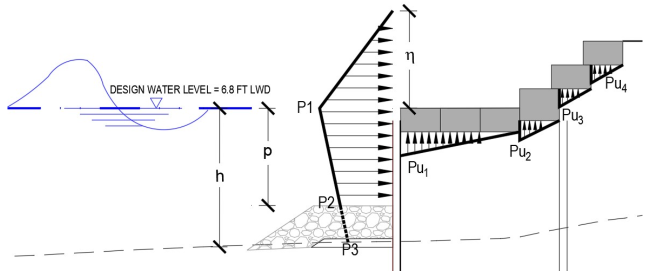
APPENDIX A

Appendix B - Coastal Calculations For Initial Cut Limestone Investigation

RUBBLEMOUND FOUNDATION ALTERNATIVE: R1 NORTH SECTION

Design Parameters:



-Significant Wave Height: $Hs := 11.24\ ft$

-Peak Spectral Wave Period: $Tp := 11.96\ s$

- Deepwater wave length: $Lo := \frac{g \cdot Tp^2}{2 \cdot \pi} = 732.47\ ft$

- Water depth in front of structure from LWD: $h := 18\ ft$

- Still water level (Water level above LWD): $SWL := 6.8\ ft$

- Total water depth at toe: $ht := h + SWL = 24.80\ ft$ $\frac{ht}{Lo} = 0.03$

- Total water depth at an offshore distance of 5 significant wave heights: $hb := 18\ ft + SWL = 24.80\ ft$

- Total water depth at toe on top of mound armoring units: $d := ht - 10\ ft = 14.80\ ft$

- Total water depth at toe of Upright Wall: $h' := ht$

- Max Design Breaking Wave H_D=Hmax $H_D := min(1.8 \cdot Hs, 0.78 \cdot ht) = 19.34\ ft$

- Local wave length (APPROX must have ht/Lo<0.35):

$$L := \sqrt[2]{2\ \pi \cdot ht \cdot Lo} \cdot \left(1 - \frac{ht}{Lo}\right) = 326.40\ ft$$

- Wave Angle to Shore: $\beta := 0$

- Density of Water: $\rho o := 62.43\ \frac{lb}{ft^3}$

- Height above SWL at which wave pressure is 0: $\eta := SWL + 0.75 \cdot (1 + \cos(\beta))\ H_D = 35.82\ ft$

$$\alpha_1 := 0.6 + \frac{1}{2} \left(\frac{\left(4 \cdot \pi \cdot \frac{ht}{L}\right)}{\sinh\left(4 \cdot \pi \cdot \frac{ht}{L}\right)} \right)^2 = 0.97$$

$$\alpha_2 := min\left(\frac{(hb-d)}{3 \cdot hb}\left(\frac{H_D}{d}\right)^2, 2 \cdot \frac{d}{H_D}\right) = 0.23$$

$$\alpha_3 := 1 - \frac{h'}{h}\left(1 - \frac{1}{\cosh\left(2\,\pi \cdot \frac{h}{L}\right)}\right) = 0.92$$

- Wave Pressure Modification Factors* See page 109 OCDI coefficients if rubblemound is in front of vertical structure:

$$\lambda_1 := 0.8 \qquad \lambda_2 := 0 \qquad \lambda_3 := 0.8$$

- Pressure at Still Water Level SWL :

$$P_1 := \frac{1}{2}\left(1+\cos(\beta)\right) \cdot \left(\alpha_1 \cdot \lambda_1 + \alpha_2 \cdot \lambda_2 \cdot \cos(\beta)^2\right) \cdot \rho o \cdot g \cdot H_D = 0.94\ \frac{kip}{ft^2}$$

$$P_1 = 0.94\ \frac{kip}{ft^2}$$

- Pressure at Sea Floor:

$$P_2 := \frac{P_1}{\cosh\left(2 \cdot \pi \cdot \frac{ht}{L}\right)} = 0.84\ \frac{kip}{ft^2}$$

- Pressure at Toe of Wall:

$$P_3 := \alpha_3 \cdot P_1 = 0.87\ \frac{kip}{ft^2} \qquad P_3 = 41.43\ \frac{1}{m^2} \cdot kN$$

- Wave Pressure at Different Elevations Below SWL Celevb and Above SWL Celeva:

$SWL = 6.80\ ft$

$$Celev_b := \begin{bmatrix} 1 \\ 7 \\ 5 \end{bmatrix} ft \qquad Celev_a := \begin{bmatrix} 9 \\ 12 \\ 15 \end{bmatrix} ft$$

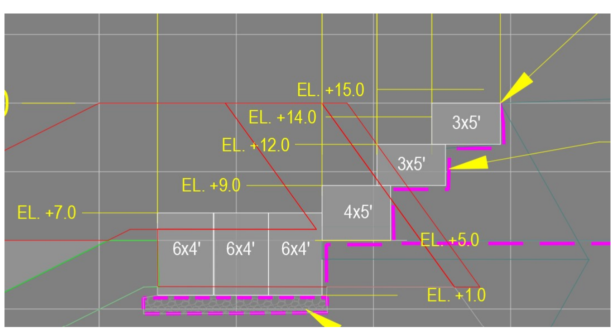


Figure: Celev of each block row

$$P_{4b} := P_2 + (P_1 - P_2) \cdot \frac{(h + Celev_b)}{(SWL + h)} = \begin{bmatrix} 0.92 \\ 0.94 \\ 0.93 \end{bmatrix} \frac{kip}{ft^2}$$

$$P_{4a} := \frac{\eta - (Celev_a - SWL)}{\eta} \cdot P_1 = \begin{bmatrix} 0.88 \\ 0.80 \\ 0.72 \end{bmatrix} \frac{kip}{ft^2}$$

- Uplift Pressure at bottom: * In case of Caisson Structure

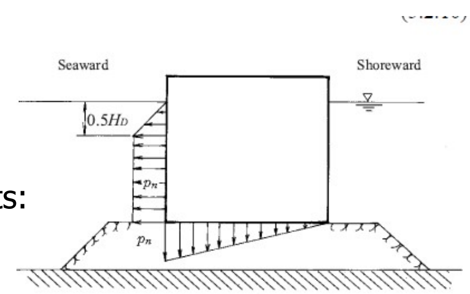
$$P_u := \frac{1}{2} \cdot (1 + \cos(\beta)) \cdot \alpha_1 \cdot \alpha_3 \cdot \lambda_3 \cdot \rho o \cdot g \cdot H_D = 0.87 \frac{kip}{ft^2}$$

CALCULATION OF "NEGATIVE" WAVE TROUGH PRESSURE FORCE

$$p_n := \frac{1}{2} \cdot \rho o \cdot g \cdot H_D = 0.60 \frac{kip}{ft^2} \qquad p_n = 28.91 \frac{1}{m^2} \cdot kN$$

- Elevation from SWL where triangular distribution starts:

$$SWL - \frac{H_D}{2} = -2.87 \; ft$$



T- 5.2.4 Negative Wave Pressure Distribution

CALCULATION OF REQUIRED BLOCK SIZE TO WITHSTAND WAVE FORCE

BLOCKS AT BOTTOM ROW with Elevation base at +1' and crest at +7'

Dimensions of block LxDxH:

$$L_{block} := 6\ ft \quad D_{block} := 4\ ft \quad H_{block} := 6\ ft$$

Density of stone and water * Lower stone density will require larger blocks:

$$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$$

Weight of Individual block W_b and displaced water W_w:

$$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 11.52\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.92\ \frac{ton}{ft}$$

$$W_w := D_{block} \cdot H_{block} \cdot \gamma_w = 0.75\ \frac{ton}{ft}$$

Horizontal Wave force on face of the block

$$Celev_b \qquad F_h := \left(P_{4b}(0) \cdot H_{block} + \frac{\left(\left(P_{4b}(0) - P_{4b}(1)\right) \cdot H_{block}\right)}{2}\right) = 5.43\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of **3** blocks at +1' F_{v1}

$$F_{v1} := 3\ \left(P_{4b}(0)\right)\ \frac{D_{block}}{2} = 5.50\ \frac{1}{ft} \cdot kip$$

Resisting uplift Block Weight Force F_{vblock} 3 blocks at promenade level +1'

$$F_{vblock} := g \cdot \left(W_b - W_w\right)\ (3) = 7.03\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$$F_{vblock} > F_{v1} = 1.00$$

*Blocks withstand the vertical uplift force with no safety factor considered

$$Fs := 1.25$$

$$F_{vblock} > Fs\ F_{v1} = 1.00$$

Blocks withstand uplift force with a safety factor of 1.25. Additional dowels recommended ton increase resilience

$$F_{vblock} - Fs\ F_{v1} = 0.15\ \frac{kip}{ft}$$

Resisting HORIZONTAL FORCE F_{hres}

Friction angle $\upsilon := 0.6$

Normal 3 blocks (weight-submergence-uplift force) $N := 3 \cdot (g \cdot (W_b - W_w)) = 7.03 \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 4.22 \frac{1}{ft} \cdot kip$ $F_h = 5.43 \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force. The backfill on the land side will increase resistance. Recommended to be doweled to provide additional resistance to horizontal push

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35 °$

$$K_p := \tan\left(45 ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2} K_p \left(Celev_a(2) - Celev_b(0)\right)^2 \cdot \gamma_s \cdot g = 57.86 \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25\ F_h = 55.29 \frac{1}{ft} \cdot kip$$

Blocks can resist horizontal pressure given backfill behind them

BLOCK AT SECOND ROW with Elevation base at +5' and crest at +9'

$Celev_b(2) = 5.00\ ft$ $Celev_a(0) = 9.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft$ $D_{block} := 5\ ft$ $H_{block} := 4\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3}$ $\gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 9.60\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.60\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.59\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$ $F_h := \left(P_{4b}(2) \cdot H_{block} + \frac{((P_{4b}(2) - P_{4a}(0)) \cdot H_{block})}{2}\right) = 3.83\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of 3 blocks +1 Fv1

$F_{v1} := 1\ (P_{4b}(1))\ \frac{D_{block}}{2} = 2.35\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force F_{vblock} 1 block at first step

$F_{vblock} := g \cdot (W_b - 0.25\ W_w) + g \cdot (W_b)\ (0.3) = 3.86\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$

Blocks with two layers of blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

$F_{vblock} - Fs\ F_{v1} = 0.93\ \frac{kip}{ft}$

Blocks withstand uplift force with a safety factor of 1.25. The third column of blocks at +7' need to be doweled to provide additional vertical resistance to the wave uplift force.

