COMPARATIVE ANALYSIS FOR REUSE & DISPOSAL OF CONCRETE RESIDUALS FROM HYDRODEMOLITION, DIAMOND GRINDING, & DIAMOND GROOVING OPERATIONS

by

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A thesis submitted to the faculty of
The University of North Carolina at Charlotte
In partial fulfillment of the requirements
For the degree of Master of Science in
Construction & Facilities Management

Charlotte

2016

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ABSTRACT

CHRISTOPHER J. ALBERGO. Comparative analysis for reuse & disposal of concrete residuals from hydrodemolition, diamond grinding, and diamond grooving operations. (Under the direction of DR. NICHOLAS TYMVIOS)

Large quantities of concrete residual slurries, solids, and liquids are currently being produced from hydrodemolition, diamond grinding, and diamond grooving operations within North Carolina. North Carolina Department of Transportation (NCDOT) and environmental organizations, such as North Carolina Department of Environmental Quality (NCDEQ), are working to identify and implement strategies to promote the most environmentally friendly, economically viable, and most risk averse methods for disposal/reuse of these residual materials. The available methods for slurry handling are containment in a fractioning tank, or Frac Tank, or creation of a Decanting Pond for settlement. The available options for Liquid disposal is insertion into a Wastewater Treatment Plant (WWTP)/Publically Owned Treatment Works (POTW) or reuse via deposition onto a state certified Land Application site. The available options for Solid disposal/reuse are beneficial fill onsite or offsite, or placement into one of the three available landfills: Land Clearing and Inert Debris (LCID), Construction and Demolition (C&D), or Municipal Solid Waste (MSW).

The currently feasible reuse/disposal methods have been combined into 20 total combinations of options. The objective of the project was to create a Cost Benefit Model (BCM) using Multi-Criteria Decision Making (MCDM) to compare these 20 options in order to find the most favorable option. The BCM used the Monte Carlo Method to simulate 5000 iterations of the model to estimate the most likely costs based on the

available cost data gathered from various available sources. The model allows for specific project information to be input to reliably estimate the costs of residual management for that unique project. The model differs in cost depending upon the region of North Carolina that the work is taking place in: Mountain, Piedmont, or Coastal. Each option has specific costs associated with it, which varied depending on project specific information; such as the quantity of the residual materials, and how and where the residuals would be disposed.

Once the costs for each option are calculated, they can be viewed side-by-side to compare costs directly. The user will then provide the model with a rating of the risks and environmental benefits of each option for disposal /reuse based on the user's specific capabilities, and will then place a level of comparative importance between risk, environmental benefit, and cost. The model will use of these inputs to provide a ranking of the 20 available options of disposal/reuse.

The Cost data was gathered from contacting the facilities, either by phone or email, which would accept the residuals. The risks and environmental benefits incorporated into the model were gathered by contacting the contractors that were performing the work, either within North Carolina, or throughout the United States and Canada. Those contractors also provided ranges for the most likely rate of slurry generation resulting from the previously mentioned construction projects. The model was then validated and approved by an environmental consultant that had previously performed the environmental compliance portion of the work in North Carolina.

The model shows that for a typical project within North Carolina the most cost effective options of slurry handling was the creation of a decanting pond. The most cost effective method of liquid management was deposition into a WWTP/POTW. The most cost effective method of solid residual management is beneficial fill onsite. The options perceived to be the most environmentally friendly and least risky options were determined based on the specific inputs based on the user's opinion of their capabilities. Generally the options that did not involve the creation of waste, the transportation of the residual material, or the lowest possibility of releasing the residual material into the environment were determined to be the most environmentally friendly and most risk averse. The ranking of the options provided by the BCM allows the flexibility to select the second most desirable option in the case where the most desirable option is not available.

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CHAPTER 1: INTRODUCTION

Currently, the North Carolina Department of Transportation (NCDOT) is conducting transportation construction operations in which diamond grinding, diamond grooving, and hydrodemolition are being used on infrastructure projects, including bridge decks and interstate highways. These operations are creating large amounts of concrete residual slurry, liquid, and solids, the disposal of which is increasingly becoming an issue for the NCDOT and environmental organizations like North Carolina Department of Environmental Quality (NCDEQ). Currently change orders and other delays are causing state funds to be inefficiently utilized. These changes and delays are caused by contractor's lack of knowledge of how to manage these residual materials in a way that is not detrimental (both environmentally and financially).

Hydrodemolition involves the removal of unsound concrete material from concrete structures through the use of high-pressure water jets. These jets are mounted on a mechanical hydrodemolition robots, or via worker spraying specific areas with a handheld lance. The process of diamond grinding is used to improve smoothness and skid resistance to in-situ concrete roadway structures, and can be used to improve surface characteristics of new roadways. The process involves using a large diamond studded circular saw blade, in conjunction with continuous water flow to grind the surface of a roadway, in a parallel direction, to improve rideability characteristics. Diamond grooving is used as a treatment technique on portland cement concrete paved roadways, using a diamond studded saw blade, to cut parallel or perpendicular grooves into a pavement surface to improve drainage characteristics. The cuts in the grooved section can be up to six times the size of the grinded section, and the cuts are spaced much further apart. According to a 2004 report by the International Concrete Repair Institute (ICRI), the four waste products associated with these processes are waste water, wet sand, chips/chunks of concrete, and concrete slurry water (ICRI, 2004). The residuals for hydrodemolition, diamond grinding, and grooving have many similar properties; however the chips/chunks of concrete resulting from hydrodemolition activities are larger in size as compared to the chips/chunks resulting from grinding/grooving activities.

There are numerous methods of disposal/reuse of these materials. These methods have varying degrees of risk and environmental impact. The NCDOT's intent is to present the methods to contractors within the state, and provide them with a tool for estimating their costs for disposal/reuse of these residual materials, as well as realizing the risks and environmental benefits available with each option of disposal/reuse.

1.1 Objectives

The objective of the project is to provide the NCDOT with a Benefit-Cost Model (BCM) using Multi-Criteria Analysis to estimate the true costs of disposal/reuse of the residuals. This model will allow contractors in the future to provide more accurate bid estimates, which will ultimately lead to better utilization of funds and a more efficient bidding process. Another goal of the project is to conduct a risk analysis that can be used to compare several feasible alternative methods of disposal/reuse of the residuals. The risk analysis will take into account the true costs of disposal/reuse, provide acceptable methods for disposing of residuals, and assess the monetary and environmental risks associated with the residual disposal options.

CHAPTER 2: LITERATURE REVIEW

The construction processes will be explained in the following chapter. The various DOT's across the country were studied and their specifications in regards to the following construction activities were compiled and can be seen in the chapter to follow. The regulations across North Carolina are laid out in regards to various waste products and the required methods of disposal are discussed in the following chapter. Statistical analysis methods used on within the project are also explained in this chapter.

2.1 The Construction Processes

As described in Chapter 1, the following construction processes are to be discussed in greater detail:

- Hydrodemolition
- Diamond Grinding
- Diamond Grooving

2.1.1 Hydrodemolition

Hydrodemolition has become one of the go-to methods for concrete bridge deck removal, since its development in Europe in the 1970's (Nittinger, 2001). According to (ICRI, 2004), the emergence of hydrodemolition as a favorable technology can be attributed to the following:

- Consistent results on a project-to-project basis,

- Guaranteed total removal of degraded material,
- No damage to existing reinforcing steel or adjacent concrete,
- Creation of a rough surface for easy bonding to new concrete,
- No impacts, vibrations, dust, or fumes, and
- A rapid rate of work.

Hydrodemolition equipment can exist as a motorized vehicle that slowly drives on a concrete surface while it is spraying to ensure a continuous demolition process of the concrete it is driving over. This method are shown in Figure 1. Upon completion of the process, the contractor is responsible for cleaning up the area and removal of the water. The residual material, which is a combination of waste water, wet sand, chips/chunks of concrete, and concrete slurry (ICRI, 2004), is to be collected and treated until they meet the criteria for disposal set by the state. Hydrodemolition is unique because it will only demolish unsound concrete while also creating an exceptional bonding surface for new concrete (Nasvik, 2001), this can be seen in Figure 2.

FIGURE 1: Hydrodemolition equipment

FIGURE 2: Post-hydrodemolition surface

2.1.2 Diamond Grinding

The process of diamond grinding concrete roadway surfaces is used to rehabilitate a pavement surface texture to a condition that is often as good as a new pavement. The process is also used to reduce road noise while increasing surface macro texture and skid-resistance. The process uses closely spaced diamond equipped saw blades that are attached to a truck bottom and run longitudinally across a pavement surface. The saw requires a constant stream of water, which is provided to the machine by a separate truck run in conjunction with the diamond grinding equipment. A vacuum is attached around the saw blade in a fashion that picks up the water, concrete residuals, and slurry and sends them to a separate holding tank within the water holding truck. The grinding equipment and water truck used can be seen in Figures 3 & 4.

The residual materials created from this process consist of waste water, hardened concrete fines, and concrete slurry; the residual materials from the diamond grinding process is referred to as Concrete Grinding Residue (CGR). The CGR is to be collected by the vacuuming process, and to be held, treated, and disposed of at a later time.

The International Grooving & Grinding Association (IGGA) states that grinding slurry is an inert, nonhazardous byproduct of diamond grinding portland cement concrete pavement. Many tests have been done to ensure that the residual material is nonhazardous. A picture of the saw blade can be seen in Figure 5, and a typical grinded section can be seen in Figure 6. The geometry of a typical grinded section as described by (FHWA, 2001), can be seen in Figure 7. The CGR is a highly alkaline material (pH of 11-12.5+) which may cause problems for existing vegetation and topography, and contains many suspended solids. Some slurries may contain sulfates, chlorides, hydrocarbons, or other materials derived from concrete admixtures. Concrete that has been treated with a fly ash admixture was initially thought to be of concern due to possibility of elevated levels of the heavy metals; mercury, cadmium, and arsenic. However according to a characterization of the CGR done at North Dakota State University (NDSU), it was found that (DeSutter, 2011: Holmes & Narver 1997):

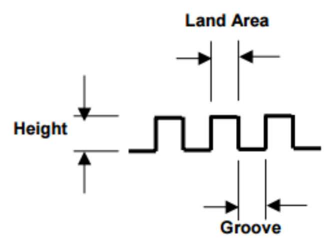
- Slurry samples displayed non-hazardous characteristics according to EPA hazardous waste standards.
- Slurry samples passed the 96-Hour Acute Toxicity testing, showing no toxic characteristics.

FIGURE 3: Diamond grinding machine

FIGURE 4: Diamond grinding water supply tank

FIGURE 5: Diamond grinding saw

FIGURE 6: Typical grinded section



	Range of Values mm (in)	Hard Aggregate mm (in)	Soft Aggregate mm (in)
Grooves	2.0 – 4.0 (0.08-0.16)	2.5 – 4.0 (0.1-0.16)	2.5 – 4.0 (0.1-0.16)
Land Area	1.5 – 3.5 (0.06-0.14)	2.0 (0.08)	2.5 (0.1)
Height	1.5 (0.06)	1.5 (0.06)	1.5 (0.06)
No. Grooves per meter	164 – 194 (50-60)	174 – 194 (53-60)	164 – 177 (50-54)

FIGURE 7: Typical grinding texture (FHWA, 2001)

2.1.3 Diamond Grooving

Diamond grooving of portland cement concrete pavement is a popular treatment for increasing traction, and decreasing the possibility of vehicular accidents caused by inclement weather. A study by IGGA shows that after grooving operations have been completed there have seen declines in wet pavement vehicular accidents by up to 70% (IGGA, 2013d). Grooving of pavement can be either parallel or perpendicular to the lane, and is used to create paths to remove water from the surface of roadways to improve drainage characteristics. The grooving process is similar to that of grinding. Grooving uses a vehicle with a mounted saw that uses cooling water while grooving, a source water tank, and a vacuum to pick up all grooving residue. A picture of a grooving machine, and its water tank truck can be seen in Figures 8 & 9. Grooving produces larger and deeper cuts that are spaced further apart than with grinding. Typically grooved section cuts are up to six times larger than grinded sections, and are spaced much further apart. Engineers typically specify grooves be 1/8- 3/16 inches deep, 1/8 inch wide, and spaced ¾ inch center-to-center (IGGA, 2013c). At typical grooved section can be seen in Figure 10, and the typical grooved texture can be seen in Figure 11. Grooving of new roads is becoming common practice, especially on large interstates, due to the enhanced safety benefits that have been realized.

According to the data provided from phone and email conversations with IGGA members in October of 2015, the residual material from grooving is roughly identical to that of the grinding residual material, except grooving produces less slurry and has a higher percent solids content. The residual material is vacuumed into a holding tank ready for treatment and disposal/reuse. The same concerns also exist for the grooving residuals: high alkalinity, high percent of suspended solids, and possibility of contaminating protected area. To ensure that contamination does not occur it is important that the residuals are collected from the road surface and are kept out of natural bodies of water.

FIGURE 8: Grooving machine

FIGURE 9: Grooving machine water storage tank

FIGURE 10: Typical grooved pavement section

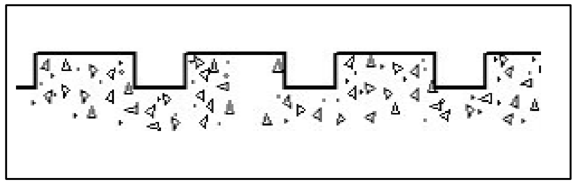


FIGURE 11: Typical texture of grooved section (Caltrans, 2008)

2.2 Residual Products and Methods of Disposal

The aforementioned construction operations create large quantities of residual materials that have multiple disposal/reuse options. Current best management practices for the handling and disposal of the slurry material have been developed by the International Grooving and Grinding Association (IGGA). The IGGA suggests that in rural areas with vegetated slopes adjacent to the roadway, the slurry can be spread on these side-slopes as the grinding operation moves along the road. This is not the case when the work is conducted adjacent to wetlands or other sensitive/protected areas. When near these protected areas or in urban designated areas, IGGA suggests that the slurry be vacuumed, picked up, and disposed of in designated areas (IGGA, 2013b). According to the Environmental Protection Agency (EPA), the wastewater from the process should be filtered to remove both coarse and fine solids and treated to lower the pH to acceptable levels and hauled to a Publically Owned Treatment Works (POTW) or Waste Water Treatment Plant (WWTP). The POTW/WWTP should be contacted first to find out their specific standards for dischargers. Another method for disposal would be containing the slurry to allow for the water to evaporate away, leaving only the solids behind for disposal (EPA 2012).

