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Project Title: Breaking Waves at Claytor Lake

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Abstract

A farm adjacent to Claytor Lake in Pulaski County, Virginia is experiencing extensive shoreline erosion. This project evaluates two sites affected by differing wave energies. The team was tasked with designing a solution to stabilize each shoreline without disturbing the local aquatic habitat. After researching several shoreline stabilization techniques, the team determined that a revetment would be the most effective solution. Both sites were surveyed and the collected points were combined with lidar data to model the topography of the area. Using this information, computer-aided design (CAD) software was used to develop construction plans. Revetment height and required rock sizes were computed based on the maximum wave heights experienced at each site. The design wave height at the Dublin Hollow site is 3.5 feet and is 1.2 feet at the Dam Site. Since the Dublin Hollow site has a larger design wave height, the limits of protection are larger than that of the Dam Site. The limits of protection at the Dublin Hollow site are 1843 feet to 1851 feet and at the Dam site are 1845.5 feet to 1849 feet. It was decided that VDOT Class I riprap will be used at each site and is sufficient in supporting both revetments. Each design can be implemented within the budget of $75 per linear foot.

Acknowledgements

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1. Introduction

Weathering is a natural process that occurs along shorelines everywhere, however along Claytor Lake in Pulaski County, Virginia, the erosion has been accelerated by human activities. Recreation on the lake, such as boating, jet skiing, and wakeboarding, has increased wave energy. As a result, the shoreline has eroded to the point where the banks are over 10 feet high in some areas and experiencing severe undercutting up to 3 feet in others, which leads to property loss. Over time, safety and accessibility issues can arise for recreational users and for Appalachian Power Company (APCO), the entity that owns the lake.

1.1. Problem Statement

This project addresses the Claytor Lake shoreline of a cattle and horse farm in Pulaski County, Virginia, (Figure 1). Approximately four miles of the farm's shoreline have eroded due to wave action. This project focuses on two specific sites. The first, referred to as the Dublin Hollow site, is in an area of the lake popular for recreational activities, such as wakeboarding. The other, called the Dam site due to its view of the APCO Dam, is a cove that focuses wind-driven waves generated from the main body of the lake.

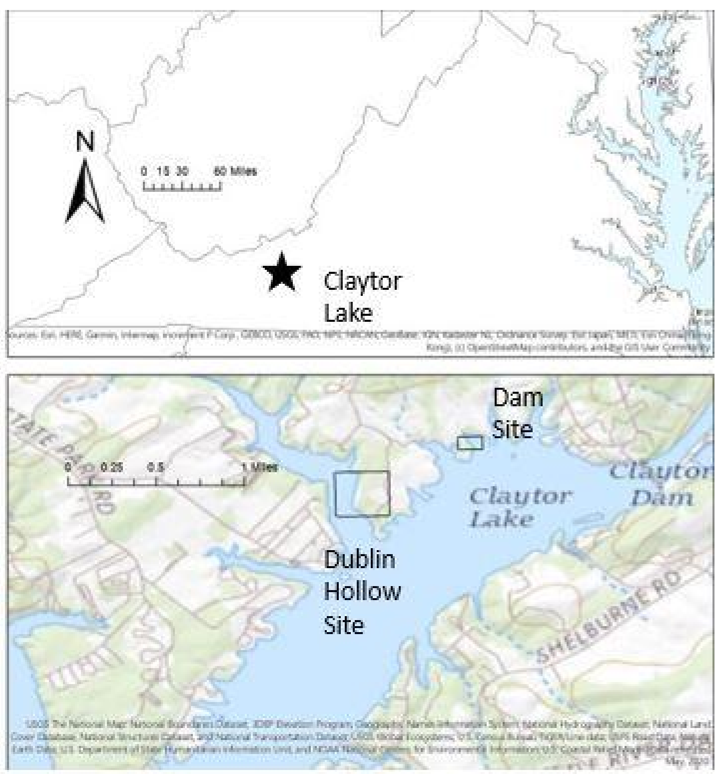


Figure 1. Site location (USGS, 2021)

Different issues have been identified with each shoreline: the Dublin Hollow site has significantly higher banks, up to 10 feet in places, while the Dam site has banks that do not exceed 5 feet in height but have significant undercutting, measured up to 3 feet horizontally. Each of these issues can be seen Figure 2. The team has developed a solution designed to reduce the erosion of these shorelines without harming the endangered mussels' habitat.

Figure 2. Erosion at Dublin Hollow site (left) & Dam site (right)

1.2. Goal & Objective

The overall goal of this project is to reduce the loss of private property due to erosion on this farm. The objective is to stop shoreline erosion while protecting native aquatic species. Of particular concern are the state-threatened *Tritogonia verrucosa*, or pistol-grip, mussels found in Claytor Lake (Jones, 2015).

1.3. Criteria & Constraints

Several criteria were established to evaluate the design alternatives. These criteria are: wave protection, cost, lifespan, ease of installation, maintenance, and habitat potential. Wave protection is defined in terms of the maximum wave height that a given solution can withstand. Cost includes the price of materials and installation. Lifespan is defined as how long each design will remain functional under assumed operational conditions and maintenance. Ease of installation is evaluated based on how accessible each site is for heavy equipment regarding both the topography and vegetation. Another criterion is the maintenance needed for each solution after installation. Lastly, habitat potential is evaluated in terms of how well the design supports the native aquatic ecosystem.

The constraints for this project are price, equipment, accessibility, and time. The landowners have requested that the project budget be less than $75 per linear foot and that equipment for installation be limited to the tractor with front-end loader and small excavator that they already have. The shoreline stabilization solution must be implemented from a steep bank or from the water. In addition, this project must be installed during a two-week period in November when the lake's water level is lowered to 1843 feet by Appalachian Power Company.

2. Potential Solutions

2.1. Overview of Potential Solutions

Nine different approaches were evaluated for reducing shoreline erosion while protecting the local aquatic habitat. The nine solutions discussed below fall into three main categories: coastal structures, living shorelines, and joint planting.

Coastal structures are usually made of rock and hard material which can be constructed along a shoreline to help prevent erosion. They include retaining walls, geosynthetics, revetments, and breakwaters (NPS, 2019). Retaining walls are built to support the soil and hold it in place by reducing the transport of eroded material and by deflecting the direct wave energy (Seachange Consulting, 2011). Geosynthetics are products mostly made of polymeric material and designed to provide protection to the soil. They include geotextiles, geogrids, geomembranes, and geonets (Kim et al., 2019). Revetments are sloped structures that are usually made of rocks and constructed to be permeable and dissipate the impact of the wave energy on the shore, reducing erosion (USDA-SCS, 1989). Breakwaters are structures built offshore to help dissipate the energy of the incoming waves to stabilize and protect ecosystems (Chasten et al., 1993).