Resisting horizontal friction angle between blocks Fhres

$v := 0.6$

$N := (g \cdot (W_b - 0.5\ W_w)) = 2.61\ \frac{kip}{ft}$

$F_{hres} := v \cdot N = 1.56\ \frac{1}{ft} \cdot kip$ $F_h = 3.83\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - Fs\ F_h = -3.22\ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2}\ K_p\ (Celev_a(2) - Celev_b(1))^2 \cdot \gamma_s \cdot g = 18.89\ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - Fs\ F_h = 15.67\ \frac{1}{ft} \cdot kip$

BLOCK AT THIRD ROW with Elevation base at +9' and crest at +12'

$Celev_a(0) = 9.00\ ft$ $Celev_a(1) = 12.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft$ $D_{block} := 5\ ft$ $H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3}$ $\gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$ $F_h := \left(P_{4a}(0) \cdot H_{block} + \frac{((P_{4a}(0) - P_{4a}(1)) \cdot H_{block})}{2}\right) = 2.76\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of 3 blocks +1 Fv1

$F_{v1} := 1\ (P_{4a}(0))\ \frac{D_{block}}{2} = 2.20\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force F_{vblock} 1 block at first step

$F_{vblock} := g \cdot (W_b)\ (1) + g \cdot (W_b)\ (0.3) = 3.12\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$

Blocks with blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

Blocks withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = 0.37\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks F_{hres}

$$\upsilon := 0.6$$

$$N := (g \cdot (W_b)) = 2.40 \frac{kip}{ft}$$

$$F_{hres} := \upsilon \cdot N = 1.44 \frac{1}{ft} \cdot kip \qquad F_h = 2.76 \frac{1}{ft} \cdot kip$$

$$F_{hres} > F_h = 0.00$$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$$F_{hres} - Fs\ F_h = -2.01 \frac{1}{ft} \cdot kip$$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2} K_p \left(Celev_a(2) - Celev_a(0)\right)^2 \cdot \gamma_s \cdot g = 10.63 \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25\ F_h = 8.61 \frac{1}{ft} \cdot kip$$

BLOCK AT FOURTH ROW with Elevation base at +12' and crest at +15'

$Celev_a(1)=12.00\ ft \qquad Celev_a(2)=15.00\ ft$

Dimensions of block LxDxH:

$$L_{block}:=6\ ft \qquad D_{block}:=5\ ft \qquad H_{block}:=3\ ft$$

Density of stone and water:

$$\gamma_s:=160\ \frac{lb}{ft^3} \qquad \gamma_w:=62.4\ \frac{lb}{ft^3}$$

Weight of Individual block:

$$W_{bt}:=L_{block}\cdot D_{block}\cdot H_{block}\cdot \gamma_s=7.20\ ton \qquad W_b:=D_{block}\cdot H_{block}\cdot \gamma_s=1.20\ \frac{ton}{ft}$$

$$W_w:=D_{block}\cdot\left(H_{block}-0.2\ ft\right)\cdot \gamma_w=0.44\ \frac{ton}{ft}$$

Wave force on face of the block

$$Celev_b \qquad F_h:=\left(P_{4a}(0)\cdot H_{block}+\frac{\left(\left(P_{4a}(0)-P_{4a}(1)\right)\cdot H_{block}\right)}{2}\right)=2.76\ \frac{1}{ft}\cdot kip$$

Wave uplift force on first row of 3 blocks +1 Fv1

$$F_{v1}:=1\ \left(P_{4a}(0)\right)\ \frac{D_{block}}{2}=2.20\ \frac{1}{ft}\cdot kip$$

Resisting uplift Block Weight Force F_{vblock} 1 block at first step

$$F_{vblock}:=g\cdot\left(W_b\right)\ (1)+g\cdot\left(W_b\right)\ (0.3)=3.12\ \frac{1}{ft}\cdot kip$$

Weight of blocks above

$$F_{vblock}>F_{v1}=1.00$$

Blocks with blocks above can withstand the vertical uplift force

$$Fs:=1.25$$

$$F_{vblock}>Fs\ F_{v1}=1.00$$

Blocks withstand uplift force with a safety factor of 1.25.

$$F_{vblock}-Fs\ F_{v1}=0.37\ \frac{kip}{ft}$$

Resisting horizontal friction angle between blocks Fhres

$v := 0.6$

$N := \left(g \cdot \left(W_b\right)\right) = 2.40\ \frac{kip}{ft}$

$F_{hres} := v \cdot N = 1.44\ \frac{1}{ft} \cdot kip$ $\quad F_h = 2.76\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - 1.25\ F_h = -2.01\ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

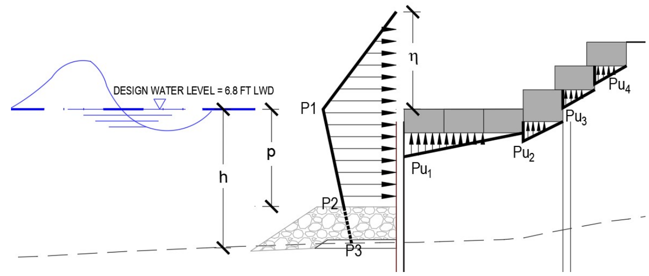
$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(2) - Celev_a(1)\right)^2 \cdot \gamma_s \cdot g = 2.66\ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - Fs\ F_h = 0.64\ \frac{1}{ft} \cdot kip$

RUBBLEMOUND FOUNDATION ALTERNATIVE: R2 SOUTH SECTION

Design Parameters:



-Significant Wave Height: $Hs := 8.9\ ft$

-Peak Spectral Wave Period: $Tp := 9.12\ s$

- Deepwater wave length: $Lo := \frac{g \cdot Tp^2}{2 \cdot \pi} = 425.91\ ft$

- Water depth in front of structure from LWD: $h := 12\ ft$

- Still water level (Water level above LWD): $SWL := 6.8\ ft$

- Total water depth at toe: $ht := h + SWL = 18.80\ ft$ $\quad \frac{ht}{Lo} = 0.04$

- Total water depth at an offshore distance of 5 significant wave heights: $hb := 18\ ft + SWL = 24.80\ ft$

- Total water depth at toe on top of mound armoring units: $d := ht - 10\ ft = 8.80\ ft$

- Total water depth at toe of Upright Wall: $h' := ht$

- Max Design Breaking Wave H_D=Hmax $\quad H_D := min(1.8 \cdot Hs, 0.78 \cdot ht) = 14.66\ ft$

- Local wave length (APPROX must have ht/Lo<0.35):

$$L := \sqrt[2]{2\ \pi \cdot ht \cdot Lo} \cdot \left(1 - \frac{ht}{Lo}\right) = 214.40\ ft$$

- Wave Angle to Shore: $\beta := 0$

- Density of Water: $\rho o := 62.43\ \frac{lb}{ft^3}$

- Height above SWL at which wave pressure is 0: $\eta := SWL + 0.75 \cdot (1 + \cos(\beta))\ H_D = 28.80\ ft$

$$\alpha_1 := 0.6 + \frac{1}{2} \left(\frac{\left(4 \cdot \pi \cdot \frac{ht}{L}\right)}{\sinh\left(4 \cdot \pi \cdot \frac{ht}{L}\right)} \right)^2 = 0.94$$

$$\alpha_2 := min\left(\frac{(hb-d)}{3 \cdot hb}\left(\frac{H_D}{d}\right)^2, 2 \cdot \frac{d}{H_D}\right) = 0.60$$

$$\alpha_3 := 1 - \frac{h'}{h}\left(1 - \frac{1}{\cosh\left(2\,\pi \cdot \frac{h}{L}\right)}\right) = 0.91$$

- Wave Pressure Modification Factors* See page 109 OCDI coefficients if rubblemound is in front of vertical structure:

$\lambda_1 := 0.8$ $\lambda_2 := 0$ $\lambda_3 := 0.8$

- Pressure at Still Water Level SWL :

$$P_1 := \frac{1}{2}\,(1+\cos(\beta)) \cdot \left(\alpha_1 \cdot \lambda_1 + \alpha_2 \cdot \lambda_2 \cdot \cos(\beta)^2\right) \cdot \rho o \cdot g \cdot H_D = 0.69\,\frac{kip}{ft^2}$$

$$P_1 = 0.69\,\frac{kip}{ft^2}$$

- Pressure at Sea Floor:

$$P_2 := \frac{P_1}{\cosh\left(2 \cdot \pi \cdot \frac{ht}{L}\right)} = 0.59\,\frac{kip}{ft^2}$$

- Pressure at Toe of Wall:

$$P_3 := \alpha_3 \cdot P_1 = 0.62\,\frac{kip}{ft^2} \qquad P_3 = 29.88\,\frac{1}{m^2} \cdot kN$$

- Wave Pressure at Different Elevations Below SWL Celevb and Above SWL Celeva:

$SWL = 6.80\ ft$

$$Celev_b := \begin{bmatrix} 1 \\ 6 \\ 5 \end{bmatrix} ft \qquad Celev_a := \begin{bmatrix} 7 \\ 9 \\ 11 \\ 13 \end{bmatrix} ft$$