According to IGGA, (IGGA, 2013a), the disposal of the slurry is dependent upon the area in which the work is being conducted; rural or urban. In rural sites, as depicted by Figure 12, the slurry is allowed to be spread onto vegetated slopes as the equipment progresses along the road by means of a flexible hose, but not within one foot of the road shoulder. Any areas that have been deemed “protected” by the engineer must be kept clear from the slurry. The engineer will have to call out any protected areas and clearly indicate/flag them, and describe what preventative action must be taken. Slurry is not to be disposed of within 100 feet from natural streams and lakes. It is also noted that the slurry is not permitted to flow into adjacent lanes, especially when there is traffic in that lane. Lastly the slurry is not allowed to enter into closed drainage systems.

FIGURE 12: Side slope slurry spreading (Penhall, 2014)

In urban areas, IGGA (2013a) suggests, a different set of rules. The slurry is to be collected in water-tight hauling units, as operations progress. The slurry is then to be deposited in a lined settlement pond that has been constructed by the contractor and designed by the engineer. These settlement ponds are allowed to be within the right of way, or outside of it as long as the engineer’s orders are maintained. The solids will settle to the bottom and the water is to be collected and reused for further grooving/grinding operations. After grinding/grooving has been completed, the water in the settlement pond can be left to evaporate or decanted and disposed of. The solids may be reused as a fill material or reused as a recycled aggregate. Upon completion, the pond area is to be returned to its original condition.

Depending on the operation chosen, the size of the solids residuals will vary; hydrodemolition has larger residual solids and a larger quantity of liquid than the residuals produced from grinding or grooving. The residual slurry contains suspended and dissolved concrete solids. Some states allow for all of the residuals to be distributed on side slopes, while others mandate that all work be maintained as a non-discharge system. Land application has been another popular method of beneficial use, where the residual material is applied to open land at predetermined rates and has no detrimental effect on vegetation or groundwater (IGGA, 2011).

The wastewater contains suspended solids, and is highly alkaline (pH of 11 – 12.5+). The wastewater is commonly collected in a settling tank/pond to remove solids by addition of flocculants or simply by gravity settlement. The pH in these tanks/ponds will also need to be lowered for disposal by either introduction of acid, CO_2, or other basic compounds. ICRI (2004) suggests placing the remaining solids in a holding container for disposal by recycling/landfill placement with the cooperation of the controlling authority. The ICRI report however does not mention any possible methods for the reuse of the material.

The American Concrete Institute (ACI) has set limitations on the disposal of the waste water associated with hydrodemolition. ACI suggests following the state/local regulatory guidelines which may include acquiring permits to discharge into local sanitary systems, however in many cases the waste must be treated before discharge. In some cases, the waste may be discharged on the ground and be allowed to evaporate/be absorbed. The waste should never be discharged into lakes, streams, or wetlands. (ACI, 2010).

The options for managing grinding, grooving, and hydrodemolition slurry are:

- Disposing in vegetated slopes,
- Dumping on roadway shoulders where applicable,
- Placing into Frac tank units to separate liquids and solids to process liquids, and
- Placing in a settlement pond to allow for separation of solids and liquids, and evaporation/decanting of liquids.

The options for liquid disposal/reuse are:

- Disposal via
  - Waste Water Treatment Plant (WWTP) and
  - Publically Owned Treatment Works (POTW)
- Reuse via
  - Land Application

The options available for solid disposal/reuse are:

- Disposal via
  - Municipal Solid Waste (MSW) Landfill,
  - Construction & Demolition (C&D) Landfill, and
  - Land Clearing and Inert Debris (LCID) Landfill.
- Reuse via
  - Beneficial Fill Onsite and
  - Beneficial Fill Offsite

2.3 Current North Carolina Regulations

2.3.1 Wastewater Regulation

The residual materials generated from diamond grinding, diamond grooving, and hydrodemolition of Portland Cement Concrete Pavement (PCCP) are all very similar. The EPA published Guidelines for Water Reuse (EPA, 2012) which provides suggestions for states to follow to ensure proper cleanup of these activities. This is particularly important for sites located in sensitive areas; near natural water bodies, wetlands, or in urban areas. The EPA has set standards for which water must attain before being reused. The EPA (2012) requires, for urban spaces:

- Adjustment of pH to a range of 6-9,
- Biochemical Oxygen Demand (BOD) less than 10mg/l,
- Nephelometic Turbidity Unit (NTU) less than 2,
- No Fecal Coliform per 100 mL, and
- No more than 1 mg/Cl_2

The recommendations that are provided by the EPA are meant to provide guidelines for states to develop their own regulations based on state specific characteristics. Specifically in the state of North Carolina, the regulations that govern water reuse fall under “15a North Carolina Administrative Code Chapter 02 – Environmental Management”. More specifically in subchapter 02-U “Reclaimed Water”. The state standards for “reclaimed water effluent standards” (N.C.A.C., 2011) are as follows:

- Monthly BOD average of less than 10mg/L,
- Daily BOD maximum of less than 15mg/L,

- Monthly average of total suspended solids (TSS) of less than or equal to 5 mg/L, and a daily maximum TSS of less than or equal to 15mg/L,
- Monthly limit on ammonia of less than or equal to 4mg/L,
- Daily limit of less than or equal to 6mg/L,
- Monthly geometric E. coli/fecal coliform level less than or equal to 25/100mL, and
- Maximum turbidity level of 10NTU's or less.

This however changes when considering water reuse for irrigation of food chain crops, which offers a much more stringent environmental standards. The criteria is as follows:

- Monthly BOD less than or equal to 5mg/L,
- Daily maximum BOD of less than or equal to 10mg/L,
- Monthly TSS average of less than or equal to 5mg/L and a daily maximum TSS of less than or equal to 10mg/L.
- Monthly ammonia limit of less than or equal to 1mg/L with a daily maximum ammonia limit of less than or equal to 2mg/L,
- Geometric average E. coli/fecal coliform level less than or equal to 10/100mL, and
- Maximum turbidity of 10 NTU's.

A flow chart was created to help visualize the NCDOT approved options available for reuse and disposal of the residual materials, whether liquid or solid from grinding, grooving, and hydrodemolition operations. The options for disposal and reuse of the various associated residual products within the North Carolina can be seen in Figure 12.

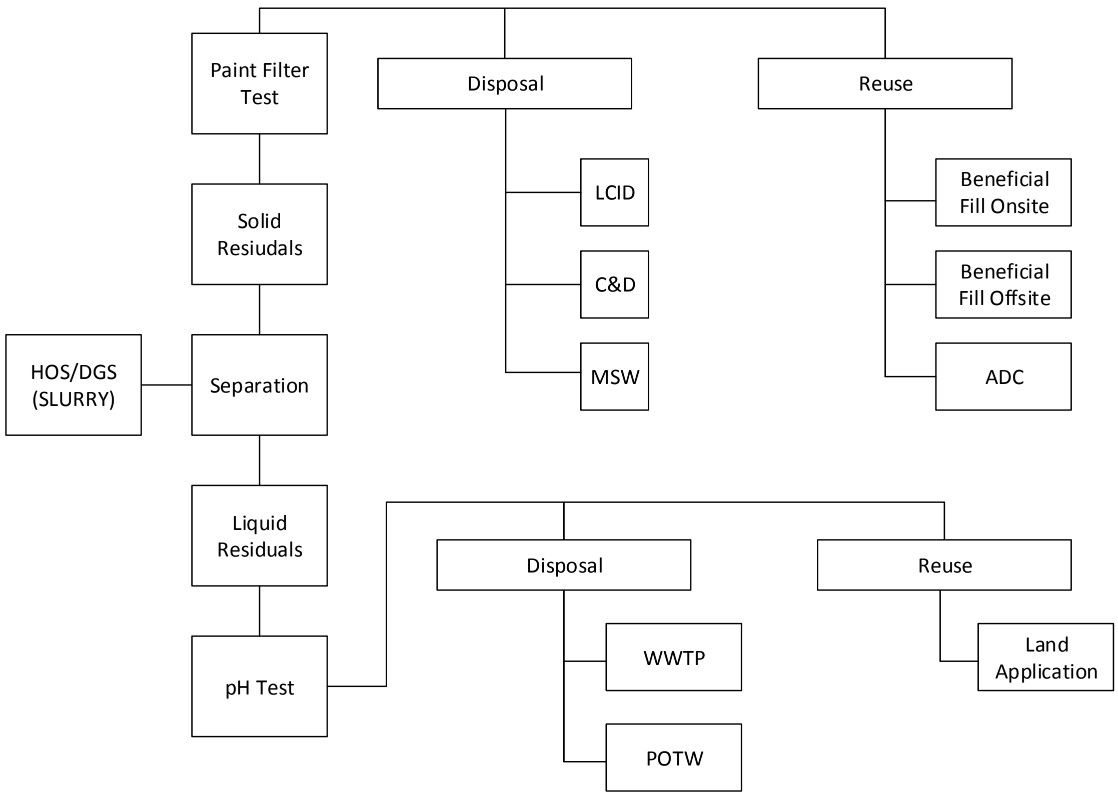


FIGURE 13: Flow chart of approved concrete residual disposal/reuse options.

2.3.2 Solid Waste Regulations

Identification, treatment, storage and disposal of the solid waste materials associated with hydrodemolition, diamond grinding, and diamond grooving of concrete is governed by the hazardous and solid waste amendment of the Resource Conservation and Recovery Act (RCRA). A cradle-to-grave approach is suggested when managing these waste products, and treatment of the waste prior to its disposal. The NCDOT's Roadside Environmental Unit works closely with the Division of Waste Management and North Carolina Department of Environmental Quality (NCDEQ) to develop the Residual Management Program (RMP) so that waste is disposed of in accordance with state and federal regulations (NCGS, 2007).

The Environmental Protection Agency (EPA) specifies that the generators of waste materials are responsible for testing and identifying their waste as hazardous. Waste generators are required to perform an analysis of corrosivity, ignitability, and toxicity, as well as an analysis of the Toxicity Characteristics Leaching Procedure (TCLP). The goal for North Carolina's Residual Management Program is to work alongside of waste generators, land owners, and other stakeholders to identify, regulate, and manage land application and disposal of residual solids. According to the North Carolina's Division of Water Quality, in their 2010 Residual Management Program Summary, under North Carolina General Statute (NCGS), "residuals are defined as waste, and any system designated to collect, treat, or dispose of waste cannot be constructed or operated without a permit". The statute grants power to the state's Environmental Management Commission (EMC) to work with NCDEQ to develop regulations and issue permits to the generators of residuals. These functions are to be carried out by NCDEQ's Division of Water Quality (DWQ). The DWQ has stated that for the Residuals Management Program (RMP), residuals are not to be discharged to surface waters. These rules have defined residuals as solid, semi-solid, or liquid waste, that are considered to be a non-effluent/residue from agricultural products and processes, generated from wastewater treatment facility, water supply treatment facility, or air pollution control facility permitted under the authority of the EMC (DWQ, 2006).

2.3.2.1 Land Clearing and Inert Debris (LCID)

Inert debris, as defined in the North Carolina General Statutes, "is solid waste which consists solely of material that is virtually inert and that is likely to retain its physical and chemical structure under expected conditions of disposal" (NCGA 2014). Mecklenburg County (Mecklenburg County 2015) defines the following as inert debris:

- Untreated wood,
- Brick,
- Concrete,
- Concrete Block,
- Asphalt,
- Uncontaminated Soil,
- Rock and Gravel, &
- Stumps, brush, and limbs.

All solid residual materials are to be transported to the LCID landfill locations by the contractor. Concrete is only accepted as an inert debris if it is considered "clean" by the accepting facility. Clean was described as free of rebar by employees of the various LCID landfills contacted within North Carolina.

2.3.2.2 Municipal Solid Waste (MSW)

Municipal Solid Waste (MSW), as defined by North Carolina General Statue, is any solid residual waste from residential, commercial, industrial, governmental, or institutional operation that would have been collected, processed, and disposed of via a public or private waste management service. This does not include hazardous waste, sludge, or solid waste from mining or agricultural operations. MSW also does not include industrial waste that is managed in a solid waste facility owned and operated by the generator of that waste (NCGA 2014). The solid concrete residual material could be disposed of at a MSW landfill according to the state statute.

2.3.2.3 Construction and Demolition (C&D) Waste

Construction & Demolition (C&D) waste, as defined by North Carolina General Statue, is the residual material from construction, remodeling, repair, or demolition operations on pavements or structures. C&D does not include inert debris, or debris that has been cleared from land or yard waste (NCGA 2014). The solid residuals resulting from the demolition/remediation techniques studied in this paper could also be considered C&D waste, allowing it to be disposed of in C&D landfills.

2.3.2.4 Beneficial Fill

NCDOT mandates that residual solids can be used beneficially inside ROW fill sections. North Carolina Administrative Code (NCDEQ 1993) states that beneficial fill must consist of only inert debris, which concrete is considered. In order for the fill to be considered beneficial, no excavation is to be done, and the purpose must be to improve land use potential or other beneficial purposes. The fill activity must comply with all zoning, flood plain, wetland, and sedimentation and erosion control restrictions and regulations. Perhaps most importantly, the beneficial fill is not to violate any groundwater standards.

In an effort to reduce the amount of solid waste that is getting distributed to landfills, local governments have put in place waste reduction programs. It is the policy of North Carolina to promote methods of solid waste reduction as a management policy.

According to this policy (NCGA 1996), disposal of solid waste in a landfill is the least preferred method of disposal.

In order to reduce waste, local governments have allowed for demolition debris consisting of used asphalt, or used asphalt mixed with dirt, sand, gravel, rock, concrete, or similar nonhazardous material to be used as fill. The demolition debris does not need to be disposed of in a landfill or solid waste disposal facility, provided that demolition debris is not be placed in waters of the state or at or below the seasonal high water table (NCGA 2014).