Living shorelines include the use of both living and nonliving materials that can help stabilize the shorelines and enhance the natural ecosystems (NOAA Fisheries, 2020). Sills, edging, soil bioengineering, and shoreline planting are all applications of living shorelines (NOAA Fisheries, 2020). Sills incorporate methods from both revetments and breakwaters and are usually made of stone, built close to shore, and combine the use of hard structures with living material (Hardaway et al., 1999). Edging is the method of using a structure to hold the lower bank of the site in place with vegetation that can slow down the waves and become more effective over time as it accumulates sediment and begins sprouting new plant life (NOAA Fisheries, 2020). Soil bioengineering is the method of mitigating streambank erosion or enhancing other designs by utilizing plant materials in combination with natural and synthetic support materials for slope stabilization and erosion control (USDA, 2007). Shoreline planting is the installation of plants and aquatic vegetation along the shore (Gittman et al., 2016). The roots of the plants help to stabilize the banks as well as absorb the energy from the waves (Gittman et al., 2016). In addition to providing a habitat for aquatic life, these natural buffers can also reduce the sediment and contaminants transported via runoff, resulting in improved water quality at the site (Florida Living Shorelines, 2020).

A combination of coastal structures and living shorelines is joint planting, which is the placement of dormant stakes of woody plants in a revetment after it has been constructed. This method requires slopes of 2:1 or flatter to be successful and is best when completed in fall (City of Franklin, TN, 2014). Plants must be suitable for the climate and have high habitat potential and good rooting ability; native plants are preferred.

2.2. Decision Matrices

Decision matrices were made for each site to evaluate each method using six criteria defined in Section 1.3. Each criterion was given a weighted value based on its significance to the objectives. For both sites, wave protection was assigned the highest weight of 25%. Weightings were the same for both sites for all criteria except ease of installation and habit potential. Due to the more extreme topography at the Dublin Hollow site, ease of installation was given a higher weight (15%) than at the Dam site (10%). Due to the prevalence of threatened mussel species (pistol-grip) at the Dam site, habitat potential was given a higher weight (15%) than at the Dublin Hollow site (10%).

Table 1: Decision matrix for the Dublin Hollow site

	Weight	Retaining Walls	Geosynthetics	Revetments	Breakwaters	Sills	Edging	Soil Bioengineering	Shoreline Planting	Joint Planting
Wave Protection	25%	5	5	5	2	2	2	1	1	4
Cost	20%	1	1	4	1	1	3	4	4	4
Lifespan	17%	5	4	5	5	5	3	3	3	5
Ease of Installation	15%	2	4	2	1	2	3	3	4	1
Maintenance	13%	4	5	5	5	2	2	2	2	5
Habitat Potential	10%	2	2	3	1	5	5	5	5	4
Total	100%	3.32	3.58	4.10	2.45	2.61	2.82	2.77	2.92	3.85

Table 2: Decision matrix for the Dam site

	Weight	Retaining Walls	Geosynthetics	Revetments	Breakwaters	Sills	Edging	Soil Bioengineering	Shoreline Planting	Joint Planting
Wave Protection	25%	5	5	5	4	4	4	3	1	5
Cost	20%	1	1	5	1	1	3	4	4	4
Life span	17%	5	4	5	5	5	3	3	3	5
Habitat Potential	15%	2	2	3	1	5	5	5	5	4
Maintenance	13%	4	5	5	5	2	2	2	2	5
Ease of Installation	10%	3	4	3	1	2	4	2	4	2
Total	100%	3.42	3.48	4.50	2.95	3.26	3.52	3.27	2.97	4.35

2.3. Final Decision

After reviewing the potential solutions, a revetment was chosen to be the most effective approach for both sites based on the total score for each alternative (Tables 1 and 2). Wave protection, habitat potential, life span, and maintenance were all given the same score for revetments at each site. Differing scores between each site were due to topographical differences that make it harder to install a revetment at the Dublin Hollow site. Cost was given a lower score at the Dublin Hollow site because it requires more earth work than the Dam site.

3. Revetment Design

3.1. Definition

A revetment is a structure that is placed on top of a filter material over a bare slope to absorb the energy of incoming water. The filter material is typically a geosynthetic, with the most common being a Class I non-woven geotextile. There are several types of revetments, such as concrete, wooden, and rock. A rock revetment (riprap) will be used for this project because it allows growth of vegetation and free movement by aquatic organisms.

3.2. Design Process

Revetment design parameters include topography, wave height, protection limits, geotextile type, and rock size. The Dublin Hollow and Dam sites were surveyed to obtain below-water topography not captured by lidar (Figure 3), as outlined in Appendix A.

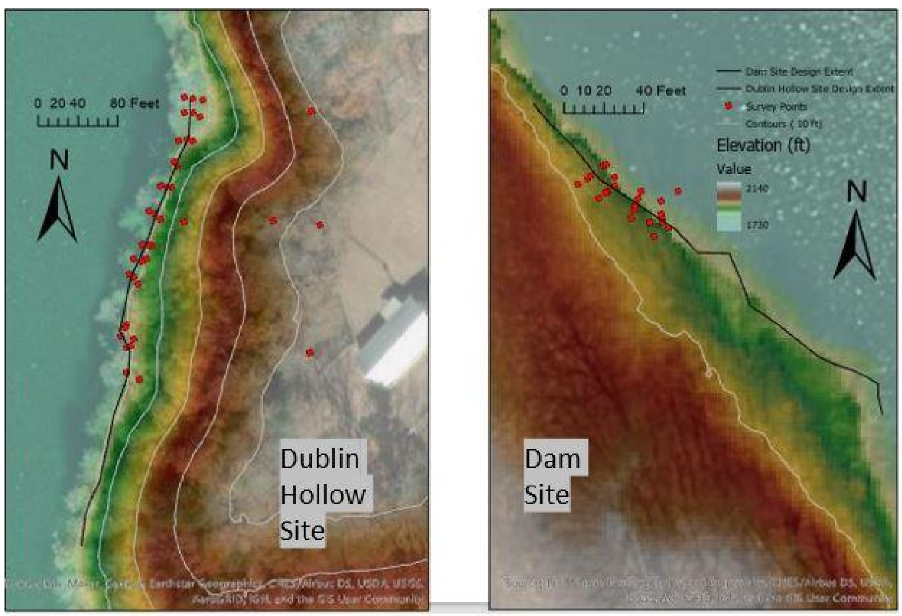


Figure 3. Survey points and extent of revetment at both sites

Survey points were combined with lidar data (1 m bare earth) from the Virginia Geographic Information Network to create a surface to model the topography of the two sites (VGIN, 2021). The topography models were used to create profiles that were used in the grading plans. At both sites, a 2:1 slope was selected to maintain the integrity of the revetment while preserving the most land. Design wave heights were calculated according to TR-56 (NRCS, 2014), considering both wind-driven and boat-generated waves (see Appendix B). The anatomy of a typical wave can be seen in Figure 4.