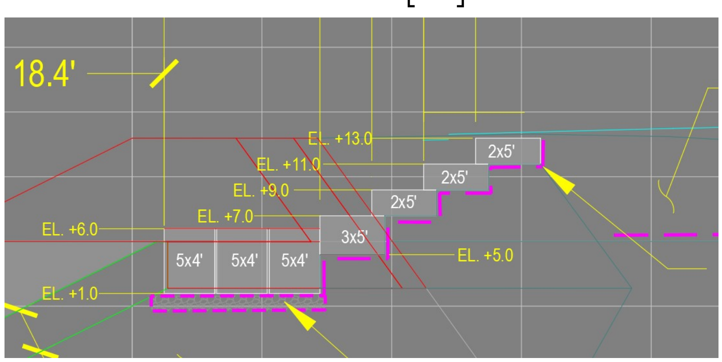


Figure: Celev per Block Row

$$P_{4b} := P_2 + (P_1 - P_2) \cdot \frac{(h + Celev_b)}{(SWL + h)} = \begin{bmatrix} 0.66 \\ 0.68 \\ 0.68 \end{bmatrix} \frac{kip}{ft^2}$$

$$P_{4a} := \frac{\eta - (Celev_a - SWL)}{\eta} \cdot P_1 = \begin{bmatrix} 0.68 \\ 0.63 \\ 0.59 \\ 0.54 \end{bmatrix} \frac{kip}{ft^2}$$

- Uplift Pressure at bottom: * In case of Caisson Structure

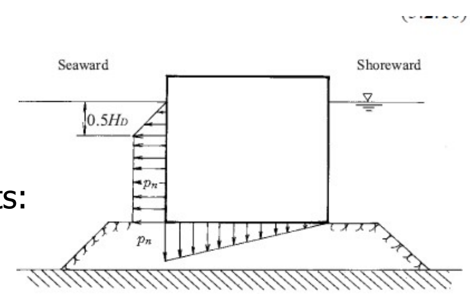
$$P_u := \frac{1}{2} \cdot (1 + \cos(\beta)) \cdot \alpha_1 \cdot \alpha_3 \cdot \lambda_3 \cdot \rho o \cdot g \cdot H_D = 0.62 \ \frac{kip}{ft^2}$$

CALCULATION OF "NEGATIVE" WAVE TROUGH PRESSURE FORCE

$$p_n := \frac{1}{2} \cdot \rho o \cdot g \cdot H_D = 0.46 \ \frac{kip}{ft^2} \qquad p_n = 21.92 \ \frac{1}{m^2} \cdot kN$$

- Elevation from SWL where triangular distribution starts:

$$SWL - \frac{H_D}{2} = -0.53 \ ft$$



T- 5.2.4 Negative Wave Pressure Distribution

CALCULATION OF REQUIRED BLOCK SIZE TO WITHSTAND WAVE FORCE

BLOCKS AT BOTTOM ROW with Elevation base at +1' and crest at +7'

Dimensions of block LxDxH:

$$L_{block} := 5\ ft \quad D_{block} := 4\ ft \quad H_{block} := 5\ ft$$

Density of stone and water:

$$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$$

Weight of Individual block Wb and displaced water Ww:

$$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 8.00\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.60\ \frac{ton}{ft}$$

$$W_w := D_{block} \cdot H_{block} \cdot \gamma_w = 0.62\ \frac{ton}{ft}$$

Horizontal Wave force on face of the block

$$Celev_b \qquad F_h := \left(P_{4b}(0) \cdot H_{block} + \frac{\left(\left(P_{4b}(0) - P_{4b}(1)\right) \cdot H_{block}\right)}{2}\right) = 3.23\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of **3** blocks at +1' F_{v1}

$$F_{v1} := 3\ \left(P_{4b}(0)\right)\ \frac{D_{block}}{2} = 3.95\ \frac{1}{ft} \cdot kip$$

Resisting uplift Block Weight Force F_{vblock} 3 blocks at promenade level +1'

$$F_{vblock} := g \cdot \left(W_b - W_w\right)\ (3) = 5.86\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$$F_{vblock} > F_{v1} = 1.00$$

*Blocks withstand the vertical uplift force with no safety factor considered

$$Fs := 1.25$$

$$F_{vblock} > Fs\ F_{v1} = 1.00$$

Blocks withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = 0.91\ \frac{kip}{ft}$

Resisting HORIZONTAL FORCE F_{hres}

Friction angle $\upsilon := 0.6$

Normal 3 blocks (weight-submergence-uplift force) $N := 3 \cdot (g \cdot (W_b - W_w)) = 5.86\ \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 3.51\ \frac{1}{ft} \cdot kip$ $F_h = 3.23\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 1.00$

Blocks alone can withstand the horizontal push force. The backfill on the land side will increase resistance

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(3) - Celev_b(0)\right)^2 \cdot \gamma_s \cdot g = 42.51\ \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25\ F_h = 41.98\ \frac{1}{ft} \cdot kip$$

Blocks can resist horizontal pressure

BLOCK AT SECOND ROW with Elevation base at +5' and crest at +7'

$Celev_b(2) = 5.00\ ft$ $Celev_a(0) = 7.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft$ $D_{block} := 5\ ft$ $H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3}$ $\gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$

$$F_h := \left(P_{4b}(2) \cdot H_{block} + \frac{((P_{4b}(2) - P_{4a}(0)) \cdot H_{block})}{2}\right) = 2.03\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of 3 blocks +1 Fv1

$$F_{v1} := 1\ (P_{4b}(1))\ \frac{D_{block}}{2} = 1.71\ \frac{1}{ft} \cdot kip$$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$$F_{vblock} := g \cdot (W_b - 0.25\ W_w) = 2.18\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$

Blocks with two layers of blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

Blocks withstand uplift force with a safety factor of 1.25. Even without considering block on top.

$F_{vblock} - Fs\ F_{v1} = 0.05\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks Fhres

$v := 0.6$

$N := \left(g \cdot \left(W_b - 0.5\ W_w\right)\right) = 1.96\ \frac{kip}{ft}$

$F_{hres} := v \cdot N = 1.18\ \frac{1}{ft} \cdot kip$ $F_h = 2.03\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - Fs\ F_h = -1.36\ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(3) - Celev_b(2)\right)^2 \cdot \gamma_s \cdot g = 18.89\ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - 1.25\ F_h = 17.53\ \frac{1}{ft} \cdot kip$

Blocks at second row can withstand the horizontal force

BLOCK AT THIRD ROW with Elevation base at +7' and crest at +9'

$Celev_a(0)=7.00\ ft$ $Celev_a(1)=9.00\ ft$

Dimensions of block LxDxH:

$L_{block}:=6\ ft$ $D_{block}:=5\ ft$ $H_{block}:=2\ ft$

Density of stone and water:

$\gamma_s:=160\ \frac{lb}{ft^3}$ $\gamma_w:=62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt}:=L_{block}\cdot D_{block}\cdot H_{block}\cdot \gamma_s=4.80\ ton$ $W_b:=D_{block}\cdot H_{block}\cdot \gamma_s=0.80\ \frac{ton}{ft}$

$W_w:=D_{block}\cdot (H_{block}-0.2\ ft)\cdot \gamma_w=0.28\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$ $F_h:=\left(P_{4a}(0)\cdot H_{block}+\frac{((P_{4a}(0)-P_{4a}(1))\cdot H_{block})}{2}\right)=1.41\ \frac{1}{ft}\cdot kip$

Wave uplift force on first row of 3 blocks +1 Fv1

$F_{v1}:=1\ (P_{4a}(0))\ \frac{D_{block}}{2}=1.71\ \frac{1}{ft}\cdot kip$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$F_{vblock}:=g\cdot (W_b)\ (1)+g\cdot (W_b)\ (0.5)=2.40\ \frac{1}{ft}\cdot kip$

Weight of blocks above

$F_{vblock}>F_{v1}=1.00$ Blocks with blocks above can withstand the vertical uplift force

$Fs:=1.25$

$F_{vblock}>Fs\ F_{v1}=1.00$

$F_{vblock}-Fs\ F_{v1}=0.27\ \frac{kip}{ft}$

Blocks at third row can withstand uplift force with a safety factor of 1.25. It needs the block on top to resist the uplift force it is recommended to dowel

Resisting horizontal friction angle between blocks Fhres

$\upsilon := 0.6$

$N := (g \cdot (W_b)) = 1.60 \ \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 0.96 \ \frac{1}{ft} \cdot kip$ $\quad F_h = 1.41 \ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - Fs \ F_h = -0.81 \ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35 \ °$

$K_p := \tan\left(45 \ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2} K_p \ (Celev_a(3) - Celev_a(0))^2 \cdot \gamma_s \cdot g = 10.63 \ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - 1.25 \ F_h = 9.82 \ \frac{1}{ft} \cdot kip$

Blocks at third row can withstand the horizontal push considering the backfill.