A memo from NCDEQ's Solid Waste Division goes further to state "dewatered CGR's may be beneficially reused within the DOT project boundary or areas under DOT control at agronomic rates suitable for the establishment of vegetation. Dewatered CGR's may also be used within the roadbed at rates approved by DOT staff for soil modification purposes" (Scott 2013). If the residual solids are to be reused as beneficial fill NCDOT states that there is to be only one representative TCLP sample from the project taken to ensure that no RCRA 8 metals in the sample.

2.3.2.5 Land Application

In the state of North Carolina, residuals may be applied to agricultural lands as long as EPA and NCDEQ regulations are adhered to, and the proper limits stated earlier are obtained. In North Carolina, concrete residuals have been classified as Class A (treated, exceptional quality), and are suitable for land application or burial. Federal rules on residuals also contain provisions for limiting metal content, as well as pathogens and use requirements that are similar to the disposal of organic waste solids (municipal sewage sludge). The EPA has designated regulations for land application of "sludge", which includes an analysis of composition of the waste material, toxicity, and liquid/solids content. The EPA also calls for an evaluation of the disposal sites including topography, soil profiles, and provisions for monitoring the site (DWQ, 2006).

The state of North Carolina requires the issuance of a permit for land application of residuals (NCDOT, 2015). A Land Owner's Agreement form must be completed, which provides the application parameters, describes the land use, and outlines the responsibilities for the generator of the residuals, the landowner, and other parties that are involved in each situation. Permits are specific to the site, and may need to be modified to allow for changes related to residual source, type, application parameters or other variables. The Department of Water Quality is responsible for reviewing the permits, communicating with local agencies, and delegating responsibilities. Responsibilities for the permit holders include the submittal of an annual report, which will highlight information on application activities, tests on water quality, and nutrient management. Permit holders are also responsible for self-reporting of any violations of the permit. Although the permit requirements address limitations on components of residuals, operations, monitoring, and reporting, they do little to address the final disposal of the residuals after the completion of the construction operations (NC-Environmental-Management-Commission, 2013).

2.4 Current Regulations Throughout the United States

An investigation was conducted to examine the current regulations that exist for the diamond grinding, diamond grooving, and hydrodemolition operations around the United States. There was a large amount of disparity on a state-to-state basis; some states specify thorough regulations in regards to cleanup and disposal of the residual materials, while others made no mention of the processes whatsoever. The data presented in Appendix A is a summary of the state-to-state examination of state department of transportation policies regarding diamond grinding, diamond grooving, and hydrodemolition will be discussed below.

2.4.1 Diamond Grinding & Diamond Grooving

Currently there are 35 states that make reference to the processes of diamond grinding and grooving, and how to handle the residual materials. Figure 13 displays the 28 of the 35 states, highlighted in blue, that mention minimum requirements for grinding and grooving. These 28 states require, at a minimum, the following:

- Continuous removal of CGR,
- Collection via vacuum pumping or equivalent, and
- No CGR to enter:
    - Adjacent lanes,
    - Drainage structure/gutters, or
    - Natural bodies of water (lake, river, etc.)

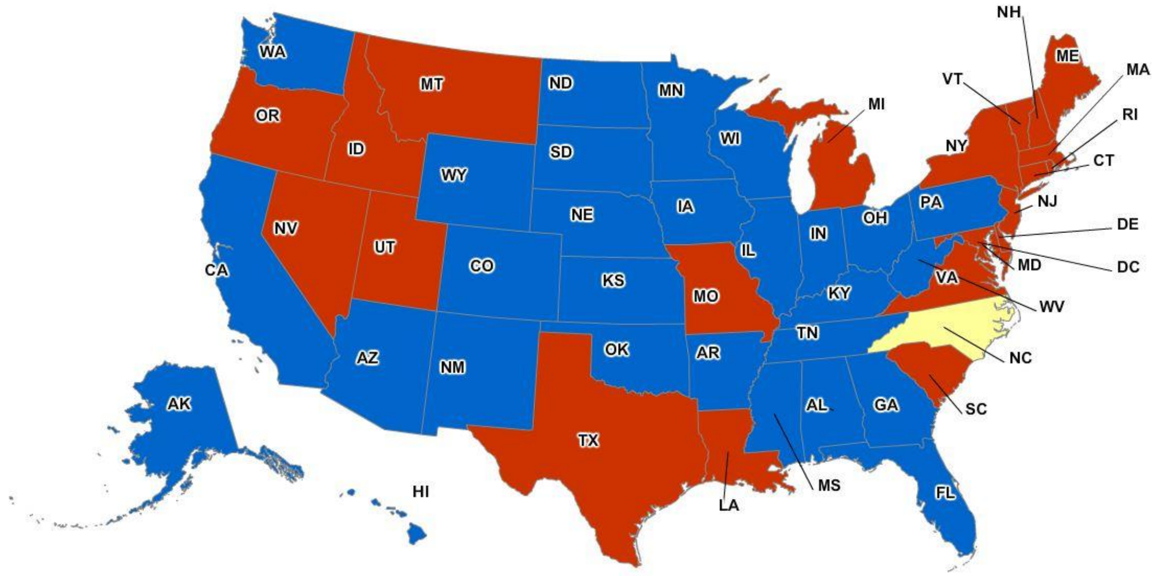


FIGURE 14: States meeting minimum CGR requirements

Of the 35 states that mention residual materials from the grinding/grooving process, there are 13 that make mention of the residual materials being contained, treated, or filtered. Specifications state that this can be done by requiring the contractor furnish wastewater treatment plans, residual management plans, or some other plan to minimize the residuals impact. Some specifications say the residuals are to be maintained onsite in temporary concrete washout facilities, and routed into a sedimentation basin or stored in tanks for holding. Figure 14, displays these states, highlighted in blue.

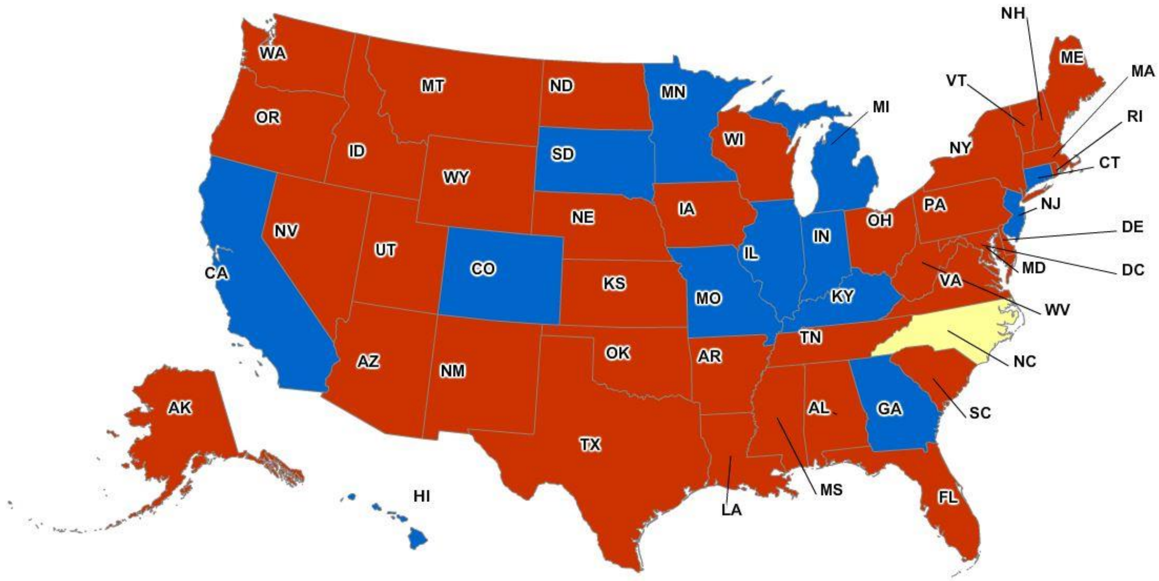


FIGURE 15: States requiring containment/filtrations/treatment

Finally, 19 of the 35 states make mention to some type of disposal, recycling, or reuse options that exist in regards to the residual materials. The environmental implications of these options, however, are not the same. Some states allow for the residuals to be disposed of in bulk directly onto the side slopes of the project ROW. Others state that solid residuals are allowed to be placed inside of embankments as a beneficial fill material, taken to MSW or C&D landfills, or disposed of at a permanent waste management facility. Some states allow for the liquid residuals to be decanted from the slurry and reused for other construction operations, while others recommend the liquid be diverted to a sanitary sewer or POTW. These states can be seen in Figure 15 highlighted in blue.

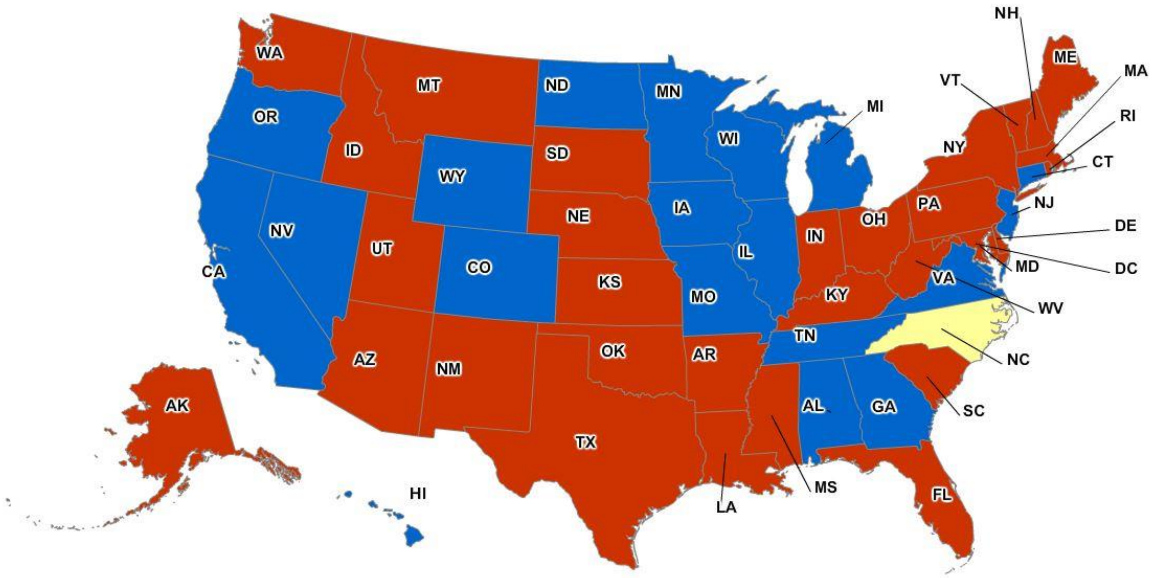


FIGURE 16: States requiring residual disposal/reuse methods

2.4.2 Hydrodemolition

Of the construction processes researched in this project, hydrodemolition is the least regulated construction process across the United States. There are only 15 state DOT's that mention the process within their standard specifications. Of those 15 states, only 10 mention that the residuals are to be removed from the surface, no residual materials are to flow across adjacent lanes, or to enter into drainage facilities or bodies of water within the state.

There are 15 state DOT's that require that there be a plan for collection, containment, or treatment of the residual material; these states are shown in Figure 16, highlighted in blue. This includes:

- Onsite wastewater treatment plant,
- Placing into concrete washout facilities,
- Submitting a plan for containing residuals and contaminants generated from the hydrodemolition process, and

- Chemical additions to reduce the pH of residuals.

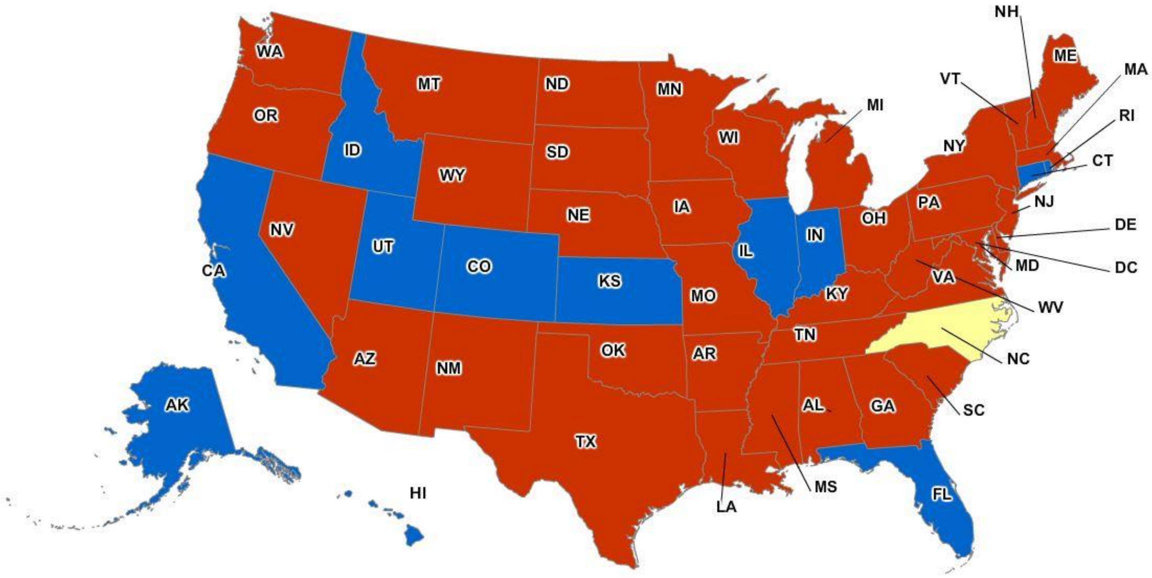


FIGURE 17: States requiring HOS collection/containment/treatment

Ten of the fifteen states, make mention of the methods of disposal or reuse for the residual materials. These states can be seen in Figures 17 and 18 highlighted in blue. For liquid residuals, some states recommend:

- Placement in a settlement pond where liquids can be decanted and disposed/reused or allowed to evaporate,
- Slurry placed in temporary onsite concrete washout facilities,
- Dispersed on the side of the road,
- Beneficially reused via land application, and
- Liquids recycled at appropriate treatment plant.