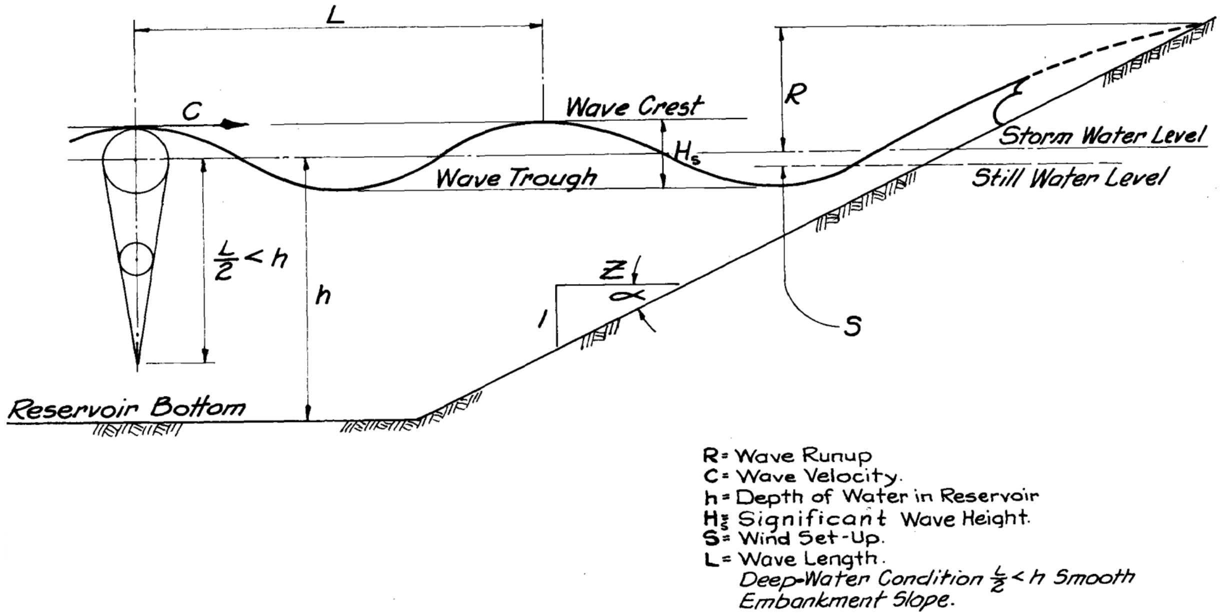


Figure 4. Illustration of the wave anatomy (USDA-SCS, 1983)

Upper and lower protection limits were calculated according to TR-69 (USDA-SCS, 1983). The lower limit is calculated to prevent toe scour and establish a lower boundary at the bottom of the revetment. This is done by multiplying the design wave height (H_s) by 1.5 and subtracting this number from the normal water elevation or using the lowest controlled water elevation. For the Dublin Hollow site, the typical drawdown elevation of 1843 feet was used as the lower limit of protection. The first step in finding the upper limit is calculating the wave runup (R) and wind set-up (S). The wave runup is the height to which a wave can reach up a shoreline during a storm, and was determined using Figure 13 in Appendix D. The effective fetch and design wind velocity for each site are used in Figure 11 to determine the wavelength (L). This wavelength and the embankment slope are then used in Figure 13 to determine the wave runup. Since the design wave height is less than 5 feet for both sites, the wind set-up is calculated by multiplying the design wave height by 0.1 (USDA-SCS, 1983). Finally, the wave runup, wind set-up, and the normal water elevation are summed to get the upper limit elevation.

Class I, nonwoven geotextile for soil filtration and retention under the riprap was chosen due to their high puncture resistance and permeability (John Fripp, NRCS. Personal communication. 22 March 2021). Needle-punched geotextile is specified because heat-bonded geotextiles are too smooth to be used on the steep slopes in this project (U.S. Bureau of Reclamation, 2014). A rock toe key is built to stabilize the revetment at the bottom where the structure meets the ground and to prevent toe scour.

A median rock weight (W_{50}) was selected based on design wave height and revetment slope, as seen in Appendix D (TR 69, USDA-SCS, 1983). Once the median weight was found, the median diameter rock size (D_{50}) for cube shaped-rocks was calculated using Equation 1 (USDA-SCS, 1983).

$$D_{50} = \sqrt[3]{\frac{W_{50}}{62.4 \times 2.65}} \tag{1}$$

Where: D_{50}= median diameter rock size; W_{50}= median diameter rock weight; 62.4=specific weight of water; 2.65=specific gravity of the rock

3.3. Design for Dublin Hollow Site

To ensure that the revetment will be stable and to minimize excavation, the site with existing slope of 0.1:1 will be graded to a 2:1 slope (Figure 5). VDOT Class I riprap (D_{50}=1 foot) is specified to save on project cost by using readily available material sufficiently similar to the calculated requirements (D_{50}=1.12 feet) The design will use a Class I, non-woven geotextile that is needle-punched. The limits of protection elevations will be 1843 feet to 1851 feet above sea level, based on the calculated wave height of 3.5 feet. This is to ensure that the shore will be protected at the maximum possible wave height. The rock toe key depth was calculated by multiplying the D_{50} rock size value by 2 (USDA-SCS, 1983).

A representative profile of the Dublin Hollow site is shown in Figure 5 with the design specifications. To achieve the desired slope and minimize land loss, fill dirt is used to create a 2:1 slope. Additionally, a 3:2 cut slope above the revetment design helps to stabilize the slope and allow for potential seeding in the future. The geotextile is placed on the earth from the rock toe key up to the upper elevation to provide separation between the rock and soil and allow seepage of water through the geotextile. The rock toe key depth is two times the D_{50}, making it 2 feet deep. The revetment rock is placed on top of the geotextile to create a rock layer 2 feet thick.

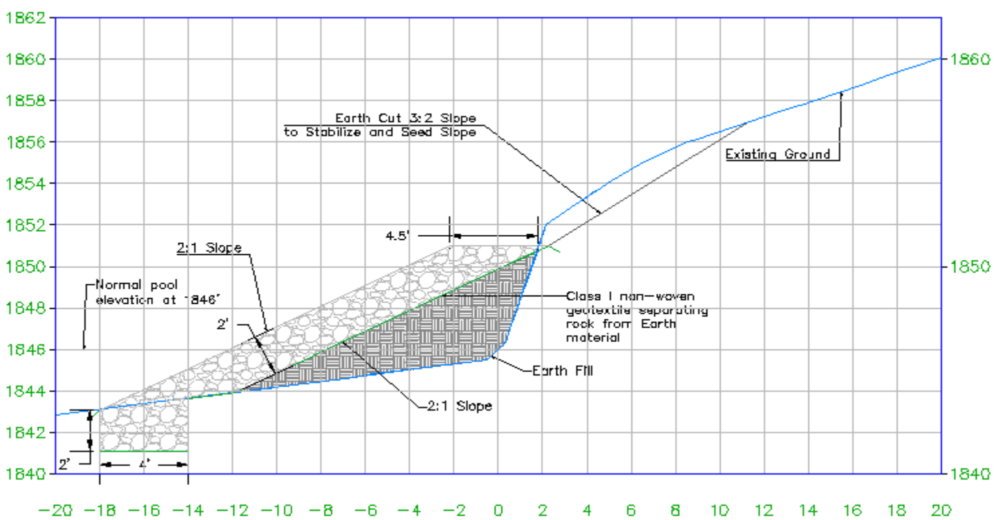


Figure 5. Typical profile of the Dublin Hollow site

The design covers 475 feet of the shoreline, as seen in Figure 6. Also featured are the bank keys at the ends of the design. These are used to stabilize the revetment at its ends and go 8 feet back into the shoreline. These calculations can be found in Appendix E.