BLOCK AT FOURTH ROW with Elevation base at +9' and crest at +11'

$Celev_a(1) = 9.00\ ft \qquad Celev_a(2) = 11.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft \quad D_{block} := 5\ ft \quad H_{block} := 2\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 4.80\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 0.80\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.28\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b \qquad F_h := \left(P_{4a}(0) \cdot H_{block} + \frac{((P_{4a}(0) - P_{4a}(1)) \cdot H_{block})}{2}\right) = 1.41\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of 3 blocks +1 Fv1

$F_{v1} := 1\ (P_{4a}(0))\ \frac{D_{block}}{2} = 1.71\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$F_{vblock} := g \cdot (W_b)\ (1) + g \cdot (W_b)\ (0.5) = 2.40\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$ Blocks with blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

Blocks can withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = 0.27\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks F_{hres}

$$\upsilon := 0.6$$

$$N := \left(g \cdot \left(W_b\right)\right) = 1.60 \ \frac{kip}{ft}$$

$$F_{hres} := \upsilon \cdot N = 0.96 \ \frac{1}{ft} \cdot kip \qquad F_h = 1.41 \ \frac{1}{ft} \cdot kip$$

$$F_{hres} > F_h = 0.00$$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$$F_{hres} - 1.25 \ F_h = -0.81 \ \frac{1}{ft} \cdot kip$$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35 \ °$

$$K_p := \tan\left(45 \ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2} K_p \left(Celev_a(3) - Celev_a(1)\right)^2 \cdot \gamma_s \cdot g = 4.72 \ \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25 \ F_h = 3.92 \ \frac{1}{ft} \cdot kip$$

BLOCK AT FIFTH ROW with Elevation base at +11' and crest at +13'

$Celev_a(2) = 11.00\ ft \qquad Celev_a(3) = 13.00\ ft$

Dimensions of block LxDxH:

$$L_{block} := 6\ ft \qquad D_{block} := 5\ ft \qquad H_{block} := 2\ ft$$

Density of stone and water:

$$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$$

Weight of Individual block:

$$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 4.80\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 0.80\ \frac{ton}{ft}$$

$$W_w := D_{block} \cdot \left(H_{block} - 0.2\ ft\right) \cdot \gamma_w = 0.28\ \frac{ton}{ft}$$

Wave force on face of the block

$$F_h := \left(P_{4a}(0) \cdot H_{block} + \frac{\left(\left(P_{4a}(0) - P_{4a}(1)\right) \cdot H_{block}\right)}{2}\right) = 1.41\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of 3 blocks +1 Fv1

$$F_{v1} := 1\ \left(P_{4a}(0)\right)\ \frac{D_{block}}{2} = 1.71\ \frac{1}{ft} \cdot kip$$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$$F_{vblock} := g \cdot \left(W_b\right)\ (1) + g \cdot \left(W_b\right)\ (0.5) = 2.40\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$ Blocks with blocks above can withstand the vertical uplift force

$F_{vblock} > Fs\ F_{v1} = 1.00$

Blocks can withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = 0.27\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks Fhres

$$N := (g \cdot (W_b)) = 1.60 \ \frac{kip}{ft}$$

$$F_{hres} := \upsilon \cdot N = 0.96 \ \frac{1}{ft} \cdot kip \qquad F_h = 1.41 \ \frac{1}{ft} \cdot kip$$

$$F_{hres} > F_h = 0.00$$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$$F_{hres} - 1.25 \ F_h = -0.81 \ \frac{1}{ft} \cdot kip$$

Additional backfill horizontal pressure:

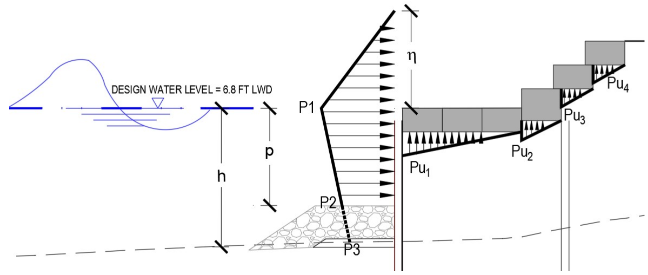
Back fill friction angle: $\phi := 35 \ °$

$$K_p := \tan\left(45 \ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2} K_p \ \left(Celev_a(3) - Celev_a(2)\right)^2 \cdot \gamma_s \cdot g = 1.18 \ \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25 \ F_h = 0.37 \ \frac{1}{ft} \cdot kip$$

RUBBLEMOUND FOUNDATION ALTERNATIVE: R3 PROTECTED SECTION



Design Parameters:

-Significant Wave Height: $Hs := 6.16\ ft$

-Peak Spectral Wave Period: $Tp := 6.28\ s$

- Deepwater wave length: $Lo := \dfrac{g \cdot Tp^2}{2 \cdot \pi} = 201.95\ ft$

- Water depth in front of structure from LWD: $h := 10\ ft$

- Still water level (Water level above LWD): $SWL := 6.8\ ft$

- Total water depth at toe: $ht := h + SWL = 16.80\ ft$ $\dfrac{ht}{Lo} = 0.08$

- Total water depth at an offshore distance of 5 significant wave heights: $hb := h + SWL = 16.80\ ft$

- Total water depth at toe on top of mound armoring units: $d := ht - 10\ ft = 6.80\ ft$

- Total water depth at toe of Upright Wall: $h' := ht$

- Max Design Breaking Wave H_D=Hmax $H_D := min(1.8 \cdot Hs, 0.78 \cdot ht) = 11.09\ ft$

- Local wave length (APPROX must have ht/Lo<0.35):

$$L := \sqrt[2]{2\ \pi \cdot ht \cdot Lo} \cdot \left(1 - \frac{ht}{Lo}\right) = 133.86\ ft$$

- Wave Angle to Shore: $\beta := 0$

- Density of Water: $\rho o := 62.43\ \dfrac{lb}{ft^3}$

- Height above SWL at which wave pressure is 0: $\eta := SWL + 0.75 \cdot (1 + \cos(\beta))\ H_D = 23.43\ ft$

$$\alpha_1 := 0.6 + \frac{1}{2}\left(\frac{\left(4 \cdot \pi \cdot \dfrac{ht}{L}\right)}{\sinh\left(4 \cdot \pi \cdot \dfrac{ht}{L}\right)}\right)^2 = 0.83$$

$$\alpha_2 := min\left(\frac{(hb-d)}{3 \cdot hb}\left(\frac{H_D}{d}\right)^2, 2 \cdot \frac{d}{H_D}\right) = 0.53$$

$$\alpha_3 := 1 - \frac{h'}{h}\left(1 - \frac{1}{\cosh\left(2\,\pi \cdot \frac{h}{L}\right)}\right) = 0.83$$

- Wave Pressure Modification Factors* See page 109 OCDI coefficients if rubblemound is in front of vertical structure:

$\lambda_1 := 0.8$ $\lambda_2 := 0$ $\lambda_3 := 0.8$

- Pressure at Still Water Level SWL :

$$P_1 := \frac{1}{2}\left(1+\cos(\beta)\right) \cdot \left(\alpha_1 \cdot \lambda_1 + \alpha_2 \cdot \lambda_2 \cdot \cos(\beta)^2\right) \cdot \rho o \cdot g \cdot H_D = 0.46\ \frac{kip}{ft^2}$$

$$P_1 = 0.46\ \frac{kip}{ft^2}$$

- Pressure at Sea Floor:

$$P_2 := \frac{P_1}{\cosh\left(2 \cdot \pi \cdot \frac{ht}{L}\right)} = 0.35\ \frac{kip}{ft^2}$$

- Pressure at Toe of Wall:

$$P_3 := \alpha_3 \cdot P_1 = 0.38\ \frac{kip}{ft^2} \qquad P_3 = 18.31\ \frac{1}{m^2} \cdot kN$$

- Wave Pressure at Different Elevations Below SWL Celev$_b$ and Above SWL Celev$_a$:

$SWL = 6.80\ ft$

$$Celev_b := \begin{bmatrix} -1.6 \\ 2.6 \\ 1.4 \\ 4.6 \end{bmatrix} ft \quad Celev_a := \begin{bmatrix} 7.6 \\ 10.6 \end{bmatrix} ft$$

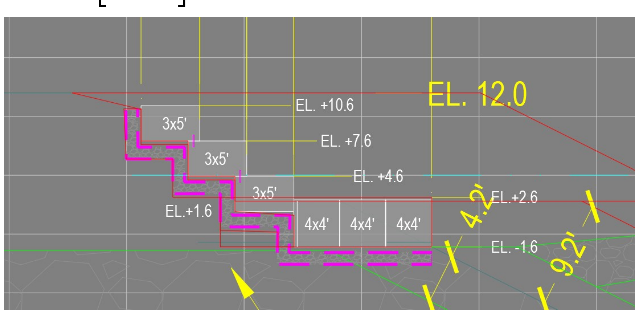


Figure: Celev per Block Row

$$P_{4b} := P_2 + (P_1 - P_2) \cdot \frac{(h + Celev_b)}{(SWL + h)} = \begin{bmatrix} 0.40 \\ 0.43 \\ 0.42 \\ 0.45 \end{bmatrix} \frac{kip}{ft^2}$$

$$P_{4a} := \frac{\eta - (Celev_a - SWL)}{\eta} \cdot P_1 = \begin{bmatrix} 0.44 \\ 0.39 \end{bmatrix} \frac{kip}{ft^2}$$

- Uplift Pressure at bottom: * In case of Caisson Structure

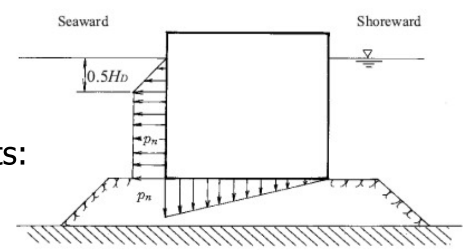
$$P_u := \frac{1}{2} \cdot (1 + \cos(\beta)) \cdot \alpha_1 \cdot \alpha_3 \cdot \lambda_3 \cdot \rho o \cdot g \cdot H_D = 0.38 \frac{kip}{ft^2}$$

CALCULATION OF "NEGATIVE" WAVE TROUGH PRESSURE FORCE

$$p_n := \frac{1}{2} \cdot \rho o \cdot g \cdot H_D = 0.35 \frac{kip}{ft^2} \qquad p_n = 16.57 \frac{1}{m^2} \cdot kN$$

- Elevation from SWL where triangular distribution starts:

$$SWL - \frac{H_D}{2} = 1.26 \; ft$$



T- 5.2.4 Negative Wave Pressure Distribution

CALCULATION OF REQUIRED BLOCK SIZE TO WITHSTAND WAVE FORCE

BLOCKS AT BOTTOM ROW with Elevation base at -1.6' and crest at +2.6'

$Celev_b(0) = -1.60\ ft \qquad Celev_b(1) = 2.60\ ft$

Dimensions of block LxDxH:

$L_{block} := 5\ ft \quad D_{block} := 4\ ft \quad H_{block} := 4\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block Wb and displaced water Ww:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 6.40\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.28\ \frac{ton}{ft}$