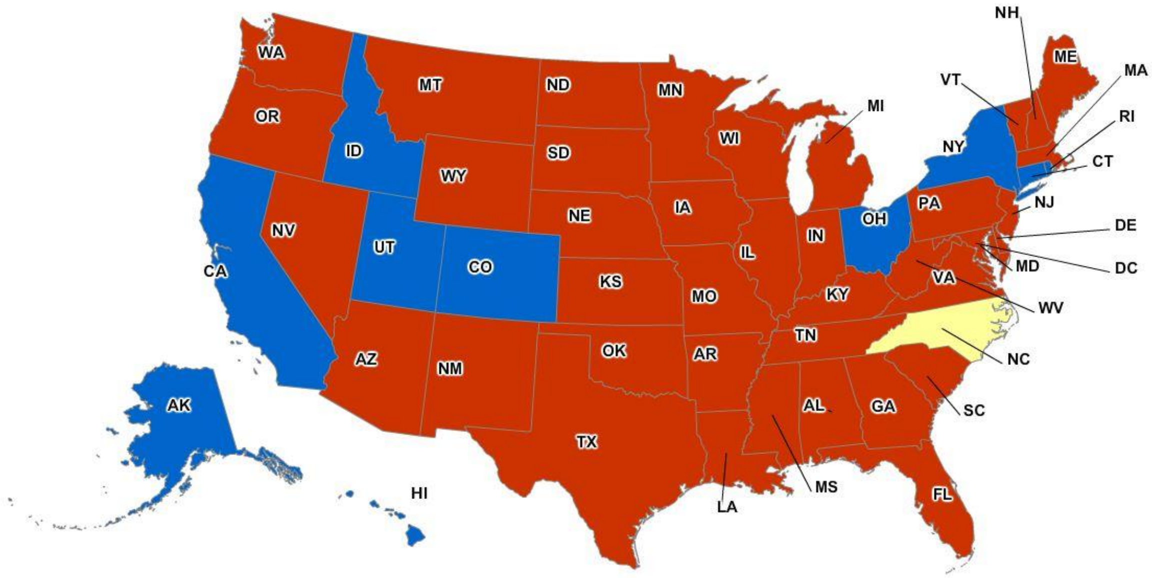


FIGURE 18: States requiring disposal/reuse of hydrodemolition liquids

For solid residuals of hydrodemolition activities, some states recommend that these residuals be:

- Placed within embankments,
- Solid disposal at DEC approved landfill,
- Solids recycled at appropriate treatment plant, and
- Solids beneficially reused inside ROW as a fill material.

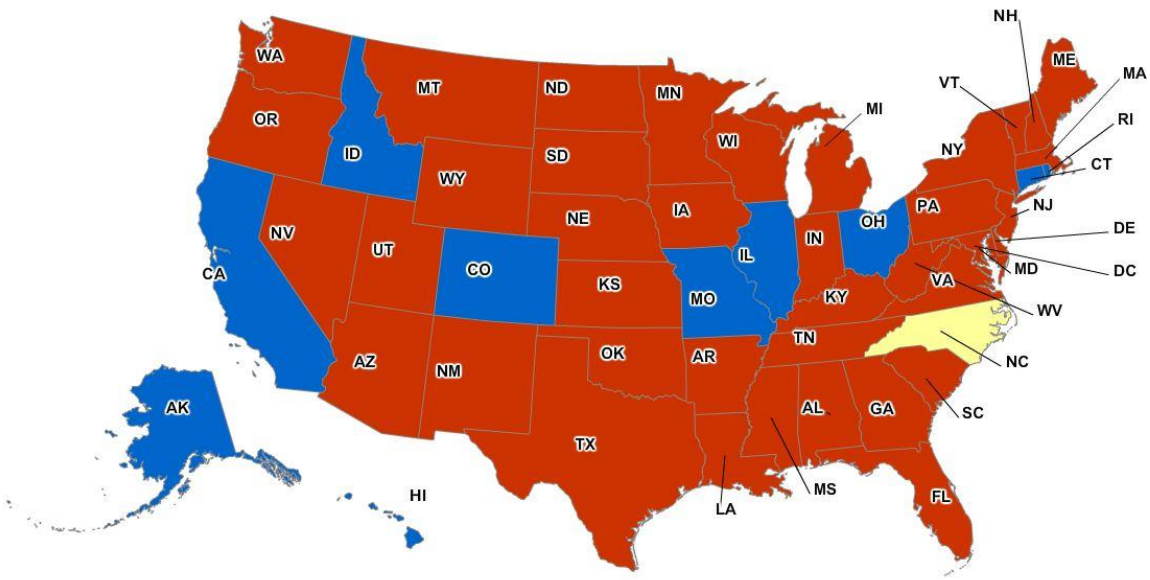


FIGURE 19: States requiring disposal/reuse of hydrodemolition solids

2.4.3 States Without Literature on Construction Methods

Based on the findings of this survey, the states that did not mention the operation or cleanup of hydrodemolition, diamond grinding, or diamond grooving in their standard specification were as follows:

- Arkansas, Delaware, District of Columbia (DC), Louisiana, Maine, Maryland, Massachusetts, Montana, New Hampshire, South Carolina, Texas, and Vermont.

2.5 Multi-Criteria Decision Making

Multi-Criteria Decision Making (MCDM) tools have the ability objectively judge alternative decisions based on input criteria to evaluate and choose the best decision. For more complex decisions that have multiple alternatives, with their own separate cost items, MCDM tools can be helpful. MCDM allows the user to select which criteria is important to them, based on a relative score or weight, and come to the decision that is most optimal for the user. MCDM is based upon the notion of “alternatives” and “attributes”: alternatives being the different choices or options the decision maker has at their disposal, attributes being various details and metrics about an alternative. Each alternative has many attributes that make it different from the other alternatives. Attributes may also be represented as a goal or decision criteria (Triantaphyllou, 2000).

A MDCM model may be either “discrete” or “continuous”: Discrete models have their decision alternative predetermined, while continuous models are far more complex and contain an infinite/very large number of alternatives and must contain mathematical programming with many objective functions. Discreet models are more practical and user friendly. MCDM is a blanket term for tools used to make a decision, and there are many different techniques that fall under the definition of MCDM. In order to choose the most appropriate technique to use (Triantaphyllou, 2000), the following three steps are to be considered:

1. Determine the relevant criteria and alternatives,
2. Attach numerical measures to the relative importance of the criteria and to the impacts of the alternatives of these criteria, and
3. Process the numerical values to determine a ranking of each alternative. (Triantaphyllou, 2000)

The most popular methods are represented in the form of decision matrix, which can be seen in Figure 19. The “A” values represent the possible alternatives for the specified decision. The “C” values represent the decision criteria used in the evaluation of each alternative. Each “C” value is given a weight of importance to the overall decision, as specified by the decision maker. The coming subsections will discuss the most used methods of MCDM, which are the following:

- Weighted Sum Method (WSM)

- Weighted Product Method (WPM)
- Analytical Hierarchy Process (AHP)
- Revised Analytical Hierarchy Process (RAHP)

$$
\begin{array}{ccccc}
 & C1 & C2 & \cdots & C_n \\
Alt & w_1 & w_2 & \cdots & w_n \\
A_1 & a_{11} & a_{12} & \cdots & a_{1n} \\
A_2 & a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_m & a_{m1} & a_{m2} & \cdots & a_{mn}
\end{array}
$$

FIGURE 20: Typical MCDM decision matrix

2.5.1 Weighted Sum Method (WSM)

The weighted sum method is the most widely used MCDM method for conducting an analysis of alternatives. The WSM is particularly useful when measuring alternatives in a singular dimension. Since all criteria is measured in the same dimension, each alternative will have a relative score, and the alternative with the highest score is the one that should be chosen. An alternative's score is calculated using Equation 2.1. This is the simplest MCDM method when conducting an investigation in one dimension (Triantaphyllou, 2000).

$$A_i = \sum_{k=1}^{n} a_{ij}\ w_j \qquad \text{(Eq. 2.1)}$$

2.5.2 Weighted Product Method (WPM)

The Weighted Product Method differs from the WSM in that instead of addition, multiplication is used to find the ranking score. This method can be done in terms of ratios, or as a standalone calculation; the former is used to compare two different alternatives directly to each other. Each ratio is then raised to the power equivalent of the relative weight of that criteria within the model as shown in in Equation 2.2.

$$R\left(\frac{A_K}{A_L}\right) = \prod_{j=1}^{n}\left(\frac{a_{Kj}}{a_{Lj}}\right)^{w_j} \quad \text{(Eq. 2.2)}$$

If the term "R (A_K/A_L)" is greater than 1, then alternative A_K is comparatively better than A_L. The most desirable alternative is the one that scores best relative to the other alternatives. The use of the ratio is particularly effective because it eliminates the need for a dimension, and alternatives with different units can be compared directly to each other. The WPM can also be used without ratios, as seen in Equation 2.3. This method is used to find the relative performance value of each alternative to be compared (Triantaphyllou, 2000).

$$R(A_K) = \prod_{j=1}^{n}\left(a_{Kj}\right)^{w_j} \quad \text{(Eq. 2.3)}$$

2.5.3 Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP), uses a system of hierarchies to compare alternatives. The AHP is similar to the WSM, however each alternative criteria is normalized by dividing its score by the sum score for that criteria. As with the WSM, the best alternative is the one that receives the best score. The AHP is a popular method due to its application in single and multi-dimensional decision making, and it is easy to implement with readily available online software programs. The AHP is not without its limitations however. When identical alternatives are being compared in a model, the numbers are skewed since each criteria adds up to one; this can lead to false results to occur when the identical alternatives cancel each other out (Triantaphyllou, 2000). The decision matrix for the AHP can be seen in Figure 20.

$$\begin{array}{lcccc} & C_1 & C_2 & \cdots & C_n \\ & w_1 & w_2 & \cdots & w_n \\ Alt. & & & & \\ A_1 & a_{11}/\sum_1^m a_{i1} & a_{12}/\sum_1^m a_{i2} & \cdots & a_{1n}/\sum_1^m a_{in} \\ A_2 & a_{21}/\sum_1^m a_{i1} & a_{22}/\sum_1^m a_{i2} & \cdots & a_{2n}/\sum_1^m a_{in} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & a_{m1}/\sum_1^m a_{i1} & a_{m2}/\sum_1^m a_{i2} & \cdots & a_{mn}/\sum_1^m a_{in} \end{array}$$

FIGURE 21: Decision matrix for AHP

2.5.4 Revised Analytical Hierarchy Process (RAHP)

The Revised Analytical Hierarchy Process (RAHP) was developed to deal with the inconsistencies that existed in the AHP. Instead of each alternative criteria being divided by the sum total for that criteria, it is divided by the maximum value for that criteria. This creates a method where two identical alternatives can be evaluated at the same time without skewing the results. As with the WSM and AHP, the best alternative for the specified decision is the one with the highest score. RAHP is allowed to be used for single and multi-dimensional decision making (Triantaphyllou, 2000). The decision matrix for the RAHP can be seen is Figure 21.

$$\begin{array}{lcccc} & C_1 & C_2 & \cdots & C_n \\ & w_1 & w_2 & \cdots & w_n \\ Alt. & & & & \\ A_1 & a_{11}/\max(a_{i1}) & a_{12}/\max(a_{i2}) & \cdots & a_{1n}/\max(a_{in}) \\ A_2 & a_{21}/\max(a_{i1}) & a_{22}/\max(a_{i2}) & \cdots & a_{2n}/\max(a_{in}) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ A_m & a_{m1}/\max(a_{i1}) & a_{m2}/\max(a_{i2}) & \cdots & a_{mn}/\max(a_{in}) \end{array}$$

FIGURE 22: Decision matrix for RAHP

2.5.5 MCDM Method Used

The cost criteria was obtained from interviews/surveys with contractors of these operations. The MCDM method chosen was the Revised Analytical Hierarchy Process

(RAHP) method since the alternative were compared with multiple dimensions. The attributes studied are cost, risk, and environmental benefit. This allowed multiple alternatives to be evaluated based on their cost, risk, and environmental benefit attributes to be added together and compared to each other in order to find the alternative with the most optimal benefit.

2.6 Monte Carlo Method

The Monte Carlo Method is used to obtain numerical solutions in situations where solving analytically is too complicated. It was first used by scientists working on the atom bomb (Palisade-Corporation, 2016). The Monte Carlo Method uses computerized mathematical techniques to simulate a desired outcome through the use information related to that outcome. It takes into account the most conservative estimates as well as worst case scenarios to come up with a statistical simulation for an outcome that involves all possibilities to come up with an outcome of the most likely situations.

The Monte Carlo Simulation Method, in practice can be used to create a model to solve a given question that has many variables with differing probabilistic values. By running many, hundreds or thousands, of iterations, a sample average may be considered acceptable, by the probabilistic theory the law of large numbers (Renze, 2016).

Factors that make up the outcome of the model have a range of values associated with them. The Monte Carlo Method puts that range of values into a probability distribution function. The model is made up of many of these probability distribution functions. The model is run many times, (often over a thousand), and the results are calculated over and over again, each time with a different set of values from each probability distribution function. The final values in a model created using the Monte

Carlo Method will be a distribution of values from high to low, allowing the user to get a range that is most likely to occur for that outcome based on the input values (Takeshi, 2013).

The Monte Carlo Method holds advantage over deterministic models because it shows not only what could happen, but how likely that result is to happen in a clear graphical manner. The Monte Carlo Method also allows for the user to easily determine what factors are likely to have the largest impact on the final outcome, identifying for the user what factors should be most closely monitored to decrease risk.

By using data that has been gathered directly by means of survey or other direct data collection methods, the range of values can be assumed to the correct. When these ranges are assumed to be correct, it can be assumed that the model is valid. Data gathering is a very important part in creating a Monte Carlo Simulation.