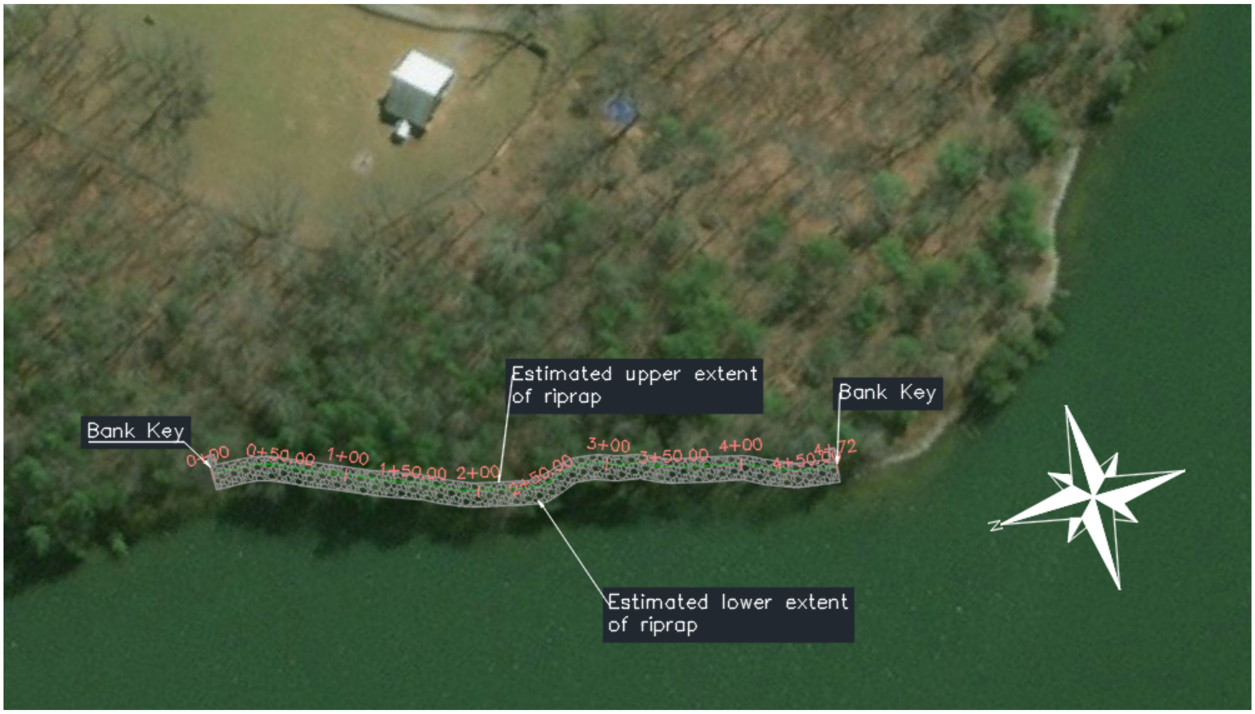


Figure 6. Plan view of the Dublin Hollow site

3.4. Design for Dam Site

At the Dam site, the undercut portion will be filled in order to stabilize it. The revetment will be graded to a 2:1 slope to decrease land loss and provide a stable slope. The minimum rock size was determined based on a 1.5 foot design wave height despite having calculated a 1.2 feet wave height in order to avoid interpolating in Figure 12. A D_{50} of 0.6 was calculated according to TR 210-69, but VDOT Class I (D_{50}=1 foot) was selected since a well-graded product with a D_{50} of 0.6 was not available at a reasonable price. The design will also use a Class I, needle-punched, non-woven geotextile. Limits of protection elevations will be 1844 feet to 1848 feet above sea level. The rock toe key depth was calculated by multiplying the D_{50} rock size value by 2 (USDA-SCS, 1983)

A representative profile of the Dam site is shown in Figure 7 with the design specifications. To address the undercutting at the bank, fill dirt will be brought in. The material excavated from this section cannot be used due to its high quantity of organic matter that will not adequately stabilize the slope. Geotextile is placed on the earth from the rock toe key to the upper limit. The rock toe key depth will be two times the D_{50}, making it 2 feet deep. The riprap is then placed on top of the geotextile to create a rock layer that is 2 feet thick. The top of the revetment will meet the existing ground at 1849 feet, which results in a minimal amount of land loss.

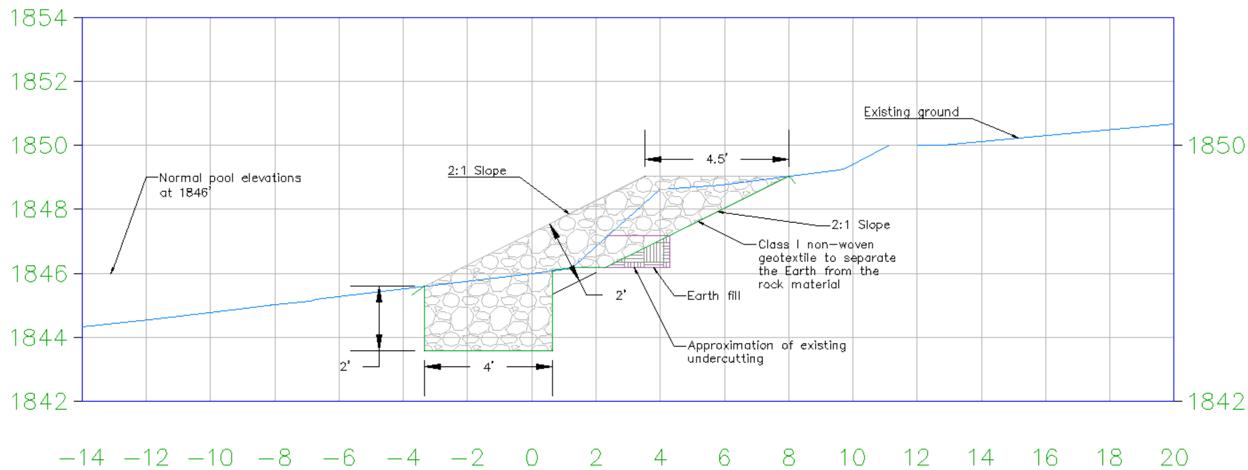


Figure 7. Typical profile of the Dam site

The design covers 250 feet of the shoreline, as seen in Figure 8. While the maximum length allowed for a shoreline stabilization project is 500 feet, a design that covers 250 feet was chosen due to the presence of thick brush on the southwest side and the presence of a cove on the northeast side. Also featured are the bank keys at the ends of the design, which are used to stabilize the revetment at its ends. These calculations can be found in Appendix E.