$W_w := D_{block} \cdot H_{block} \cdot \gamma_w = 0.50\ \frac{ton}{ft}$

Horizontal Wave force on face of the block

$Celev_b \qquad F_h := \left(P_{4b}(0) \cdot H_{block} + \frac{\left(\left(P_{4b}(0) - P_{4b}(1)\right) \cdot H_{block}\right)}{2}\right) = 1.56\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of **3** blocks at +1' Fv1

$F_{v1} := 3\ \left(P_{4b}(0)\right)\ \frac{D_{block}}{2} = 2.42\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force Fvblock 3 blocks at promenade level +1'

$F_{vblock} := g \cdot \left(W_b - W_w\right)\ (3) = 4.68\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$ *Blocks withstand the vertical uplift force with no safety factor considered

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$ Blocks withstand uplift force with a safety factor of 1.25.

$$F_{vblock} - Fs\ F_{v1} = 1.66\ \frac{kip}{ft}$$

Resisting HORIZONTAL FORCE F_{hres}

Friction angle $\upsilon := 0.6$

Normal 3 blocks (weight-submergence-uplift force) $N := 3 \cdot \left(g \cdot \left(W_b - W_w\right)\right) = 4.68\ \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 2.81\ \frac{1}{ft} \cdot kip$ $F_h = 1.56\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 1.00$

Blocks alone can withstand the horizontal push force. The backfill on the land side will increase resistance

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(1) - Celev_b(0)\right)^2 \cdot \gamma_s \cdot g = 43.94\ \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25\ F_h = 44.80\ \frac{1}{ft} \cdot kip$$

Blocks can resist horizontal pressure

BLOCK AT SECOND ROW with Elevation base at +1.4' and crest at +4.6' $Celev_b(2) = 1.40\ ft$ $Celev_b(3) = 4.60\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft$ $D_{block} := 5\ ft$ $H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3}$ $\gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$ $F_h := \left(P_{4b}(2) \cdot H_{block} + \frac{((P_{4b}(2) - P_{4b}(3)) \cdot H_{block})}{2}\right) = 1.24\ \frac{1}{ft} \cdot kip$

Wave uplift force Fv1

$F_{v1} := (P_{4b}(2))\ \frac{D_{block}}{2} = 1.06\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force F_{vblock} 1 block at first step

$F_{vblock} := g \cdot (W_b - W_w) = 1.53\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$ Blocks with two layers of blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

Blocks withstand uplift force with a safety factor of 1.25. Even without considering block on top.

$F_{vblock} - Fs\ F_{v1} = 0.20\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks Fhres

$$\upsilon := 0.6$$

$$N := \left(g \cdot \left(W_b - W_w\right)\right) = 1.53\ \frac{kip}{ft}$$

$$F_{hres} := \upsilon \cdot N = 0.92\ \frac{1}{ft} \cdot kip \qquad F_h = 1.24\ \frac{1}{ft} \cdot kip$$

$$F_{hres} > F_h = 0.00$$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$$F_{hres} - Fs\ F_h = -0.63\ \frac{1}{ft} \cdot kip$$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(1) - Celev_b(2)\right)^2 \cdot \gamma_s \cdot g = 24.99\ \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25\ F_h = 24.35\ \frac{1}{ft} \cdot kip$$

Blocks at second row can withstand the horizontal force

BLOCK AT THIRD ROW with Elevation base at +4.6' and crest at +7.6'

$Celev_b(3) = 4.60\ ft \qquad Celev_a(0) = 7.60\ ft$

Dimensions of block LxDxH:

$$L_{block} := 6\ ft \qquad D_{block} := 5\ ft \qquad H_{block} := 3\ ft$$

Density of stone and water:

$$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$$

Weight of Individual block:

$$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$$

$$W_w := D_{block} \cdot \left(H_{block} - 0.2\ ft\right) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$$

Wave force on face of the block

$Celev_b$

$$F_h := \left(P_{4b}(3) \cdot H_{block} + \frac{\left(\left(P_{4b}(3) - P_{4a}(0)\right) \cdot H_{block}\right)}{2}\right) = 1.34\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of 3 blocks +1 Fv1

$$F_{v1} := 1\ \left(P_{4b}(3)\right)\ \frac{D_{block}}{2} = 1.11\ \frac{1}{ft} \cdot kip$$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$$F_{vblock} := g \cdot \left(W_b\right)\ (1) + g \cdot \left(W_b\right)\ (0.5) = 3.60\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$ — Blocks with blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

$F_{vblock} - Fs\ F_{v1} = 2.21\ \frac{kip}{ft}$ — Blocks at third row can withstand uplift force with a safety factor of 1.25. It needs the block on top to resist the uplift force it is recommended to dowel

Resisting horizontal friction angle between blocks Fhres

$\upsilon := 0.6$

$N := \left(g \cdot \left(W_b - 0.5\ W_w\right)\right) = 1.96\ \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 1.18\ \frac{1}{ft} \cdot kip$ $\quad F_h = 1.34\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks can withstand the horizontal push force need to consider the back fill.

$F_{hres} - Fs\ F_h = -0.49\ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(1) - Celev_b(3)\right)^2 \cdot \gamma_s \cdot g = 10.63\ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - 1.25\ F_h = 10.13\ \frac{1}{ft} \cdot kip$

Blocks at third row can withstand the horizontal push considering the backfill.

BLOCK AT FOURTH ROW with Elevation base at +7.6' and crest at +10.6' $Celev_a(0) = 7.60\ ft$ $Celev_a(1) = 10.60\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft$ $D_{block} := 5\ ft$ $H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3}$ $\gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$ $F_h := \left(P_{4a}(0) \cdot H_{block} + \frac{((P_{4a}(0) - P_{4a}(1)) \cdot H_{block})}{2}\right) = 1.42\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of 3 blocks +1 Fv1

$F_{v1} := 1\ (P_{4a}(0))\ \frac{D_{block}}{2} = 1.11\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$F_{vblock} := g \cdot (W_b)\ (1) = 2.40\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$ Blocks with blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

Blocks can withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = 1.01\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks Fhres

$\upsilon := 0.6$

$N := (g \cdot (W_b)) = 2.40 \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 1.44 \frac{1}{ft} \cdot kip$ $\quad F_h = 1.42 \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 1.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - 1.25\ F_h = -0.34 \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

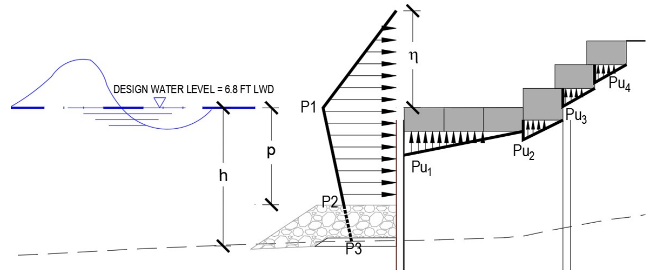
Back fill friction angle: $\phi := 35\ °$

$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2} K_p \left(Celev_a(1) - Celev_a(0)\right)^2 \cdot \gamma_s \cdot g = 2.66 \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - 1.25\ F_h = 2.32 \frac{1}{ft} \cdot kip$

SHEET PILE FOUNDATION ALTERNATIVE: SP1-S NORTH SECTION



Design Parameters:

-Significant Wave Height: $Hs := 11.24\ ft$

-Peak Spectral Wave Period: $Tp := 11.96\ s$

- Deepwater wave length: $Lo := \frac{g \cdot Tp^2}{2 \cdot \pi} = 732.47\ ft$

- Water depth in front of structure from LWD: $h := 18\ ft$

- Still water level (Water level above LWD): $SWL := 6.8\ ft$

- Total water depth at toe: $ht := h + SWL = 24.80\ ft \quad \frac{ht}{Lo} = 0.03$

- Total water depth at an offshore distance of 5 significant wave heights: $hb := 18\ ft + SWL = 24.80\ ft$

- Total water depth at toe on top of mound armoring units: $d := ht - 10\ ft = 14.80\ ft$

- Total water depth at toe of Upright Wall: $h' := ht$

- Max Design Breaking Wave H_D=Hmax $H_D := min(1.8 \cdot Hs, 0.78 \cdot ht) = 19.34\ ft$

- Local wave length (APPROX must have ht/Lo<0.35):

$$L := \sqrt[2]{2\ \pi \cdot ht \cdot Lo} \cdot \left(1 - \frac{ht}{Lo}\right) = 326.40\ ft$$

- Wave Angle to Shore: $\beta := 0$

- Density of Water: $\rho o := 62.43\ \frac{lb}{ft^3}$

- Height above SWL at which wave pressure is 0: $\eta := SWL + 0.75 \cdot (1 + \cos(\beta))\ H_D = 35.82\ ft$

$$\alpha_1 := 0.6 + \frac{1}{2} \left(\frac{\left(4 \cdot \pi \cdot \frac{ht}{L}\right)}{\sinh\left(4 \cdot \pi \cdot \frac{ht}{L}\right)} \right)^2 = 0.97$$

$$\alpha_2 := min\left(\frac{(hb-d)}{3 \cdot hb}\left(\frac{H_D}{d}\right)^2, 2 \cdot \frac{d}{H_D}\right) = 0.23$$

$$\alpha_3 := 1 - \frac{h'}{h}\left(1 - \frac{1}{\cosh\left(2\ \pi \cdot \frac{h}{L}\right)}\right) = 0.92$$

- Wave Pressure Modification Factors* See page 109 OCDI coefficients if rubblemound is in front of vertical structure:

$$\lambda_1 := 1 \qquad \lambda_2 := 1 \qquad \lambda_3 := 1$$

- Pressure at Still Water Level SWL :

$$P_1 := \frac{1}{2}\ (1+\cos(\beta)) \cdot \left(\alpha_1 \cdot \lambda_1 + \alpha_2 \cdot \lambda_2 \cdot \cos(\beta)^2\right) \cdot \rho o \cdot g \cdot H_D = 1.45\ \frac{kip}{ft^2}$$

$$P_1 = 1.45\ \frac{kip}{ft^2}$$

- Pressure at Sea Floor:

$$P_2 := \frac{P_1}{\cosh\left(2 \cdot \pi \cdot \frac{ht}{L}\right)} = 1.30\ \frac{kip}{ft^2}$$