The EPA has used Monte Carlo Simulations as a supplementary data gathering tool for Risk Assessment when there is multiple descriptors of risk (R. Smith, 1994). The Monte Carlo Simulation can repeatedly calculate randomly selected “what if scenarios” and report the found data is simple user friendly graphs and tables. The EPA however notes that Monte Carlo Simulations have significant limitations in the area of uncertainty. If values are unknown it is impossible for the simulations to assign an accurate value to a given range. If the ranges used in certain factors are unknown, and their data is estimated, the validity of the model as a whole is called into question.

CHAPTER 3: METHODOLOGY

In this chapter, the methods in which the data was gathered will be explained. The available options for disposal/reuse are also discussed, and the survey that was developed to interview contractors doing this work within North Carolina will also be discussed. The other data collection methods used to make the cost benefit model will be explained below. The source of the data used to create the model are also laid out below.

3.1 The Survey/Interview

To gather information into the specifics involved in the disposal and reuse of the concrete residuals from hydrodemolition and grinding/grooving, a survey was developed to interview contractors about their chosen methods of disposal/reuse. A copy of this survey is provided in Appendix B. To create a reasonably accurate cost model for the disposal/reuse of these residuals, the cost variables of disposal/reuse must be identified. The information provided by the contractors was used to highlight the factors that influence cost on a project. The survey looks at the following areas:

- Types of materials generated,
- Testing methods used,
- Disposal/reuse options,
- Contractual obligations
- Quantities of residuals generated, and

- Unforeseen cost variables.

Once sufficient variables have been gathered, the BCM was created to reflect an accurate summation of costs associated with these construction activities. The RAHP method was used to compare the alternatives with each other to find the alternative with the highest score on a project specific basis for all options of disposal/reuse. The MCDM model created was used to evaluate past contractors decisions, to see if the appropriate decision was made. The purpose of the interview/survey was to gather relevant information from industry professionals to create an accurate pricing model to be used by contractors in future bid estimations.

3.2 Theme of Survey/Interview Questions

The contractors were asked a series of questions about the residual products and their recycling/disposal processes. These questions were developed to identify the cost factors that existed throughout these construction processes in regards to residual management, collection, storage, treatment, and ultimately reuse/recycling/disposal of the residuals. Each method of residual management has its own set of regulations and testing procedures that would influence cost. Since the goal was to create a model that could be used to accurately estimate the cost of conducting these operations from residual generation to disposal/reuse, gathering information on the most up-to-date regulations and requirements were necessary. The subsequent subsection will discuss these themes in greater detail below.

3.2.1 Types of Material

This section of the survey/interview focused on determining the type of residual material that the contractor has experience in dealing with, and from what construction type those residuals were generated. The survey was used to gather specifics about the equipment used in the process. The contractual relationship between the general contractor and the subcontractor were also studied in order to discover pre-bid qualifications and contractual responsibilities. Risks that exist within the processes were also studied, as well as the precautionary measures taken to mitigate those risks. Perceived environmental benefits, as defined by the interviewee, were also studied to determine the relative environmental friendliness of each method of disposal/reuse, although it is noted that quantification of the environmental benefits associated with each option was beyond the scope of this project. This section of the survey/interview was used to identify which options for disposal/reuse were considered by the contractor before decisions were made.

3.2.2 Tests Performed

This part of the survey/interview focused on the disposal/reuse method chosen, and what tests must be performed on the residuals in order to use that method. Depending on whether the residual is solid, slurry, or liquid, different testing methods exist for managing that residual. Typical testing methods include the Paint Filter Test, ASTM certified pH testing, and a TCLP if the solid residuals are to be buried; however some new tests may be performed that are currently unknown. These questions seek to find out what tests were performed, who performed them, the testing frequency and procedure, and all the costs involved with these tests.

3.2.3 Disposal of Solids

The disposal methods available to contractors for residual solids and their alternatives are discussed in this subsection. The goal is to present the contractor's decision making process given the information/options available to them. Locations for disposal of solids were identified in this section of the survey. Transportation methods were also an item of interest, including who performed the transportation, additional cost factors, and additional materials needed. Any unforeseen costs materializing in change orders to the NCDOT were also observed.

3.2.4 Beneficial Use of Solids

This portion of the survey focuses on the available options for reuse of solid residuals. Contractor rationale was studied, given available information and options. Transportation methods were also observed, as well as any hidden costs, and/or risks or risk mitigation techniques that could impact costs.

3.2.5 Alternative Daily Cover (ADC)

This subsection of the survey was presented to facilitate exploration of whether the contractor took the residuals to a landfill facility for use as ADC. ADC refers to a material that is spread over the "active face" of a landfill at the end of each day to control the material within the landfill. Transportation methods were also identified, as well as what contractual agreements were reached, and who accepted the residual material. The possible costs/benefits of the acceptance of material were also identified and reviewed.

3.2.6 Land Application

Lastly, in this subsection, land application of residuals were observed. Per NCDOT regulations, this method requires that specific tests be performed on the residuals prior to land application, including tests to evaluate or determine:

- Nitrates
- pH
- Agronomic Soil Rates
- Setbacks
- Corrosivity
- Chemical Oxygen Demand (COD).

This section of the survey/interview focused on identifying costs incurred from activities related to land application, including tests, agreements, legal fees, hidden costs, risks associated with spill control prevention plan, reporting costs, and any other additional costs that may exist.

3.3 Contacting Disposal Facilities within North Carolina

In order to identify the costs associated with the disposal of materials, disposal facilities within the state of North Carolina were contacted to determine whether or not they would accept the residual material, and at what price. The list of these facilities were found on the NCDEQ website. These facilities were then grouped and organized based on region and type, then selected at random to be contacted. These facilities were contacted by telephone to find out the level of quality at which they would accept these materials, whether pre-treatment was necessary, and at what price the materials would be accepted. These cost points were then compiled based upon type of facility and location, and can be seen in Appendix C. The cost data was then entered into the CBA to better estimate the price at which the residual materials would be disposed once generated. The costs ranged based on location and type of facility.

In certain cases, the residuals are placed in a pond for settlement to allow the solids to settle out over one to two days. The liquid residual, once separated, can be taken to a WWTP/POTW for disposal. The cost data for WWTP/POTW disposal can also be seen in Appendix C.

3.4 Cost Estimation Tool

A tool was created to better estimate the costs of various methods of disposal and reuse for the concrete residual materials from hydrodemolition, diamond grinding, and diamond grooving. The tool allows the user to go through and make inputs and selections for various options, and off of those inputs and selections, a final cost can be computed for the various options available. The sources of this information and what was found in them is discussed below.

3.4.1 Cost Estimation Information Sources

Information was gathered from a number of sources and combined to create the cost estimation tool. The sources of this information and what was found from these sources are discussed below.

3.4.1.1 R.S. Means

The R.S. Means Manual (R.S. Means Company, 2009) was used to define various costs, inputs, and selections. The information gathered was in regards to the types of equipment used on the project, and the capacities of those pieces of equipment. The R.S. Means manual provides information on associated output and production rates based on the size and the type of earth that the equipment is working on. The crews for each piece of equipment was also observed, however the crews used will be left up to the user to select their own choices. RSMeans was used to find the information associated with the activities involved in choosing the decanting pond option for slurry handling. The activities involved in the decanting pond method of slurry handling are:

- Excavation
- Geosynthetic Layering
- Backfilling
- Compaction

3.4.1.2 US Army Corps of Engineers

For all of the equipment found in RSMeans, the (USACE, 2014) Construction Equipment Ownership and Operating Expense Schedule for Region III was used to find the hourly costs of running the machines. The USACE manual was used to estimate the costs of:

- Hydraulic Excavators,
- Front-End Loaders,
- Compaction Equipment,
- Transportation Trucks,
- Water Tank Attachments for transportation trucks, and
- Solid Waste Transportation Vehicles.

3.4.1.3 Davis Bacon Act– Wage Determination Online

The Davis Bacon Wage Act website was used to determine the hourly wages of workers on the jobsite. The website was used to find the hourly costs of laborers and equipment operators. The wages were generated using Mecklenburg County as a baseline. The operators and laborers used was found under the highway work designation of the website. The hourly wages also included fringes and benefits for the workers where applicable.

3.4.1.4 Grinding/Grooving/Hydrodemolition Contractors

Contractors with expertise in grinding, grooving, and hydrodemolition construction operations were contacted in regards to finding ranges for the slurry generation rates, production rates, and percent solids of operation slurry. The slurry generation rates of the machinery were given in gallons per minute. The general size of the diamond grinding/grooving or hydrodemolition head was four feet in width. The contractors also provided a figure for the liner distance covered over a given period of time. These figures were combined to find a figure for slurry generated per designated area. The percent solids of the slurry generated was also provided by the contractors. This percentage was used to find and estimation for the quantity of solids and liquids in the given quantity of slurry. These figures would be used further in discussing disposal/beneficial reuse costs.

3.4.1.5 Tank Rental Companies

The tank rental company most widely recommended by the local contractors was contacted to determine the costs of renting Frac tanks, water holding tanks, and delivery costs of those tanks to the site. This company was used for the majority of grinding/grooving/hydrodemolition projects involving NCDOT that used Frac tanks as their chosen method of slurry handling. This company also has many locations throughout North Carolina making its figures applicable in all regions of North Carolina. The cost for renting the tanks were given in terms of daily use and for a “cycle”. The term cycle was used to describe 28 consecutive days of onsite use. The delivery costs were given on a per mile basis for delivery from the company’s location to the location of the jobsite.

3.4.1.6 WWTP/POTW

Various WWTP’s and POTW’s were contacted throughout North Carolina. These facilities were identified based upon information found on the NCDEQ website. Operators at each site gave information in regards to the qualifications for which the material would be accepted. These qualifications were generally based on the quantity of suspended solids within the liquid and the pH. Both of these testing parameters needed to be reduced for slurry disposal at these facilities. This can be achieved by manual settlement or screening, similar to using the decanting pond or the Frac tank respectively. The pH is to be lowered by the addition of acid to achieve acceptable levels. The acceptable pH levels were generally given as under 9, however the chosen facility should be contacted beforehand to find their unique parameters.

3.4.1.7 Land Application

Various certified land Application sites were contacted throughout North Carolina. These facilities were found using the NCDOT website. Site operators were surveyed to find a range of costs at which they would accept the various liquid residual materials. The operators of these sites were also contacted to discuss the method of delivery to their site. The operators indicated that if the site was within reasonable distance from the project site, the operator would include delivery of the material in the cost of beneficial reuse.

3.4.1.8 Landfills

Various landfill sites were contacted throughout North Carolina. These facilities were found using the NCDEQ website. Operators at these landfill sites were surveyed to find a range of costs at which the residual material would be accepted at the facilities. In order to accurately identify the costs, the sites were split up based on regional location within the state and type of facility. The costs varied based on the type of landfill facility. Also, it was found that the material had different measures of acceptance based on the type of facility. For example if there was any metal or dirt mixed in with the residual solid material, most LCID landfill facilities would no longer accept the material as an inert debris. LCID facilitates had the most stringent rules, followed by C&D, and lastly MSW facilities. All facilities stated that the residual material must be brought to the site by and at the expense of the contractor. This means that the user will have to determine a method for transporting the residuals from the job site to the disposal site.

3.4.1.9 North Carolina Office of State Human Resources

The North Carolina Office of State Human Resources (NCOSHR, 2014) website was used to determine the cost of hiring a Class III vehicle operator. This is most likely the operator that would be doing the hauling of the residual material from the jobsite to the disposal/reuse site, since driving a large vehicle requires special licensing and additional skills. The NCOSHR website provided the operators salary, which was divided by (2000 hours * 40 miles per hour) to determine a figure for dollars per mile. This operator cost was used for the delivery operator for the liquid and solid residuals.

3.4.1.10 Environmental Consultants

Selected North Carolina environmental consultants were contacted to discuss the methods and payment options for testing the pH, free liquids in the solid residual material, and a TCLP. NCDOT states that if the residual solids are to be buried, a representative TCLP test will be performed. It was found that many of the contractors would hire outside environmental consultants to come to the job site to do the pH, Paint Filter tests, and a TCLP test if necessary in order to stay within permit compliance, as well as to shift the risk. The consultants provided an average cost for coming to the job site, performing the necessary tests, and recording the results of that test in a way that can be handed down the chain of custody to the final receiving location of the residuals.

3.5 Risk Assessment

For each method of handling slurry, liquids, and solids, there are specific risks involved. These risks have been defined by North Carolina General Statutes, EPA regulations, and from conversations with experienced contractors. The contractors were asked to provide the method of disposal/reuse they were familiar with, and to provide the risks associated with those methods. The risks were then put together to provide a set of risks available for each unique option for disposal/reuse. This was used in conjunction with the RAHP to provide a score for including associated risks with each option so that cost is not the only factor being evaluated.

These risks were identified in order to focus on minimizing risks in future work. The risks identified were concerns that were unforeseen to the contractors at the time of the bid, and could cost them more money than anticipated in the form of chain orders or additional disposal costs. The set of risks are to be scored by the contractors for each choice. The score and the weight of importance will give the overall Risk Assessment for each unique method of disposal/reuse.

3.6 Environmental Benefits

Each combination of reuse/disposal methods has its own associated environmental benefits. Benefits were determined from conversations with contractors, state statutes/regulations, and various research available on the subject. The benefits were then put together to provide a set of benefits available for each unique option for disposal/reuse. The set of benefits are to be scored by the contractors for each choice. The score and the weight of importance will give the overall Environmental Benefit for each unique method of disposal/reuse. In the end, the environmental benefit score will be used in conjunction with costs and risks to find the contractor's most preferred method of disposal/reuse.

The environmental benefits were gathered to give the user the option to select the level of environmental benefit that they were willing to tolerate. The user can maximize the environmental benefit of their chosen option.

3.7 Cost Benefit Model Options

The costs, risks, and environmental benefits were collects for each specific portion of residual management so that they could be directly compared to one another. The tool will allow the user to measure cost, risk, and environmental benefit for the 20 total options of residual management available to the user. Based on the user's opinion of the importance of the 3 indicators, (cost, risk, and environmental benefit), the model will rank the 20 available options in a way that reflects the user's opinion. This allows the user to select the best option not only based on cost, but also accounting for the options that are the most environmentally friendly and least risk averse, based on those factors that are most important to them. The available options can be seen in Table 1.