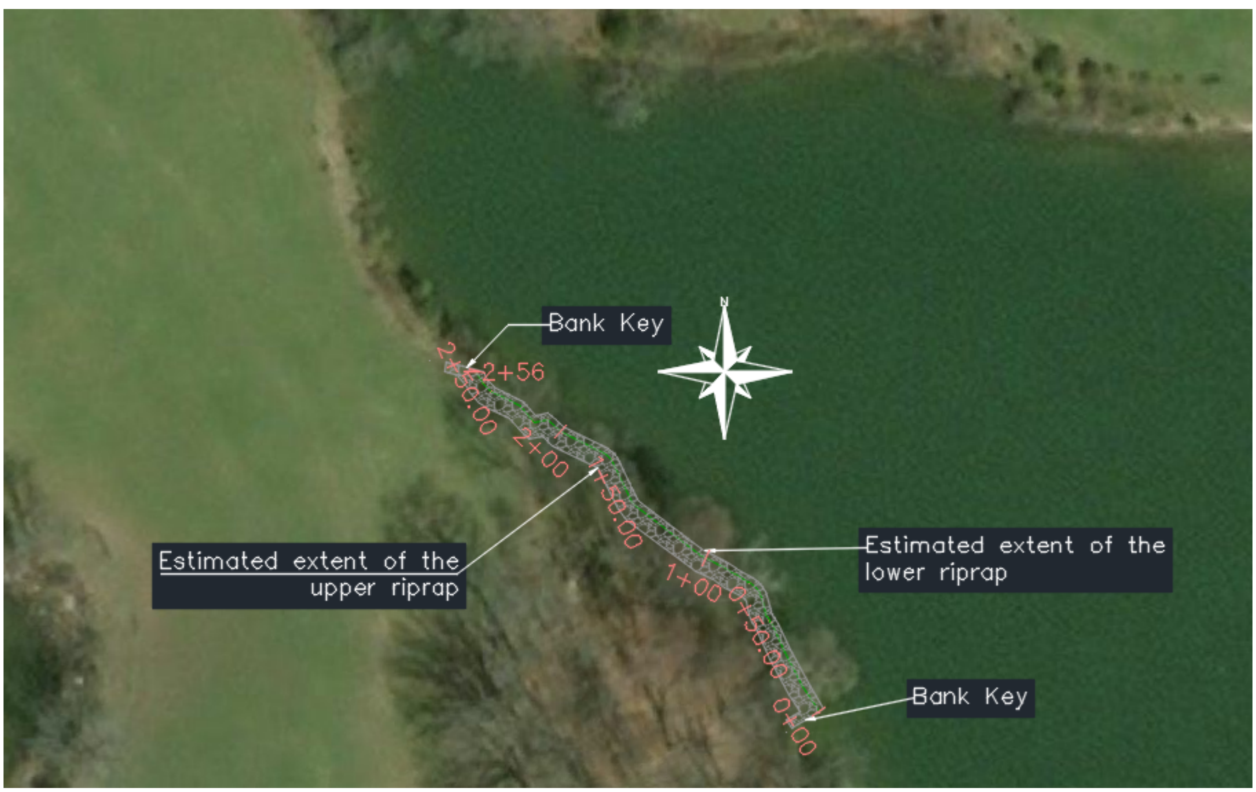


Figure 8. Plan view of the Dam site

3.5. Materials & Cost

The materials required for both designs include riprap, geotextile, and fill dirt. The cost estimate for VDOT Class I riprap is $22.15 per ton from a local quarry. The price for fill dirt is $11.20 per cubic yard at a nearby landscaping business. The cost of geotextile is $738 per roll (4,500 ft^2). The calculations for volume and total price of material can be found in Appendix E.

The total amount of material needed and the corresponding cost for the Dublin Hollow site and Dam site are listed in Table 3 and Table 4, respectively. Materials are the only cost because the landowners will be using their own equipment to install the revetments themselves. The total price for the Dublin Hollow site was $30,900, or $65.10 per linear foot. At the Dam site, the total price was $8,900, or $35.60 per linear foot.

Table 3: Cost analysis for Dublin Hollow site design

Material	Amount	Cost (Dollars)
VDOT Class I Riprap	1,190 tons	$26,600
NRCS Class I Non-woven Geotextile	13,200 ft^2	$2,680
Fill Dirt	143 yd^3	$1,600
Total		$30,900

Table 4: Cost analysis for Dam site design

Material	Amount	Cost (Dollars)
VDOT Class I Riprap	346 tons	$7,780
NRCS Class I Non-woven Geotextile	5,240 ft^2	$1,010
Fill Dirt	10 yd^3	$119
Total		$8,900

4. Standards & Specifications

4.1. Standards

For this design, the standard followed is VA NRCS Conservation Practice Standard 580-Streambank and Shoreline Protection. This standard states that protective treatments applied to shorelines need to work with the naturally present materials, not affect the water chemistry or lake hydraulics, and minimize impact on the slope surrounding the water line. This standard also highlights the importance of slope stability and the installation of keys at the bottom and ends of the armoring to provide additional stabilization of the treatment.

4.2. Specifications

Three main specifications have been used in the preparation of this design. The first is Virginia NRCS Construction Specification 795 - Geotextile. This specification discusses the materials, equipment, and labor necessary for the installation of geotextiles when installed for slope protection, subsurface drains, and road stabilization and lists the requirements for a Class I non-woven geotextile. The second specification used was Virginia Construction Specification 761- Loose Rock Riprap. This specification details materials, surface preparation, filter layers, and placement of riprap in construction projects. The third specification used was Virginia Construction Specification 721 - Excavation. This discusses removing material, disposal of excavated materials, and stabilizing the adjacent ground.

5. Conclusion

The final design chosen for both the Dublin Hollow site and the Dam site was a riprap revetment following the specific standards mentioned above. This was chosen after researching different shore stabilization techniques able to meet the requirements. Calculations were then completed to estimate the cost and construction parameters for both designs. The final cost per linear foot was calculated to be $65.10 for the Dublin Hollow site and $35.60 for the Dam site, which was well below budget. These designs will be proposed to the owner for potential implementation. Revetments are key in shoreline stabilization due to their inexpensiveness, effectiveness, and availability. For these reasons, they can be used to protect other shorelines and prevent erosion in order to minimize land loss for other owners along Claytor Lake.

References

Chasten, M. A., Rosati, J. D., McCormick, J. W. (1993). Engineering Design Guidance for Detached Breakwaters as Shoreline Stabilization Structures. U.S. Army Corps of Engineers. Retrieved from https://tamug-ir.tdl.org/bitstream/handle/1969.3/29278/a275241.pdf?sequence=1. Accessed 12 November 2020.

City of Franklin, TN. (2014). Permanent Erosion Prevention and Sediment Controls. Retrieved from https://www.franklintn.gov/home/showpublisheddocument?id=22733. Accessed 12 March 2021.

Florida Living Shorelines. (2020). Types of Living Shorelines. Retrieved from http://floridalivingshorelines.com/types-of-living-shorelines/. Accessed 18 October 2020.

Gittman, R.K., Peterson, C.H., Currin, C.A., Fodrie, F.J., Piehler, M.F., Bruno, J.F. (2016) *Living shorelines can enhance the nursery role of threatened estuarine habitats.* https://doi.org/10.1890/14-0716

Hardaway Jr,. C. S., & Byrne, R. J. (1999) *Shoreline Management in Chesapeake Bay*. Gloucester Point, VA: Sea Grant Communications

Jones, J. W. (2015). Freshwater Mussels of Virginia (Bivalvia: Unionidae): An Introduction to Their Life History, Status and Conservation. U.S. Fish and Wildlife Service. Retrieved from https://www.mussellab.fishwild.vt.edu/mussel/PDFfiles/2015/Jones_2015_Virginia_J_Science.pdf. Accessed 22 February 2021.

Kim, Y.J., Kotwal, A.R., Cho, B.Y., Wilde, J., You, B.H. (2019). *Geosynthetic Reinforced Steep Slopes: Current Technology in the United States.* https://doi.org/10.3390/app9102008

NOAA Fisheries. (2020). Understanding Living Shorelines. Retrieved from https://www.fisheries.noaa.gov/insight/understanding-living-shorelines. Accessed 18 October 2020.

National Park Service. (2019). Coastal Eng. - Hard Structures. Retrieved from https://www.nps.gov/subjects/geology/hard-structures.htm. Accessed 3 November 2020.

Seachange Consulting. (2011). How to Protect your Property from Shoreline Erosion: A handbook for estuarine property owners in North Carolina. Retrieved from https://www.nccoast.org/wp-content/uploads/2014/12/Weighing-Your-Options.pdf. Accessed 10 October 2020.