- Pressure at Toe of Wall:

$$P_3 := \alpha_3 \cdot P_1 = 1.34\ \frac{kip}{ft^2} \qquad P_3 = 64.02\ \frac{1}{m^2} \cdot kN$$

- Wave Pressure at Different Elevations Below SWL Celev$_b$ and Above SWL Celev$_a$:

$SWL = 6.80\ ft$

$$Celev_b := \begin{bmatrix} 3.5 \\ 6.5 \\ 5 \end{bmatrix} ft \qquad Celev_a := \begin{bmatrix} 9 \\ 12 \\ 15 \end{bmatrix} ft$$

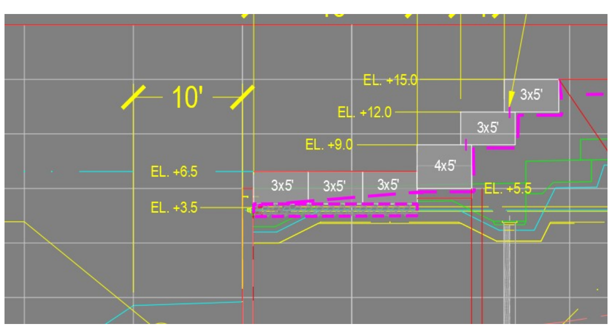


Figure: Celev per Block Row

$$P_{4b} := P_2 + \left(P_1 - P_2\right) \cdot \frac{\left(h + Celev_b\right)}{\left(SWL + h\right)} = \begin{bmatrix} 1.43 \\ 1.45 \\ 1.44 \end{bmatrix} \frac{kip}{ft^2}$$

$$P_{4a} := \frac{\eta - \left(Celev_a - SWL\right)}{\eta} \cdot P_1 = \begin{bmatrix} 1.36 \\ 1.24 \\ 1.12 \end{bmatrix} \frac{kip}{ft^2}$$

- Uplift Pressure at bottom: * In case of Caisson Structure

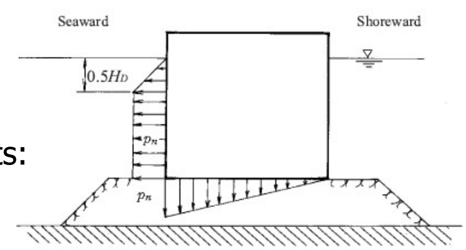
$$P_u := \frac{1}{2} \cdot \left(1 + \cos\left(\beta\right)\right) \cdot \alpha_1 \cdot \alpha_3 \cdot \lambda_3 \cdot \rho o \cdot g \cdot H_D = 1.08 \ \frac{kip}{ft^2}$$

CALCULATION OF "NEGATIVE" WAVE TROUGH PRESSURE FORCE

$$p_n := \frac{1}{2} \cdot \rho o \cdot g \cdot H_D = 0.60 \ \frac{kip}{ft^2} \qquad p_n = 28.91 \ \frac{1}{m^2} \cdot kN$$

- Elevation from SWL where triangular distribution starts:

$$SWL - \frac{H_D}{2} = -2.87 \ ft$$



T- 5.2.4 Negative Wave Pressure Distribution

CALCULATION OF REQUIRED BLOCK SIZE TO WITHSTAND WAVE FORCE

BLOCKS AT BOTTOM ROW with Elevation base at +4' and crest at +7'

$Celev_b(0) = 3.50\ ft$ $Celev_a(0) = 9.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft$ $D_{block} := 4\ ft$ $H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3}$ $\gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block Wb and displaced water Ww:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 5.76\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 0.96\ \frac{ton}{ft}$

$W_w := D_{block} \cdot H_{block} \cdot \gamma_w = 0.37\ \frac{ton}{ft}$

Horizontal Wave force on face of the block

$Celev_b$ $F_h := \left(P_{4b}(0) \cdot H_{block} + \frac{\left(\left(P_{4b}(0) - P_{4b}(1)\right) \cdot H_{block}\right)}{2}\right) = 4.27\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of **3** blocks at +1' F_{v1}

$F_{v1} := 0.2 \cdot 3\ \left(P_{4b}(0)\right)\ \frac{D_{block}}{2} = 1.72\ \frac{1}{ft} \cdot kip$

*Uplift reduction factor of 20% applied to first row due to presence of SheetPile

Resisting uplift Block Weight Force F_{vblock} 3 blocks at promenade level +1'

$F_{vblock} := g \cdot \left(W_b - W_w\right)\ (3) = 3.51\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$ *Blocks withstand the vertical uplift force with no safety factor considered

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$ Blocks withstand uplift force with a safety factor of 1.25. Additional dowels recommended ton increase resilience

$$F_{vblock} - Fs\ F_{v1} = 1.37\ \frac{kip}{ft}$$

Resisting HORIZONTAL FORCE F_{hres}

Friction angle $\upsilon := 0.6$

Normal 3 blocks (weight-submergence-uplift force) $N := 3 \cdot \left(g \cdot \left(W_b - W_w\right)\right) = 3.51\ \frac{kip}{ft}$

$$F_{hres} := \upsilon \cdot N = 2.11\ \frac{1}{ft} \cdot kip \qquad F_h = 4.27\ \frac{1}{ft} \cdot kip$$

$$F_{hres} > F_h = 0.00$$

Blocks alone cannot withstand the horizontal push force. The backfill on the land side will increase resistance. Recommended to be doweled to provide additional resistance to horizontal push

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(2) - Celev_b(0)\right)^2 \cdot \gamma_s \cdot g = 39.04\ \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25\ F_h = 35.82\ \frac{1}{ft} \cdot kip$$

Blocks can resist horizontal force given backfill behind them

BLOCK AT SECOND ROW with Elevation base at +5' and crest at +9'

$Celev_b(2) = 5.00\ ft$ $\qquad Celev_a(0) = 9.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft \qquad D_{block} := 5\ ft \qquad H_{block} := 4\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 9.60\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.60\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.59\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b \qquad F_h := \left(P_{4b}(2) \cdot H_{block} + \frac{((P_{4b}(2) - P_{4a}(0)) \cdot H_{block})}{2}\right) = 5.92\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of 3 blocks +1 Fv1

$F_{v1} := 1\ (P_{4b}(1))\ \frac{D_{block}}{2} = 3.62\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$F_{vblock} := g \cdot (W_b - 0.25\ W_w) + g \cdot (W_b)\ (0.6) = 4.82\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$

Blocks with two layers of blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

$F_{vblock} - Fs\ F_{v1} = 0.29\ \frac{kip}{ft}$

Blocks do not withstand uplift force with a safety factor of 1.25 without considering blocks above. The third column of blocks at +7' need to be doweled to provide additional vertical resistance to the wave uplift force. Overturning moments need to be considered.

Resisting horizontal friction angle between blocks Fhres

$\upsilon := 0.6$

$N := (g \cdot (W_b - 0.5\ W_w)) = 2.61\ \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 1.56\ \frac{1}{ft} \cdot kip$ $\quad F_h = 5.92\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - Fs\ F_h = -5.83\ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2}\ K_p\ (Celev_a(2) - Celev_b(1))^2 \cdot \gamma_s \cdot g = 21.33\ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - Fs\ F_h = 15.50\ \frac{1}{ft} \cdot kip$

BLOCK AT THIRD ROW with Elevation base at +9' and crest at +12'

$Celev_a(0) = 9.00\ ft$ $\quad Celev_a(1) = 12.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft \quad D_{block} := 5\ ft \quad H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3} \quad \gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton \quad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$

$$F_h := \left(P_{4a}(0) \cdot H_{block} + \frac{((P_{4a}(0) - P_{4a}(1)) \cdot H_{block})}{2}\right) = 4.27\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of 3 blocks +1 Fv1

$$F_{v1} := 1\ (P_{4a}(0))\ \frac{D_{block}}{2} = 3.41\ \frac{1}{ft} \cdot kip$$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$$F_{vblock} := g \cdot (W_b)\ (1) + g \cdot (W_b)\ (0.8) = 4.32\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$

$Fs := 1.25$

Blocks with blocks above can withstand the vertical uplift force. 80% of upper block weight applied. Dowel needs to provided

$F_{vblock} > Fs\ F_{v1} = 1.00$

Blocks withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = 0.06\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks Fhres

$\upsilon := 0.6$

$N := (g \cdot (W_b)) = 2.40\ \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 1.44\ \frac{1}{ft} \cdot kip$ $F_h = 4.27\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - Fs\ F_h = -3.90\ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(2) - Celev_a(0)\right)^2 \cdot \gamma_s \cdot g = 10.63\ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - 1.25\ F_h = 6.73\ \frac{1}{ft} \cdot kip$

BLOCK AT FOURTH ROW with Elevation base at +12' and crest at +15'

$Celev_a(1) = 12.00\ ft$ $Celev_a(2) = 15.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft$ $D_{block} := 5\ ft$ $H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3}$ $\gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$ $F_h := \left(P_{4a}(0) \cdot H_{block} + \frac{((P_{4a}(0) - P_{4a}(1)) \cdot H_{block})}{2}\right) = 4.27\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of 3 blocks +1 Fv1

$F_{v1} := 1\ (P_{4a}(0))\ \frac{D_{block}}{2} = 3.41\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$F_{vblock} := g \cdot (W_b)\ (1) + g \cdot (W_b)\ (0.8) = 4.32\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$

$Fs := 1.25$

Blocks with blocks above can withstand the vertical uplift force. 80% of above blocks weight applied to the calculation. Need to provide dowel

$F_{vblock} > Fs\ F_{v1} = 1.00$

Blocks withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = 0.06\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks F_{hres}

$$\upsilon := 0.6$$

$$N := \left(g \cdot \left(W_b\right)\right) = 2.40\ \frac{kip}{ft}$$

$$F_{hres} := \upsilon \cdot N = 1.44\ \frac{1}{ft} \cdot kip \qquad F_h = 4.27\ \frac{1}{ft} \cdot kip$$

$$F_{hres} > F_h = 0.00$$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$$F_{hres} - 1.25\ F_h = -3.90\ \frac{1}{ft} \cdot kip$$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