TABLE 1: Available options of disposal/reuse combinations

Option #	Slurry Handling Method	Liquid Management Method	Solid Management Method
1	(A) Decanting Pond	(A) POTW/WWTP	(A) MSW
2	(A) Decanting Pond	(A) POTW/WWTP	(B) C&D
3	(A) Decanting Pond	(A) POTW/WWTP	(C) LCID
4	(A) Decanting Pond	(A) POTW/WWTP	(D) Beneficial Fill (onsite)
5	(A) Decanting Pond	(A) POTW/WWTP	(E) Beneficial Fill (offsite)
6	(A) Decanting Pond	(B) Land Application	(A) MSW
7	(A) Decanting Pond	(B) Land Application	(B) C&D
8	(A) Decanting Pond	(B) Land Application	(C) LCID
9	(A) Decanting Pond	(B) Land Application	(D) Beneficial Fill (onsite)
10	(A) Decanting Pond	(B) Land Application	(E) Beneficial Fill (offsite)
11	(B) Frac Tank	(A) POTW/WWTP	(A) MSW
12	(B) Frac Tank	(A) POTW/WWTP	(B) C&D
13	(B) Frac Tank	(A) POTW/WWTP	(C) LCID
14	(B) Frac Tank	(A) POTW/WWTP	(D) Beneficial Fill (onsite)
15	(B) Frac Tank	(A) POTW/WWTP	(E) Beneficial Fill (offsite)
16	(B) Frac Tank	(B) Land Application	(A) MSW
17	(B) Frac Tank	(B) Land Application	(B) C&D
18	(B) Frac Tank	(B) Land Application	(C) LCID
19	(B) Frac Tank	(B) Land Application	(D) Beneficial Fill (onsite)
20	(B) Frac Tank	(B) Land Application	(E) Beneficial Fill (offsite)

3.8 Model Validation

In order to test the validity of the CBA model created for this project, the team consulted various members of the NCDOT and industry professionals that are familiar with the processes being described in this thesis. The meeting was with consultant who had previously worked in industry doing consulting work in regards to the concrete residuals generated from diamond grinding, grooving, and hydrodemolition and had previously worked closely with the NCDOT to create a permit used to describe the proper methods for land application of the residuals as well as the proper methods for which the residuals liquid water could be reclaimed and reused.

During that meeting, the team walked through the model step by step with the industry professional, discussing the sources of the cost data used to develop the model. The 20 possible combinations for disposal and reuse were explained to the consultant, as well as the methodology for the information collection and sources of the cost data for all the processes were gathered. The industry professional was then asked to review and validate the risks as environmental benefits involved with each process. The industry professional thought that all of the included risks and benefits were well beyond what would be considered in the industry, however they agreed with giving the contractor the ability to rank each disposal/reuse combination in terms of risks and environmental benefits. The industry professional also agreed with the overall ability of the contractor to weigh which of the 3 categories (risk, cost, and environmental benefit) was most important to them. This addition to the model lets the user decide what is most important to them, and to let whatever percentage of weight that they had designated to that category make the decision of which disposal/reuse combination to choose. The industry professional also indicated that he thought it was beneficial that the model did not just choose which option was the best, so that if the highest ranking method was not available to the user for whatever reason, the user would then be able to go down the line and choose the next available option that was both available and favorable.

The industry professional did however raise some concerns about the model. The main concern was centered on the cost of the land application. The industry professional stated that while the costs for land application appeared to be on the high end of the range, based on their previous experience, these figures were still within a realistic range for estimation. This was taken into consideration by the research team and more land application sites were contacted to discuss their pricing, however since many of the land application contractors were not willing to discuss their price, only a limited amount of research was gathered on this topic. As land application is utilized in future projects, additional cost data and other information may become available to supplement the model.

A subsequent meeting with NCDOT personnel occurred in order to share the model, and the various results gathered from the research. The NCDOT professionals agreed with the framework of the model and the considerations that were taken in regards to risks and environmental benefits. The NCDOT professional also appreciated the level of detail gathered when researching the cost items associated with the work. However, NCDOT personnel thought that this level of detail may result in the model being considered fairly complex for use by industry stakeholders. The research team acknowledged and generally agreed with these concerns. The research team also explained to NCDOT that the industry tool that would eventually be created could be customizable for the user to estimate their costs, reducing the complexity of the model.

The NCDOT professional also had similar concerns to the pervious industry professional reviewing the model with the cost figures displayed with the land application sites. The research team explained to the NCDOT professional that this was because the only data could be presented was data that was actually gathered, and that if a land application site did not feel comfortable sharing their cost data with the research team, then that data could not be estimated.

The model appeared to have been viewed favorably by the parties that had tested its validity. The model was viewed as reasonably accurate in terms of costs, risks, and environmental benefit. The addition of more land application sites reporting their cost could allow for a model that is more accurate. However, unless that information is provided by the land application site managers, or the NCDOT, that information will remain as reported based on the information that was gathered.

CHAPTER 4: COST BENEFIT ANALYSIS (CBA) MODEL

In this section, the creation of the cost benefit analysis model is explained. The collected information used in the creation of the probability distribution functions are shown in in Appendix C. The model that was created using the following data that was gathered from various sources. This chapter will show the various parts of the model and the ways in which these line items are calculated.

4.1 Residual Disposal and Reuse Options

The scope of this project was to address the collection, containment, management, handling, transportation, and disposal/reuse options for the residual liquids and solids. This led to identifying the cost items associated with each activity, finding a range of costs for each cost item, and assembling them to create a model for estimating the costs associated with the management of those residuals.

4.2 Cost Estimator Background

A major part of the CBA model included creation of a tool to be used by contractors that could be used to better estimate costs. This portion of the tool is referred to as the cost estimator. The cost estimator evaluated all the previously stated methods of disposal and reuse from the generation of the slurry, to the disposal/reuse of the liquid, to finally the disposal/reuse of the solids. The cost estimator uses a range of values for many different variables to create a simulation that can compare each method of disposal/reuse for the same activity. This allows the user to see all the possible costs before selecting the chosen method.

4.2.1 Probability Distribution Functions Affecting Cost Data

The data gathered was utilized to generate a probability distribution function (PDF) in order to produce a model that would vary based on realistic expectations of actually performing the work:

- Slurry Generation Rates
- Solid Disposal Costs
- Percent Solids
- Liquid Disposal Costs

4.2.2 Slurry Generation

Information was gathered from various contacts from IGGA members as well as contacts provided by NCDOT based on a list of the contractors that had worked in North Carolina. These contractors were contacted to identify the various levels of slurry generation experienced in past work. The general size of the grinding/grooving/hydrodemolition machine head was four feet, and data was gathered to find the speed, in feet per minute, at which the machine advanced. Slurry generation rates, in gallons per minute, were also determined. This information was compiled to develop a figure in gallons of slurry per square yardage from each of the contractors.

4.2.2.1 Diamond Grinding Slurry Generation

Data was collected from eight grinding contractors on the generation of slurry, in gallons per square yards grinded. Data was given in the form of a range due to the many variables that can affect actual slurry generation. The data ranged from a low of 2 gallons per square yard to a high of 7 gallons per square yard with an average value of 4.22 gallons per square yard. Since a small number of contractors perform this work and the response rate was relatively low, a triangular distribution was chosen. The minimum value was set at 2, the maximum value was set at 7, and the average/mostly likely value was set at 4. The 4 gallons per square yard figure was chosen as opposed to the 4.22 gallons per square yard figure because the data was more skewed toward the lower end of the distribution. The distribution can be seen in Figure 22.

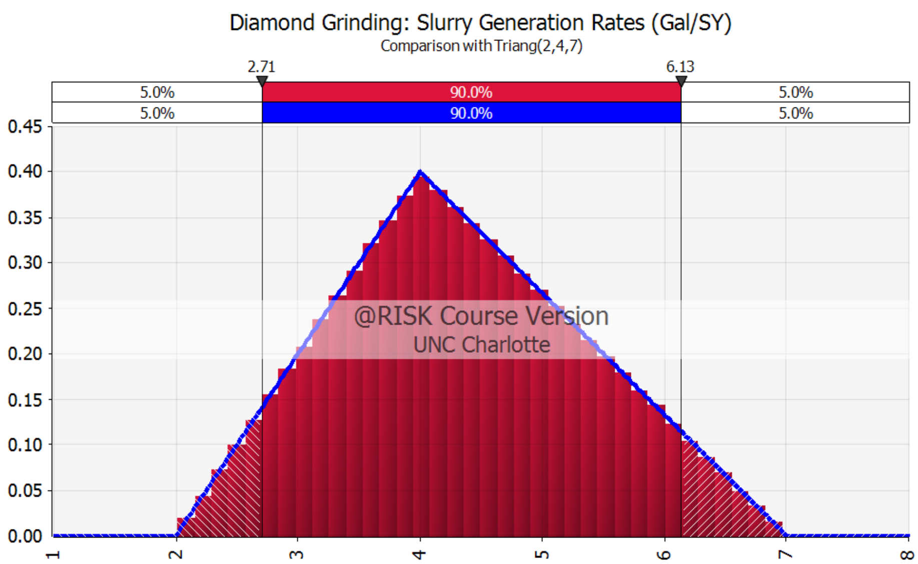


FIGURE 23: Grinding slurry generation PDF

4.2.2.2 Diamond Grooving Slurry Generation

Data was collected from 4 different grooving contractors in regards to slurry generation, in gallons per square yards grooved. The data ranged from a low of 0.47 gallons per square yard to a high of 1.8 gallons per square yard with an average value of 0.9. Since there were a small number of responses, a triangular distribution was used. The minimum value was set at 0.5, the maximum value was set at 1.8, and the most likely value was set at 0.7. The 0.7 gallons per square yard figure was chosen over the mean value of 0.9 gallons per square yard because the data was more skewed to the lower end of the range. The distribution can be seen in Figure 23.

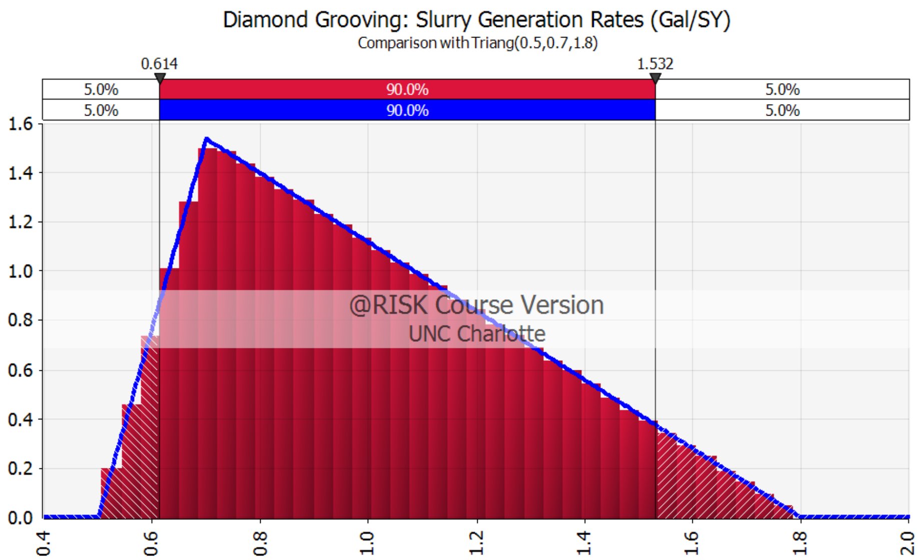


FIGURE 24: Grooving slurry generation PDF

4.2.2.3 Hydrodemolition Slurry Generation

Data was collected from one hydrodemolition company that had performed most of the hydrodemolition work for NCDOT project requiring hydrodemolition over the past 4 years. Although highly active in the North Carolina market, this company had also performed similar work in other states along the east coast of the United States. The company provided a range of slurry generation values, as well as a most likely value for slurry generated during the hydrodemolition activities. The data ranged from a low of 10 gallons per square yard to a high of 18 gallons per square yard, with an average of 14 gallons per square yard. Because the limited amount of information available in this category, a triangular distribution was chosen. The minimum value was set at 10, the maximum was set at 18, and the most likely value was set at 14. The distribution can be seen in Figure 24.

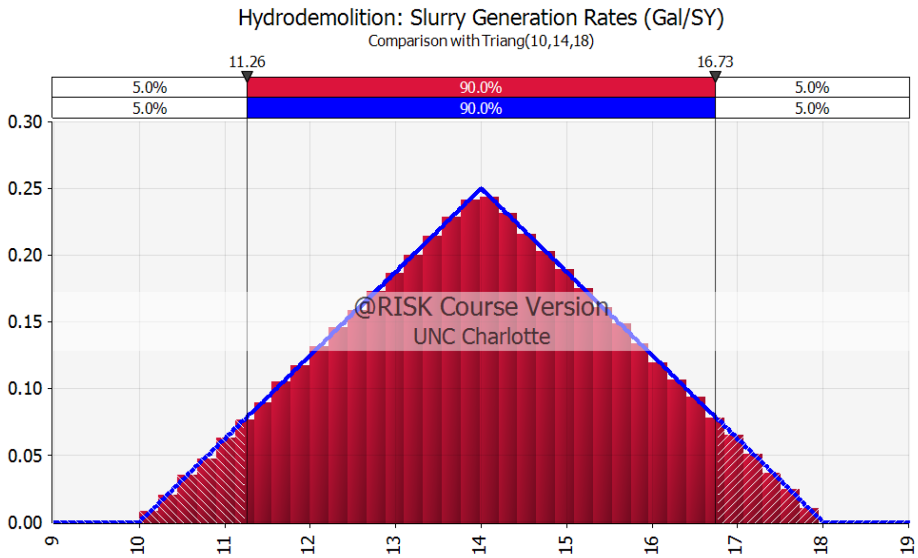


FIGURE 25: Hydrodemolition slurry generation PDF

4.2.3 Solid Disposal Costs

The NCDEQ website was used to find the location, name, and function of various facilities throughout North Carolina. These facilities were contacted to determine whether or not they would take the solid residual material, under what circumstances they would not take the material, the manner in which the solids were to be delivered, and finally the cost at which the facility would accept the material. Three PDF's were developed based on the regional location of the facility; Mountain, Piedmont, or Coastal, and the type of receiving landfill; LCID, MSW, or C&D.