United States Bureau of Reclamation. (2014). Embankment Dams Ch. 19- Geotextiles. Retrieved from https://www.usbr.gov/tsc/techreferences/designstandards-datacollectionguides/finalds-pdfs/DS13-19.pdf

USDA-NRCS. (2007). NEH Part 654, Stream Restoration Design, Technical Supplement I - Streambank Soil Bioengineering. Retrieved from https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17818.wba. Accessed 10 October 2020.

USDA-NRCS. (2014). A Guide for Design and Layout of Vegetated Wave Protection for Earthen Embankments and Shorelines. Retrieved from https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=35554.wba

USDA-SCS. (1989). Loose Riprap Protection. Retrieved from https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_022577.pdf. Accessed 18 October 2020.

USDA-SCS. (1983). Technical Release No. 69: Riprap for slope protection against wave action. Retrieved from https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=18644.wba. Accessed 22 January 2021.

USGS. (2021). The National Map. United States Geological Survey. Retrieved from https://apps.nationalmap.gov/downloader/#/startUp Accessed 23 March 2021.

VGIN, Virginia Geographic Information Network (2021). Virginia LiDAR Inventory Web Mapping Application. Accessed 26 March 2021 at https://www.arcgis.com/apps/Viewer/index.html?appid=1e964be36b454a12a69a3ad0bc1473ce

Appendices

Appendix A: Surveying Process

Surveying was completed with a Topcon GTS-105 Total Station and a survey rod and prism for measuring elevation points. Additionally, a Trimble R10 real-time kinematic global positioning system (GPS) was used and an OPUS correction was applied to the survey points in order to combine with LiDAR data.

Appendix B: Wave Calculations

Determining total wave height (H_T)
- using process outlined in NRCS TR-56 (2014)

① Calculate effective fetch (F_e)

- Dublin Hollow

from Table 5: $\Sigma(\text{distance} \times \cos(\alpha)) = 22572.47$
$\Sigma(\cos(\alpha)) = 13.51$

$$F_e = \frac{\Sigma(\text{distance} \times \cos(\alpha))}{\Sigma \cos(\alpha)} = \frac{22572.47}{13.51} = 1670.55 \text{ feet } (\sim 1670 \text{ ft.})$$

$$1670.55 \text{ ft} \times \frac{1 \text{ mile}}{5280 \text{ ft.}} = 0.316 \text{ miles}$$

- Dam site

from Table 5: $\Sigma(\text{distance} \times \cos(\alpha)) = 5438.35$
$\Sigma(\cos(\alpha)) = 13.512$

$$F_e = \frac{\Sigma(\text{distance} \times \cos(\alpha))}{\Sigma(\cos(\alpha))} = \frac{5438.35}{13.512} = 402.48 \text{ ft. } (\sim 400 \text{ ft.})$$

$$402.48 \text{ ft.} \times \frac{1 \text{ mile}}{5280 \text{ ft}} = 0.076 \text{ miles}$$

② Find maximum overwater wind velocity (V_w)

- from Figure 10, $V_L = 80$ mph
- from Figure 11, wind ratio (V_W / V_L) was found to be:
  - Dublin Hollow: 1.05 wind ratio
  - Dam: 1.01 wind ratio
- Dublin Hollow

$$V_W = \left[\frac{V_W}{V_L}\right] \times V_L = 1.05 \times 80 \text{ mph} = 84 \text{ mph}$$

- Dam

$$V_W = \left[\frac{V_W}{V_L}\right] \times V_L = 1.01 \times 80 \text{ mph} = 80.8 \text{ mph}$$

③ Determine significant wave height (H_s)

- Dublin Hollow

$$H_s = 0.0232 \times V_W^{1.06} \times F_e^{0.47}$$
$$= 0.0232 \times (84)^{1.06} \times (.316)^{.47}$$
$$H_s = 1.48 \text{ feet}$$

- Dam

$$H_s = 0.0232 \times V_W^{1.06} \times F_e^{0.47}$$
$$= 0.0232 \times (80.8)^{1.06} \times (.076)^{.47}$$
$$H_s = 0.73 \text{ feet}$$

④ Determine total wave height (H_T)

- Dublin Hollow
  - assume maximum recreation wave height
    $H_R = 2$ feet

$$H_T = H_s + H_R = 1.48 \text{ feet} + 2 \text{ feet} = 3.48 \text{ feet}$$

$$\boxed{H_T = 3.5 \text{ feet}}$$

- Dam
  - assume minimum recreation wave height
    $H_R = 0.5$ feet

$$H_T = H_s + H_R = 0.73 \text{ feet} + 0.5 \text{ feet} = 1.23 \text{ feet}$$

$$\boxed{H_T = 1.2 \text{ feet}}$$

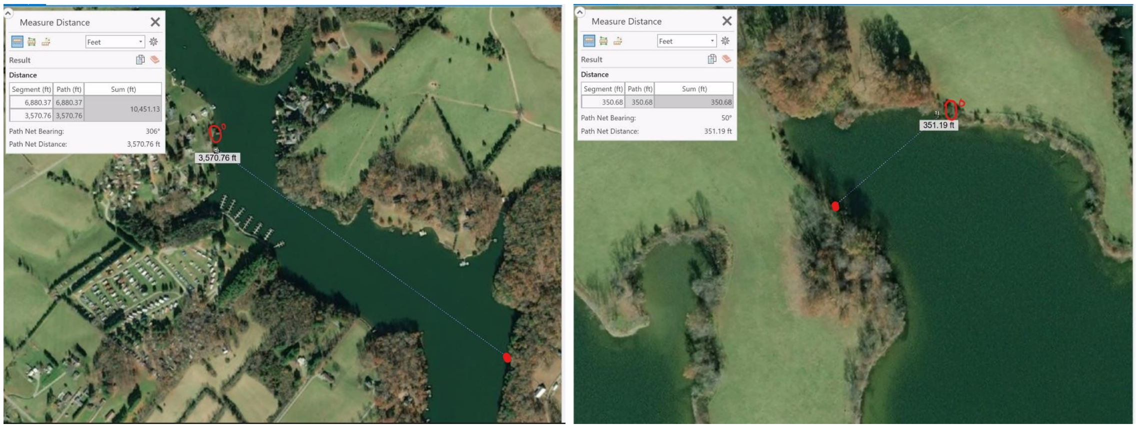


Figure 9. Initial Fetch angle for Dublin Hollow (left) & Dam (right) sites

Table 5: Dublin Hollow & Dam sites distance values

Site	Σ cos(a)	Σ distance* cos(a)
Dublin Hollow	13.512	22572.468
Dam	13.512	5438.355