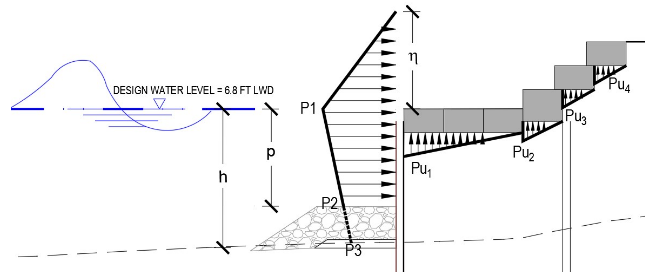
$$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2} K_p \left(Celev_a(2) - Celev_a(1)\right)^2 \cdot \gamma_s \cdot g = 2.66\ \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - Fs\ F_h = -1.24\ \frac{1}{ft} \cdot kip$$

SHEET PILE FOUNDATION ALTERNATIVE: SP2-S SOUTH SECTION

Design Parameters:



-Significant Wave Height: $Hs := 8.9\ ft$

-Peak Spectral Wave Period: $Tp := 9.12\ s$

- Deepwater wave length: $Lo := \frac{g \cdot Tp^2}{2 \cdot \pi} = 425.91\ ft$

- Water depth in front of structure from LWD: $h := 12\ ft$

- Still water level (Water level above LWD): $SWL := 6.8\ ft$

- Total water depth at toe: $ht := h + SWL = 18.80\ ft$ $\frac{ht}{Lo} = 0.04$

- Total water depth at an offshore distance of 5 significant wave heights: $hb := 18\ ft + SWL = 24.80\ ft$

- Total water depth at toe on top of mound armoring units: $d := ht - 10\ ft = 8.80\ ft$

- Total water depth at toe of Upright Wall: $h' := ht$

- Max Design Breaking Wave H_D=Hmax $H_D := min(1.8 \cdot Hs, 0.78 \cdot ht) = 14.66\ ft$

- Local wave length (APPROX must have ht/Lo<0.35):

$$L := \sqrt[2]{2\ \pi \cdot ht \cdot Lo} \cdot \left(1 - \frac{ht}{Lo}\right) = 214.40\ ft$$

- Wave Angle to Shore: $\beta := 0$

- Density of Water: $\rho o := 62.43\ \frac{lb}{ft^3}$

- Height above SWL at which wave pressure is 0: $\eta := SWL + 0.75 \cdot (1 + \cos(\beta))\ H_D = 28.80\ ft$

$$\alpha_1 := 0.6 + \frac{1}{2} \left(\frac{\left(4 \cdot \pi \cdot \frac{ht}{L}\right)}{\sinh\left(4 \cdot \pi \cdot \frac{ht}{L}\right)} \right)^2 = 0.94$$

$$\alpha_2 := min\left(\frac{(hb-d)}{3 \cdot hb}\left(\frac{H_D}{d}\right)^2, 2 \cdot \frac{d}{H_D}\right) = 0.60$$

$$\alpha_3 := 1 - \frac{h'}{h}\left(1 - \frac{1}{\cosh\left(2\,\pi \cdot \frac{h}{L}\right)}\right) = 0.91$$

- Wave Pressure Modification Factors* See page 109 OCDI coefficients if rubblemound is in front of vertical structure:

$$\lambda_1 := 1 \qquad \lambda_2 := 1 \qquad \lambda_3 := 1$$

- Pressure at Still Water Level SWL :

$$P_1 := \frac{1}{2}\,(1+\cos(\beta)) \cdot \left(\alpha_1 \cdot \lambda_1 + \alpha_2 \cdot \lambda_2 \cdot \cos(\beta)^2\right) \cdot \rho o \cdot g \cdot H_D = 1.41\ \frac{kip}{ft^2}$$

$$P_1 = 1.41\ \frac{kip}{ft^2}$$

- Pressure at Sea Floor:

$$P_2 := \frac{P_1}{\cosh\left(2 \cdot \pi \cdot \frac{ht}{L}\right)} = 1.22\ \frac{kip}{ft^2}$$

- Pressure at Toe of Wall:

$$P_3 := \alpha_3 \cdot P_1 = 1.28\ \frac{kip}{ft^2} \qquad P_3 = 61.12\ \frac{1}{m^2} \cdot kN$$

- Wave Pressure at Different Elevations Below SWL $Celev_b$ and Above SWL $Celev_a$:

$$SWL = 6.80\ ft$$

$$Celev_b := \begin{bmatrix} 3.5 \\ 5.5 \\ 5 \end{bmatrix} ft \qquad Celev_a := \begin{bmatrix} 7 \\ 10 \\ 13 \end{bmatrix} ft$$

Figure: Celev per Block Row

$$P_{4b} := P_2 + \left(P_1 - P_2\right) \cdot \frac{\left(h + Celev_b\right)}{\left(SWL + h\right)} = \begin{bmatrix} 1.37 \\ 1.39 \\ 1.39 \end{bmatrix} \frac{kip}{ft^2}$$

$$P_{4a} := \frac{\eta - \left(Celev_a - SWL\right)}{\eta} \cdot P_1 = \begin{bmatrix} 1.40 \\ 1.25 \\ 1.10 \end{bmatrix} \frac{kip}{ft^2}$$

- Uplift Pressure at bottom: * In case of Caisson Structure

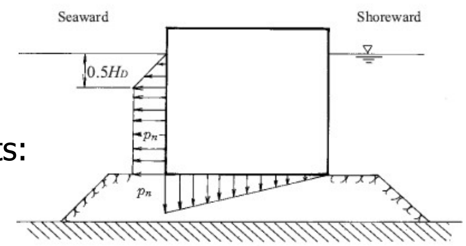
$$P_u := \frac{1}{2} \cdot \left(1 + \cos\left(\beta\right)\right) \cdot \alpha_1 \cdot \alpha_3 \cdot \lambda_3 \cdot \rho o \cdot g \cdot H_D = 0.78 \frac{kip}{ft^2}$$

CALCULATION OF "NEGATIVE" WAVE TROUGH PRESSURE FORCE

$$p_n := \frac{1}{2} \cdot \rho o \cdot g \cdot H_D = 0.46 \frac{kip}{ft^2} \qquad p_n = 21.92 \frac{1}{m^2} \cdot kN$$

- Elevation from SWL where triangular distribution starts:

$$SWL - \frac{H_D}{2} = -0.53\ ft$$



T- 5.2.4 Negative Wave Pressure Distribution

CALCULATION OF REQUIRED BLOCK SIZE TO WITHSTAND WAVE FORCE

BLOCKS AT BOTTOM ROW with Elevation base at +3.5' and crest at +5.5'

$Celev_b(0) = 3.50\ ft$ $Celev_b(1) = 5.50\ ft$

Dimensions of block LxDxH:

$L_{block} := 5\ ft$ $D_{block} := 4\ ft$ $H_{block} := 2\ ft$

Density of stone and water:

$\gamma_s := 160\ \dfrac{lb}{ft^3}$ $\gamma_w := 62.4\ \dfrac{lb}{ft^3}$

Weight of Individual block Wb and displaced water Ww:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 3.20\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 0.64\ \dfrac{ton}{ft}$

$W_w := D_{block} \cdot H_{block} \cdot \gamma_w = 0.25\ \dfrac{ton}{ft}$

Horizontal Wave force on face of the block

$Celev_b$ $$F_h := \left(P_{4b}(0) \cdot H_{block} + \frac{\left(\left(P_{4b}(0) - P_{4b}(1)\right) \cdot H_{block}\right)}{2}\right) = 2.73\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of **3** blocks at +1' F_{v1}

$$F_{v1} := 0.2 \cdot 3\ \left(P_{4b}(0)\right)\ \frac{D_{block}}{2} = 1.65\ \frac{1}{ft} \cdot kip$$

*20% factor reduction applied to uplift due to presence due to sheetpile

Resisting uplift Block Weight Force F_{vblock} 3 blocks at promenade level +1'

$$F_{vblock} := g \cdot \left(W_b - W_w\right)\ (3) = 2.34\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$ *Blocks withstand the vertical uplift force with no safety factor considered

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$ Blocks withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = 0.28\ \dfrac{kip}{ft}$

Resisting HORIZONTAL FORCE F_{hres}

Friction angle $\upsilon := 0.6$

Normal 3 blocks (weight-submergence-uplift force) $N := 3 \cdot (g \cdot (W_b - W_w)) = 2.34 \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 1.41 \frac{1}{ft} \cdot kip$ $F_h = 2.73 \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone can withstand the horizontal push force. The backfill on the land side will increase resistance

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$$

$$F_{hresfill} := \frac{1}{2} K_p \left(Celev_a(2) - Celev_b(0)\right)^2 \cdot \gamma_s \cdot g = 26.64 \frac{kip}{ft}$$

$$F_{hres} + F_{hresfill} - 1.25\ F_h = 24.64 \frac{1}{ft} \cdot kip$$

Blocks can resist horizontal pressure

BLOCK AT SECOND ROW with Elevation base at +5' and crest at +7'

$Celev_b(2) = 5.00\ ft$ $Celev_a(0) = 7.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft$ $D_{block} := 5\ ft$ $H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3}$ $\gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton$ $W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b$

$$F_h := \left(P_{4b}(2) \cdot H_{block} + \frac{((P_{4b}(2) - P_{4a}(0)) \cdot H_{block})}{2}\right) = 4.15\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of 3 blocks +1 Fv1

$$F_{v1} := 1\ (P_{4b}(1))\ \frac{D_{block}}{2} = 3.48\ \frac{1}{ft} \cdot kip$$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$$F_{vblock} := g \cdot (W_b - 0.25\ W_w) + 2 \cdot g \cdot (W_b - 0.5\ W_w) = 6.11\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$F_{vblock} > F_{v1} = 1.00$

Blocks with two layers of blocks above can withstand the vertical uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 1.00$

$F_{vblock} - Fs\ F_{v1} = 1.76\ \frac{kip}{ft}$

Blocks withstand uplift force with a safety factor of 1.25. Considering blocks on top. The blocks need to be doweled.