4.2.3.1 Piedmont Region

There were a total of 108 facilities contacted throughout the Piedmont region of North Carolina, 65 of which responded back with information to support the model. This information was used to establish price points for disposal of the solid residual material, in dollars per ton of material.

4.2.3.1.1 Piedmont - LCID Landfill

There were a total of 46 LCID landfill facilities contacted in the Piedmont region, from which the research team obtained a total of 20 responses. The responses were normalized to reflect only those facilities that established a price for the solid material to be disposed per ton. The data ranged from a low of $0 per ton to a high of $46 per ton, with an average of $11.05 per ton. Since there was a large concentration of data towards the low end of the pricing, a triangular distribution was chosen to represent the data. The minimum value was set at $0, the maximum value was set at $46, and the most likely value was set at $0 since nine of the twenty total data points represented $0 per ton of material. Many of the facilities that were taking the material for free were using it in their road bases onsite or as an alternate daily cover material at their landfills. The distribution can be seen in Figure 25.

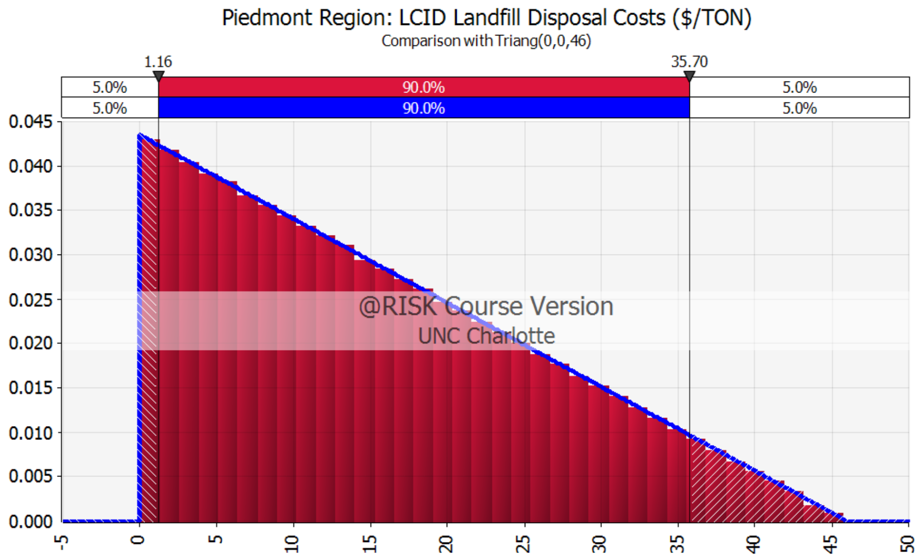


FIGURE 26: Piedmont LCID landfill price for disposal PDF

4.2.3.1.2 Piedmont – MSW Landfill

There was a total of 26 MSW landfill facilities contacted within the Piedmont region, with a total of 8 responses received. The data ranged from a low of $22 per ton to a high of $41 per ton, with an average value of $32.05 per ton. Because the limited amount of information available in this category, a triangular distribution was chosen. The minimum value was set at $22, the maximum value was set at $41, and the most likely value was set at $34.08. This value was used instead of the average since there was a large concentration of values in the middle, and the best estimate of a most likely value was found by averaging the clustered values together, which was $34.08. The distribution can be seen in Figure 26.

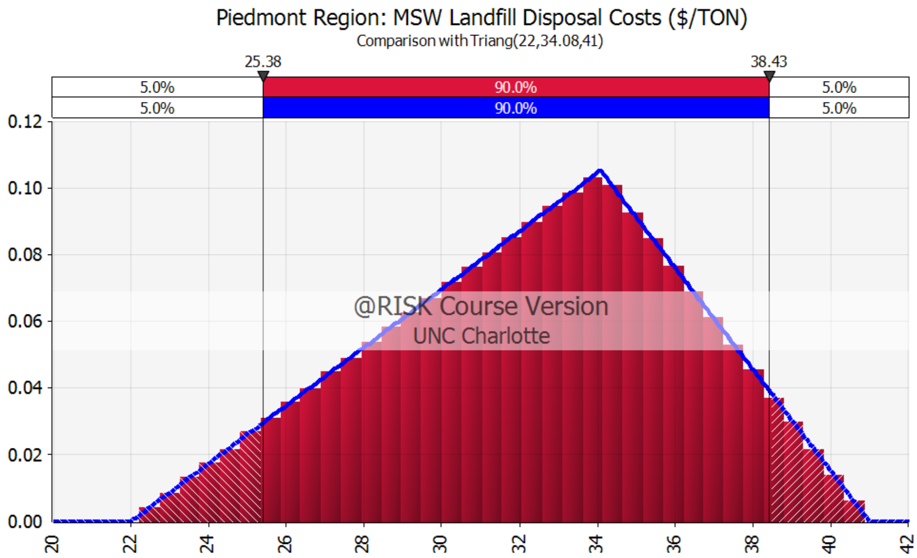


FIGURE 27: Piedmont MSW landfill price for disposal PDF

4.2.3.1.3 Piedmont – C&D Landfill

A total of 36 C&D landfill facilities from within the Piedmont region were contacted, with a total of 20 responses received. The data ranged from a low of $5 per ton to a high of $46 per ton, with an average of $30.7 per ton. The cost data was evenly distributed, and there were enough data points to produce a normal distribution. The normal distribution was created using the average of $30.7 per ton, with a standard deviation of $9.51 per ton. The distribution can be seen in Figure 27.

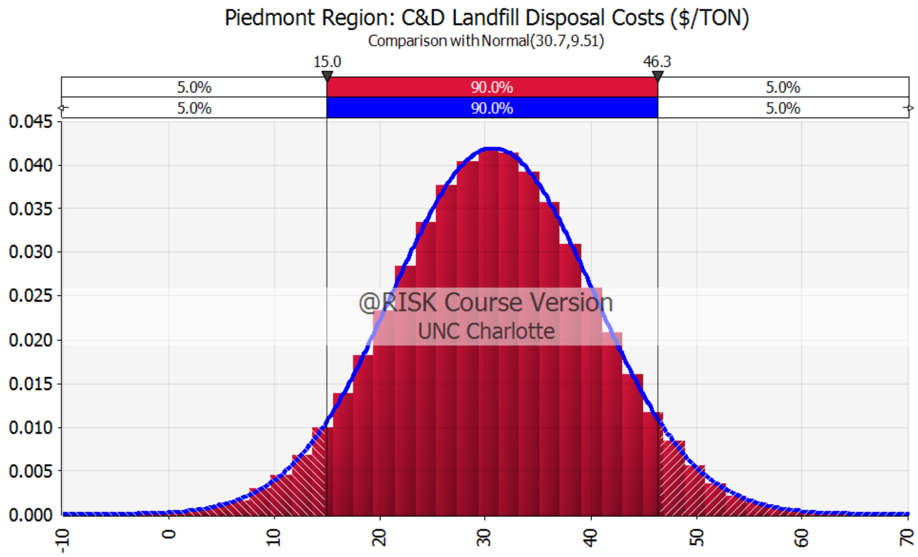


FIGURE 28: Piedmont C&D landfill price for disposal PDF

4.2.3.2 Coastal Region

There were a total of 31 facilities contacted throughout the Coastal region of North Carolina, of which 22 responded back with information to support development of the model. This information was used to establish price points for disposal of the solid residual material, in dollars per ton.

4.2.3.2.1 Coastal Region – LCID Landfill

There were a total of 16 LCID landfill facilities contacted from within the Coastal Region, and a total of 11 responses were received. The data ranged from a low of $0 per ton to a high of $65 per ton, with an average of $17.1 per ton. Because the limited amount of information available in this category, a triangular distribution was chosen for use in the model. The minimum value was set at $0, the maximum value was set at $65, and the most likely value was set at $0, due to the majority, 4, of facilities taking the solid residual material for free. The distribution can be seen in Figure 28.

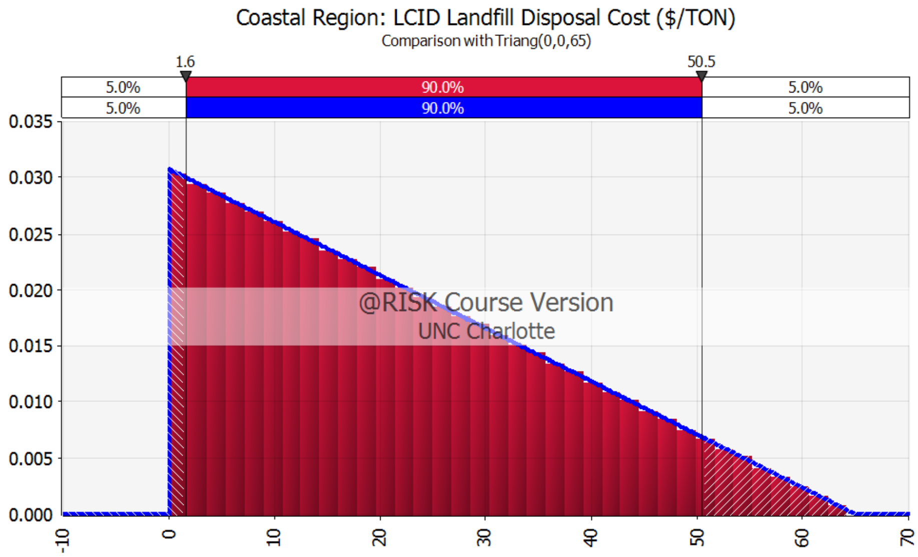


FIGURE 29: Coastal LCID landfill price for disposal PDF

4.2.3.2.2 Coastal Region – MSW Landfill

There were a total of 6 MSW landfill facilities contacted within the Coastal Region, with a total of 3 responses received. The data ranged from a low of $7 per ton to a high of $40 per ton, with an average of $28.7 per ton. Because the limited amount of information available in this category, a triangular distribution was chosen. The minimum value was set at $7, the maximum was set at $40, and the most likely value was set at $28.7. The distribution can be seen in Figure 29.

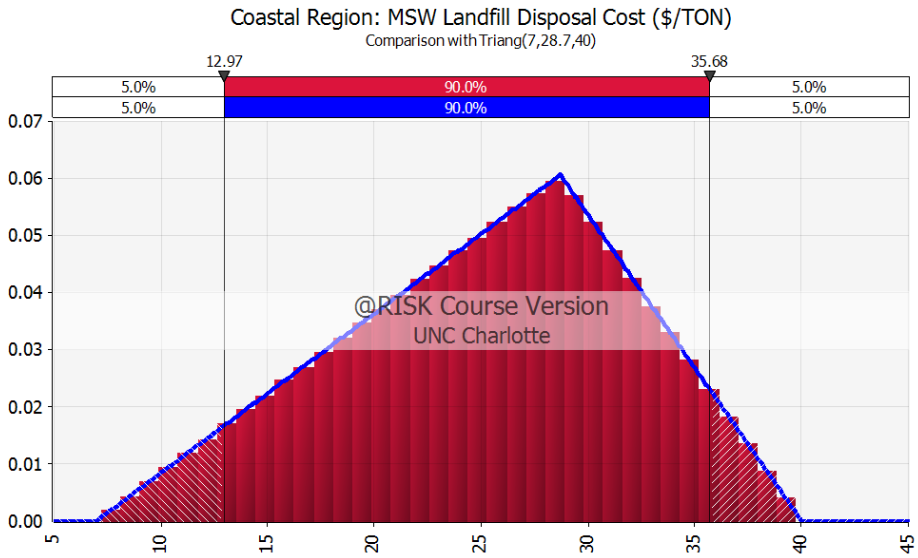


FIGURE 30: Costal MSW landfill price for disposal PDF

4.2.3.2.3 Coastal Region – C&D Landfill

A total of 9 C&D landfill facilities were contacted within the coastal region, with a total of 8 responses received. The data ranged from a low of $34 dollars per ton to a high of $68 dollars per ton, with an average of $49.1 dollars per ton. Because the limited amount of information available in this category, a triangular distribution was chosen. The minimum value was set at $34, the maximum value was set at $68, and the most likely value was set at $48; which was the average of the middle cluster of values. The distribution can be seen in Figure 30.

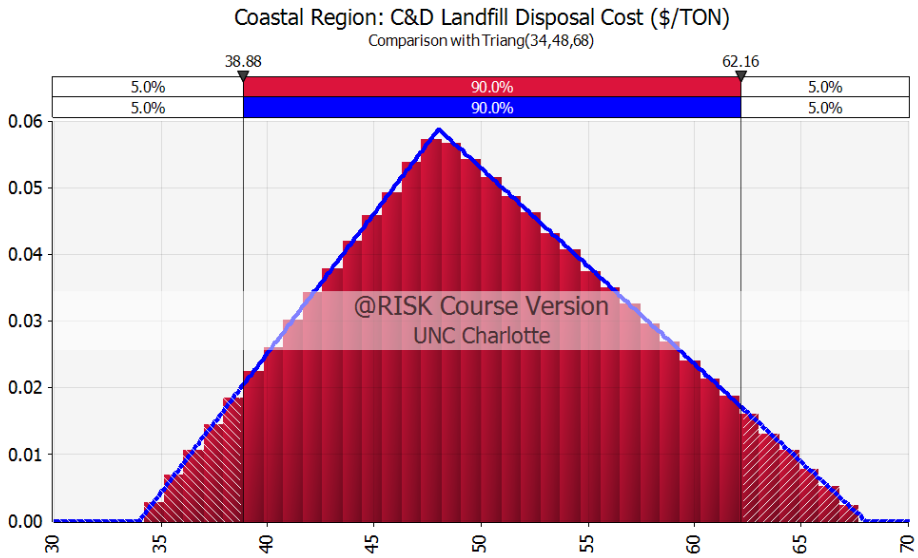


FIGURE 31: Costal C&D landfill price for disposal PDF

4.2.3.3 Mountain Region

A total of 25 facilities throughout the Mountain region of North Carolina were contacted, 16 of which responded back with information. This information was used to establish price points for disposal of the solid residual material, in dollars per ton.