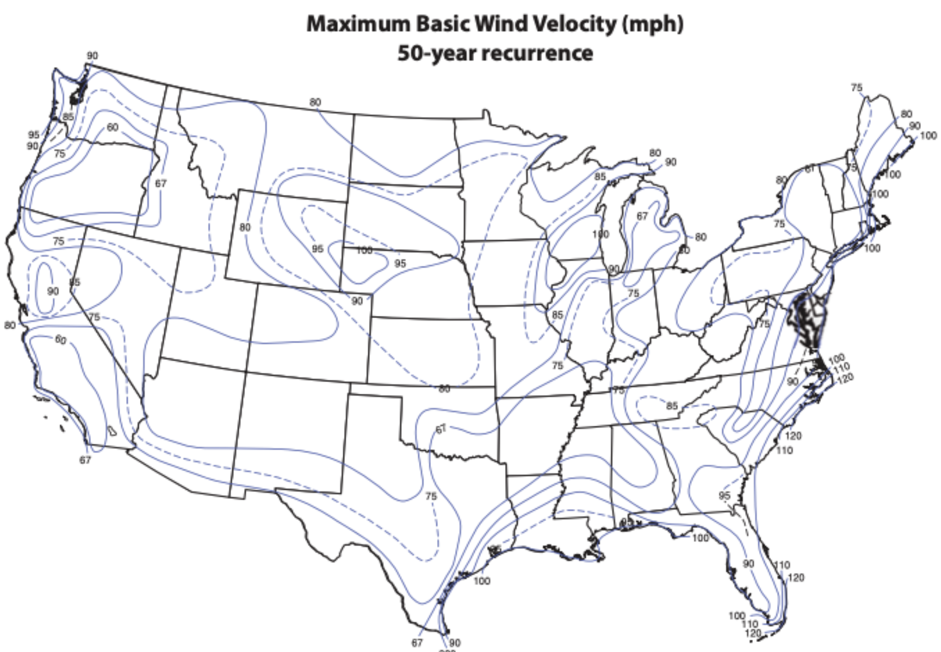


Figure 10. Maximum Basic Wind Velocity (mph) (Source: USDA-NRCS, 2014)

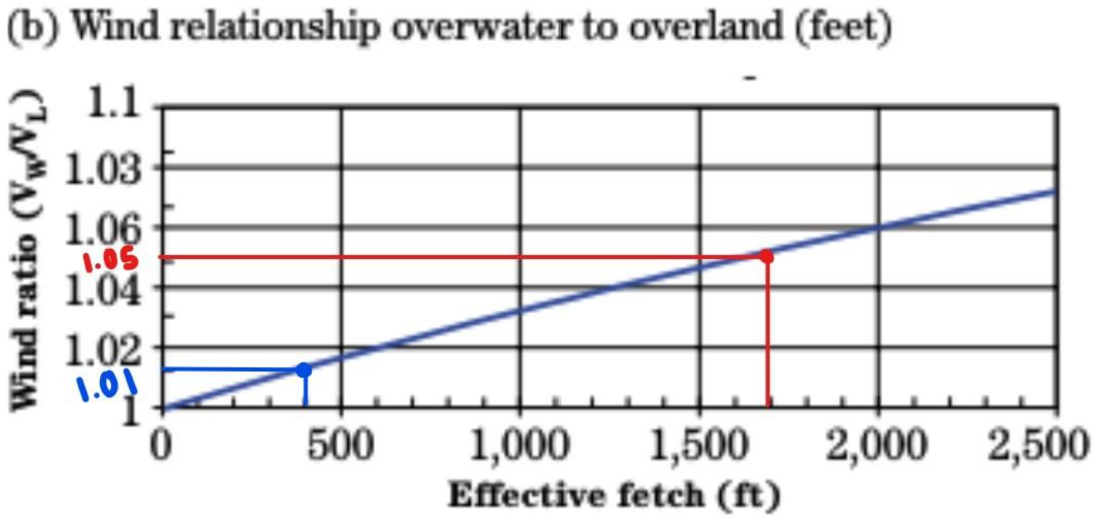


Figure 11. Wind Ratio for the Dublin Hollow site (red) and Dam site (blue) (USDA-NRCS, 2014)

Appendix C: Median Rock Weight (W_{50}) Calculations

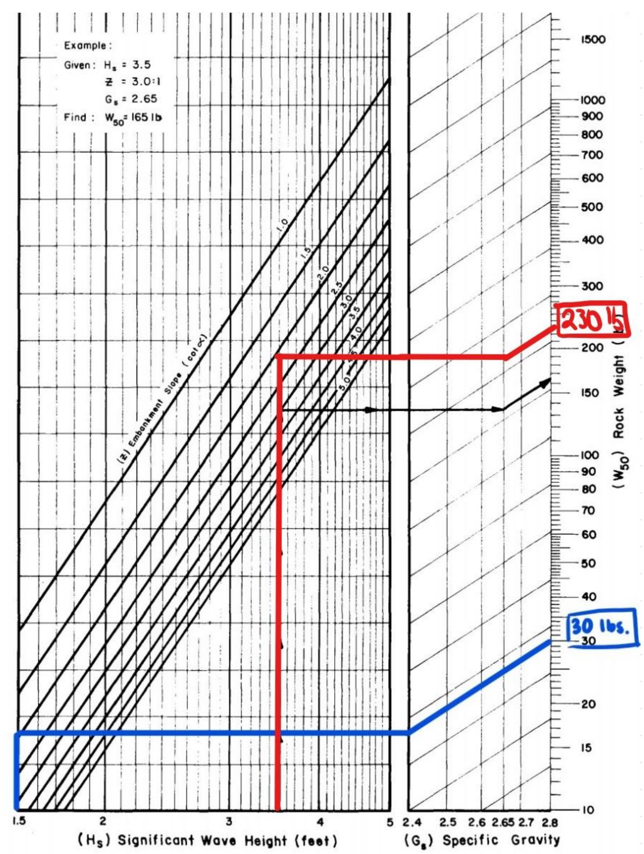


Figure 12. Graphs giving W_{50} for the Dublin Hollow site (left) and Dam site (right) (NRCS-SCS, 1983)