Resisting horizontal friction angle between blocks Fhres

$\upsilon := 0.6$

$N := \left(g \cdot \left(W_b - 0.5\ W_w\right)\right) = 1.96\ \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 1.18\ \frac{1}{ft} \cdot kip$ $\quad F_h = 4.15\ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - Fs\ F_h = -4.01\ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2}\ K_p\ \left(Celev_a(2) - Celev_b(2)\right)^2 \cdot \gamma_s \cdot g = 18.89\ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - 1.25\ F_h = 14.88\ \frac{1}{ft} \cdot kip$

Blocks at second row can withstand the horizontal force

BLOCK AT THIRD ROW with Elevation base at +7' and crest at +10'

$Celev_a(0) = 7.00\ ft \qquad Celev_a(1) = 10.00\ ft$

Dimensions of block LxDxH:

$$L_{block} := 6\ ft \qquad D_{block} := 5\ ft \qquad H_{block} := 3\ ft$$

Density of stone and water:

$$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$$

Weight of Individual block:

$$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$$

$$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$$

Wave force on face of the block

$$Celev_b \qquad F_h := \left(P_{4a}(0) \cdot H_{block} + \frac{((P_{4a}(0) - P_{4a}(1)) \cdot H_{block})}{2}\right) = 4.41\ \frac{1}{ft} \cdot kip$$

Wave uplift force on first row of 3 blocks +1 Fv1

$$F_{v1} := 1\ (P_{4a}(0))\ \frac{D_{block}}{2} = 3.49\ \frac{1}{ft} \cdot kip$$

Resisting uplift Block Weight Force F_{vblock} 1 block at first step

$$F_{vblock} := g \cdot (W_b)\ (1) + g \cdot (W_b)\ (1) = 4.80\ \frac{1}{ft} \cdot kip$$

Weight of blocks above

$$F_{vblock} > F_{v1} = 1.00$$

Blocks with blocks above can withstand the vertical uplift force

$$Fs := 1.25$$

$$F_{vblock} > Fs\ F_{v1} = 1.00$$

$$F_{vblock} - Fs\ F_{v1} = 0.44\ \frac{kip}{ft}$$

Blocks at third row can withstand uplift force with a safety factor of 1.25. It needs the block on top to resist the uplift force it is recommended to dowel

Resisting horizontal friction angle between blocks F_{hres}

$\upsilon := 0.6$

$N := (g \cdot (W_b)) = 2.40 \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 1.44 \frac{1}{ft} \cdot kip$ $\qquad F_h = 4.41 \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - Fs\ F_h = -4.07 \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35\ °$

$K_p := \tan\left(45\ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2} K_p \left(Celev_a(2) - Celev_a(0)\right)^2 \cdot \gamma_s \cdot g = 10.63 \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - 1.25\ F_h = 6.56 \frac{1}{ft} \cdot kip$

Blocks at third row can withstand the horizontal push considering the backfill.

BLOCK AT FOURTH ROW with Elevation base at +10' and crest at +13'

$Celev_a(1) = 10.00\ ft$ $\qquad Celev_a(2) = 13.00\ ft$

Dimensions of block LxDxH:

$L_{block} := 6\ ft \qquad D_{block} := 5\ ft \qquad H_{block} := 3\ ft$

Density of stone and water:

$\gamma_s := 160\ \frac{lb}{ft^3} \qquad \gamma_w := 62.4\ \frac{lb}{ft^3}$

Weight of Individual block:

$W_{bt} := L_{block} \cdot D_{block} \cdot H_{block} \cdot \gamma_s = 7.20\ ton \qquad W_b := D_{block} \cdot H_{block} \cdot \gamma_s = 1.20\ \frac{ton}{ft}$

$W_w := D_{block} \cdot (H_{block} - 0.2\ ft) \cdot \gamma_w = 0.44\ \frac{ton}{ft}$

Wave force on face of the block

$Celev_b \qquad F_h := \left(P_{4a}(0) \cdot H_{block} + \frac{((P_{4a}(0) - P_{4a}(1)) \cdot H_{block})}{2}\right) = 4.41\ \frac{1}{ft} \cdot kip$

Wave uplift force on first row of 3 blocks +1 Fv1

$F_{v1} := 1\ (P_{4a}(0))\ \frac{D_{block}}{2} = 3.49\ \frac{1}{ft} \cdot kip$

Resisting uplift Block Weight Force Fvblock 1 block at first step

$F_{vblock} := g \cdot (W_b)\ (1) = 2.40\ \frac{1}{ft} \cdot kip$

Weight of blocks above

$F_{vblock} > F_{v1} = 0.00$ Blocks can't withstand uplift force

$Fs := 1.25$

$F_{vblock} > Fs\ F_{v1} = 0.00$

Blocks can't withstand uplift force with a safety factor of 1.25.

$F_{vblock} - Fs\ F_{v1} = -1.96\ \frac{kip}{ft}$

Resisting horizontal friction angle between blocks F_{hres}

$\upsilon := 0.6$

$N := \left(g \cdot \left(W_b\right)\right) = 2.40 \ \frac{kip}{ft}$

$F_{hres} := \upsilon \cdot N = 1.44 \ \frac{1}{ft} \cdot kip$ $\qquad F_h = 4.41 \ \frac{1}{ft} \cdot kip$

$F_{hres} > F_h = 0.00$

Blocks alone cannot withstand the horizontal push force need to consider the back fill.

$F_{hres} - 1.25 \ F_h = -4.07 \ \frac{1}{ft} \cdot kip$

Additional backfill horizontal pressure:

Back fill friction angle: $\phi := 35 \ °$

$K_p := \tan\left(45 \ ° + \frac{\phi}{2}\right)^2 = 3.69$

$F_{hresfill} := \frac{1}{2} K_p \ \left(Celev_a(2) - Celev_a(1)\right)^2 \cdot \gamma_s \cdot g = 2.66 \ \frac{kip}{ft}$

$F_{hres} + F_{hresfill} - 1.25 \ F_h = -1.41 \ \frac{1}{ft} \cdot kip$

CALCULATION BASED ON EQUATION 5.188 ROCK MANUAL CIRCA

Design Parameters: NORTH REVETMENT SCOUR STONE

-Significant Wave Height: $Hs := 11.24\ ft$

-Peak Spectral Wave Period: $Tp := 11.96\ s$

-Stone Density: $\rho s := 165\ \frac{lb}{ft^3}$

-Water Density: $\rho w := 62.428\ \frac{lb}{ft^3}$ $\quad \Delta := \frac{\rho s}{\rho w} - 1 = 1.643$

-Water depth in front of toe berm: $h := 12\ ft + 1.8\ ft + 2.1\ ft = 15.9\ ft$

-Scour stone initial estimate $Dn50i := 2.1\ ft$

-Water depth at toe berm: $ht := h - (2\ Dn50i + Dn50i + 1\ ft) = 8.6\ ft$

-Number of units displaced 5%-10%: $Nod := 1$ $\quad \frac{ht}{h} = 0.541$

-Factor of Safety $FS := 1.5$

-Toe Armor Stone diameter:

$$Dn50 := \frac{FS}{\left(\frac{\Delta}{Hs} \cdot \left(6.2\ \frac{ht}{h} + 2\right) \cdot Nod^{0.15}\right)} = 1.917\ ft$$

Use D50F=2.1'
STONE TYPE B1
for uniformity

$Dn50 := 2.1\ ft$

$W50 := \rho s \cdot Dn50^3 = 0.764\ ton$

-Toe Filter Stone diameter:

$$W50f := \frac{W50}{50} = 30.561\ lb$$

$$Dn50f := \left(\frac{W50f}{\rho s}\right)^{\frac{1}{3}} = 0.57\ ft$$

STONE TYPE C
IDOT RR3
(W50=10lbs) as
nearest
commercially
available size

-Scour Stone thickness assumption confirmation: Formula applicable for 0.4<ht/h<0.9 and 3<ht/Dn50<25

$T := 2 \cdot Dn50 + 2 \cdot Dn50f + 1\ ft = 6.34\ ft$ $\quad ht := h - T = 9.56\ ft$

$\frac{ht}{Dn50} = 4.552$ $\quad \frac{ht}{h} = 0.601$

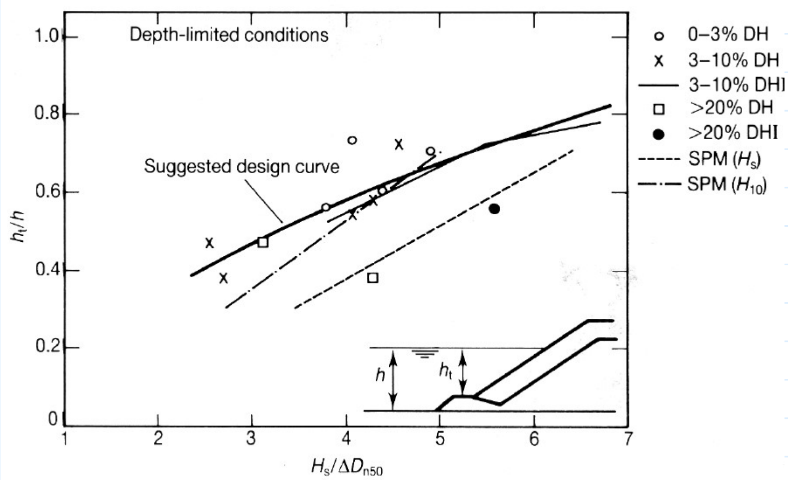


Figure 5.73 *Toe stability as a function of the relative toe depth, h_t/h*