Appendix D: Protection Limit Figures

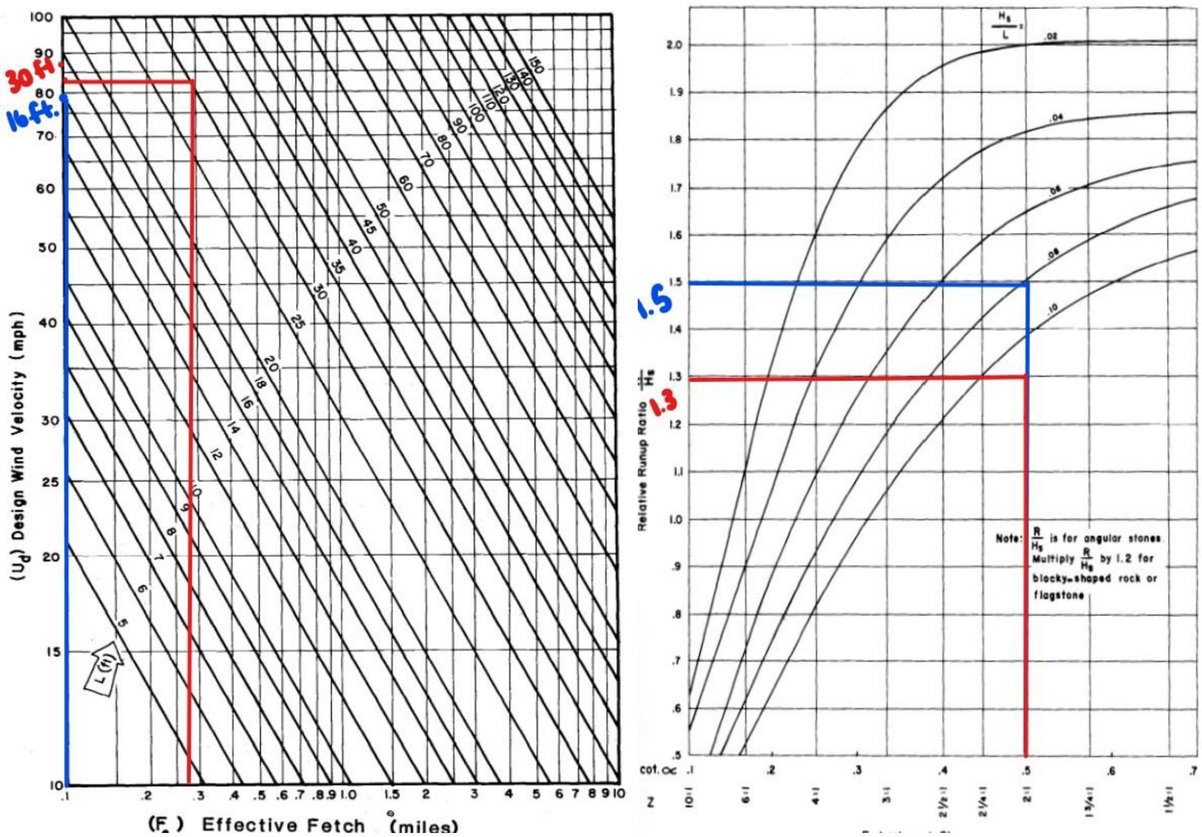
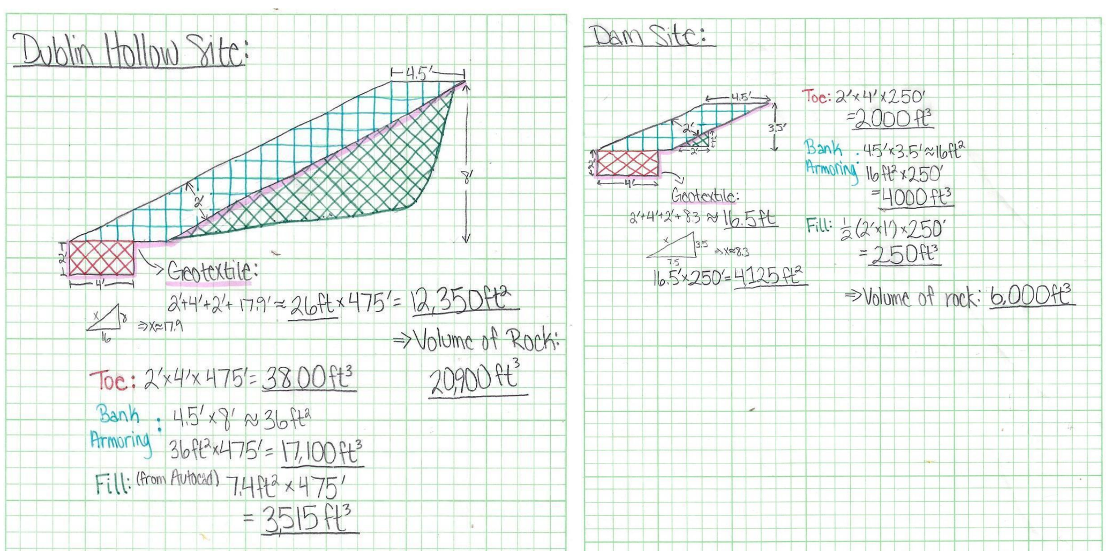


Figure 13. Graph to find length (L) to find wave runup (R) for the Dublin Hollow site (red) and Dam site (blue) (USDA-NRCS, 2014)

Appendix E: Material Volume & Cost Calculations



Fill Dirt:

Dublin Hollow Site:

$3{,}515\,ft^3 + 10\% = 3866\,ft^3$

$3{,}866\,ft^3 \div 27\,ft^3/yd^3 = 143\,yd^3$

$143\,yd^3 \times \$14/1.25\,yd^3 = \underline{\$1600}$

Dam Site:

$250\,ft^3 + 10\% = 275\,ft^3$

$275\,ft^3 \div 27\,ft^3/yd^3 = 10\,yd^3$

$10\,yd^3 \times \$14/1.25\,yd^3 = \underline{\$112}$

Rock

Dublin Hollow Site:

$20{,}900\,ft^3 + 640\,ft^3 = 21{,}540\,ft^3 \times 100\,lb/ft^3 = 2{,}154{,}000\,lb$

$2{,}154{,}000 + 10\% = 2{,}369{,}400\,lb$

$\frac{1185\text{ tons}}{15\text{ tons/truck}} \times \$22.15/\text{ton} = \$26{,}248$

$= 79\text{ trucks} \times \$5/\text{truck} = \$395$

$\underline{\$26{,}643}$ for rocks + delivery

Dam Site:

$6000\,ft^3 + 280\,ft^3 = 6{,}280\,ft^3 \times 100\,lb/ft^3 = 628{,}000\,lb$

$628{,}000 + 10\% = 690{,}800\,lb$

$\frac{346\text{ tons}}{15\text{ tons/truck}} \times \$22.15/\text{ton} = \$7{,}664$

$= 23\text{ trucks} \times \$5/\text{truck} = \$115$

$\underline{\$7{,}779}$ for rocks + delivery

Geotextile

Dublin Hollow Site:

Armoring + Toe: $12{,}350\,ft^2$

Side key: $284\,ft^2$

⇒ Total: $12{,}634\,ft^2 + 10\% = \underline{13{,}897\,ft^2}$

Dam Site:

Armoring + Toe: $4{,}538\,ft^2$

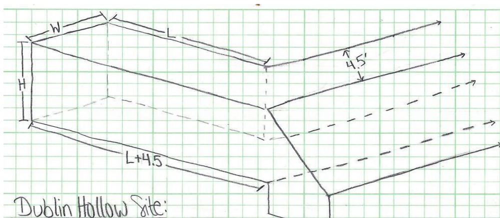
Side key: $226\,ft^2$

⇒ Total: $4{,}764\,ft^2 + 10\% = \underline{5{,}240\,ft^2}$

Total: $13{,}897 + 5240 = 19{,}137\,ft^2$

$19{,}137\,ft^2 \div 4500\,ft^2/\text{roll} = 5\text{ rolls}$

$5\text{ rolls} \times \$738/\text{roll} = \underline{\$3{,}690}$ for geotextiles at both sites



Dublin Hollow Site:

H = height = 8'

$W = 5 \times D_{50} = 5'$

$L = 8 \times D_{50} = 8'$

Volume: $L \times W \times H$

$= 8' \times 5' \times 8' = 320\,ft^3$

$320 \times 2 = \underline{640\,ft^3}$

Dam Site:

H = height = 3.5'

$W = 5 \times D_{50} = 5'$

$L = 8 \times D_{50} = 8'$

Volume: $L \times W \times H$

$= 8' \times 5' \times 3.5' = 140\,ft^3$

$140 \times 2 = \underline{280\,ft^3}$

Area:

$2(L \times W) + (L \times H) + ((L+4.5) \times H) + (H \times W)$

DH: $2(8' \times 5') + (8' \times 8') + ((8' + 4.5') \times 8') + (8' \times 5') = \underline{284\,ft^2}$

Dam: $2(8' \times 5') + (8' \times 3.5') + ((8' + 4.5') \times 8') + (3.5' \times 5') = \underline{226\,ft^2}$