4.2.3.3.1 Mountain Region – LCID Landfill

There were a total of 9 LCID landfill facilities contacted within the mountain region, and a total of 6 responses were received. The data ranged from a low of $0 per ton to a high of $42 per ton with an average of $17 per ton. Due to the limited amount of information available in this category, a triangular distribution was chosen. The minimum value was set at $0, the maximum value was set at $42, and the most likely value was the same as the average, $17 per ton. The distribution can be seen in Figure 31.

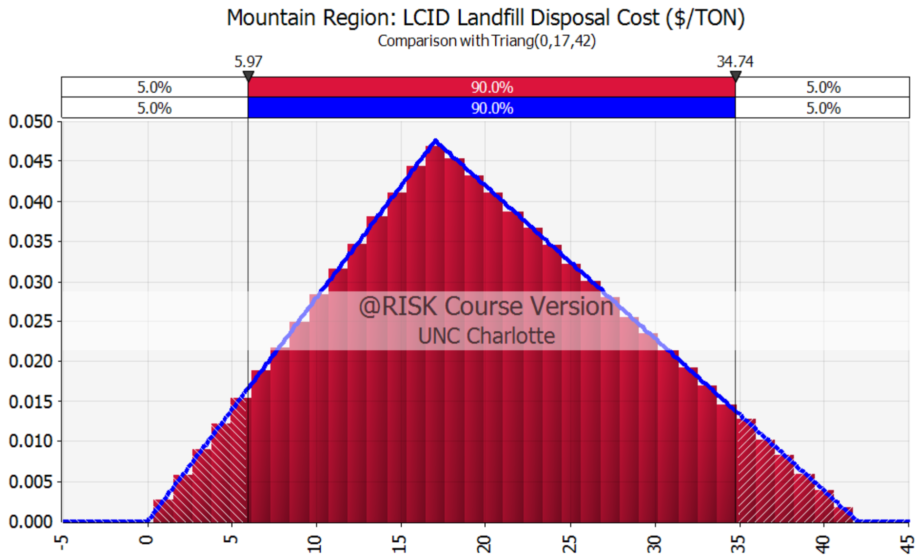


FIGURE 32: Mountain LCID landfill price for disposal PDF

4.2.3.3.2. Mountain Region – MSW Landfill

A total 10 of MSW landfill facilities within the mountain region were contracted, and a total of 6 responses were received. The data ranged from a low of $43 per ton, to a high of $67 per ton, with an average of $54.7 per ton. Because the limited amount of information available in this category, a triangular distribution was chosen. The minimum value was set at $43, the maximum value was set at $67, and the most likely value was set at $57. The most likely value of $57 was chosen because it was the average of the center clustered data, both of which happened to be $57 dollars per ton. The distribution can be seen in Figure 32.

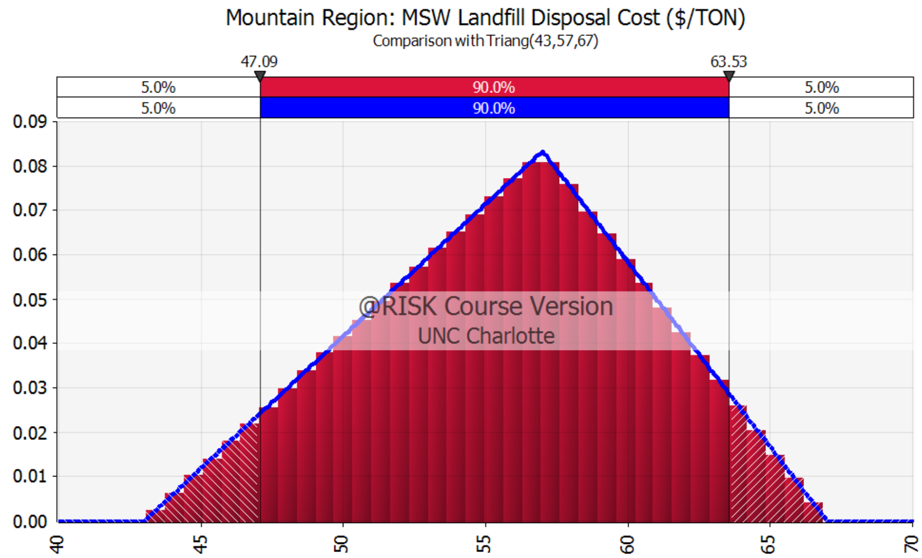


FIGURE 33: Mountain MSW landfill price for disposal PDF

4.2.3.3.3 Mountain Region C&D Landfill

There were a total of 5 C&D landfill facilities contacted within the mountain region, and a total of 3 responses were received. The data ranged from a low of $31 per ton to a high of $57 per ton with an average of $46.7 per ton. Due to the limited amount of information available in this category, a triangular distribution was chosen. The minimum value for the distribution was set at $31, the maximum value was set at $57, and the most likely value was set at $46.7, the same value was the average. The distribution can be seen in Figure 33.

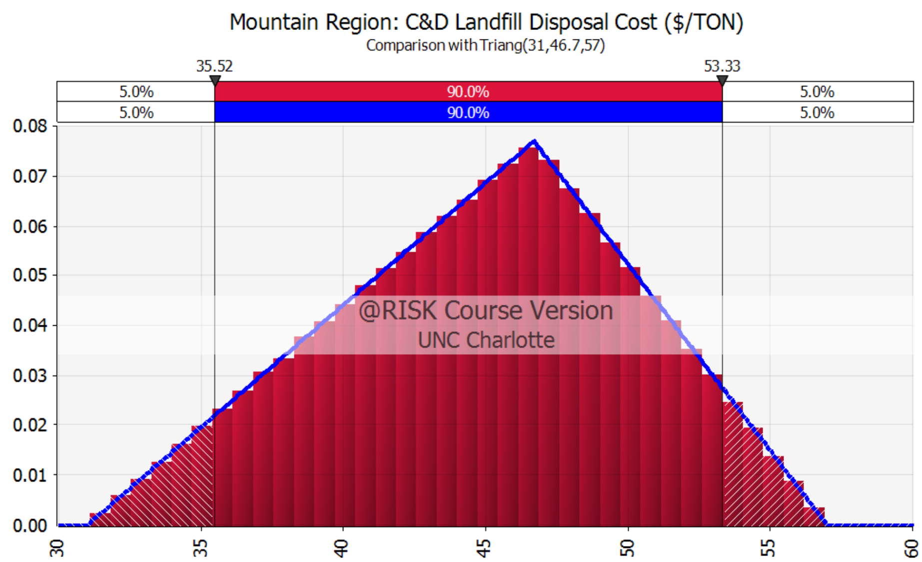


FIGURE 34: Mountain C&D landfill price for disposal PDF

4.2.4 Percent Solids

The quantity of solid material in the given slurry is based on the percent solids that makes up the structure of the residual material. The percent solids varied depending on the given construction operation.

4.2.4.1 Percent Solids Grinding

The data was given by the grinding contractors that were contacted from IGGA members. The low value was set at 20%, the high value was set at 33.3%, and the average value was 30%. A triangular distribution was chosen to depict this distribution. The minimum value was set at 20%, the maximum value was set at 33.3%, and the most likely value was set at 32.5%. This value was chosen because the low value was thought to be a rarer event based on the collected data. The skew was more towards the higher end of the distribution. The distribution can be seen in Figure 34.

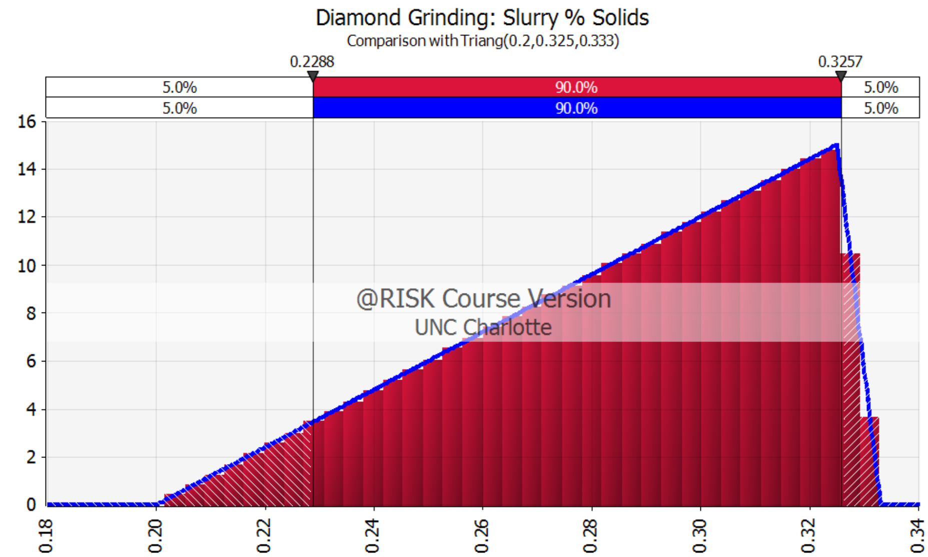


FIGURE 35: Percent solids of grinding residual slurry

4.2.4.2 Percent Solids Grooving

The data was given by the grinding contractors that were contacted from and IGGA members. The low value was set at 30%, the high value was set at 50%, and the average value was 40%. A triangular distribution was chosen to depict this distribution. The minimum value was set at 30%, the maximum value was set at 50%, and the most likely value was set at 40%. The distribution can be seen in Figure 35.

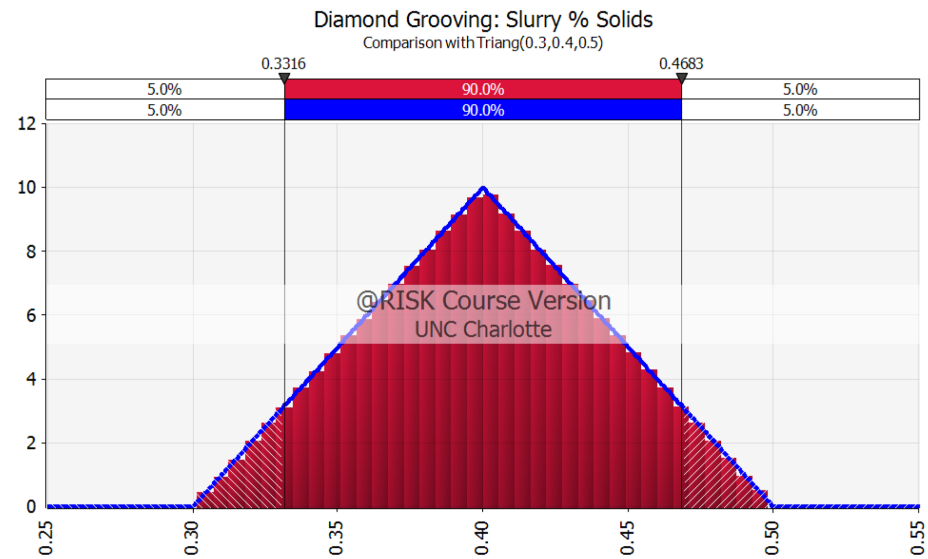


FIGURE 36: Percent solids of grooving residual slurry

4.2.4.3 Percent Solids Hydrodemolition

The information for percent solids resulting from the hydrodemolition process was gathered from the hydrodemolition contractor that is heavily active in the North Carolina (and east coast) marker, as discussed earlier. The hydrodemolition contractor was contacted and asked to provide a range for the percent of solids that make up the residual slurry material. The low value was 5%, the high value was 15%, and the average was 10%. A minimum value was set at 5%, the maximum value was set at 15%, and the most likely value was set at 10%. The distribution can be seen in Figure 36.

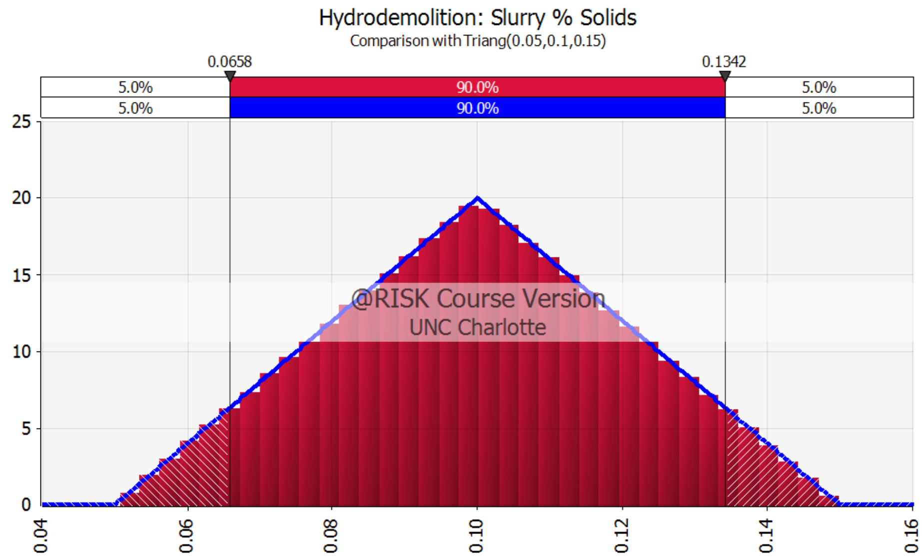


FIGURE 37: Percent solids of hydrodemolition residual slurry

4.2.5 WWTP/POTW Liquid Disposal Costs

WWTP and POTW's that would accept residuals are not as prevalent throughout North Carolina as are landfills willing to accept residuals. Additionally these facilities are not distributed based on region. The data was gathered from the NCDEQ website based on the facilities that will accept materials from contractors. There were a total of 42 facilities contacted throughout the state, and only a total of 12 responses were received. The data ranged from a low of $0.013 per gallon of liquid material received to a high of $0.10 per gallon received. Since there was a fairly even distribution throughout the range of gathered data, a normal distribution was used. The average value was $0.0475 per gallon of accepted material with a standard deviation $.02519. The distribution can be seen in Figure 37.

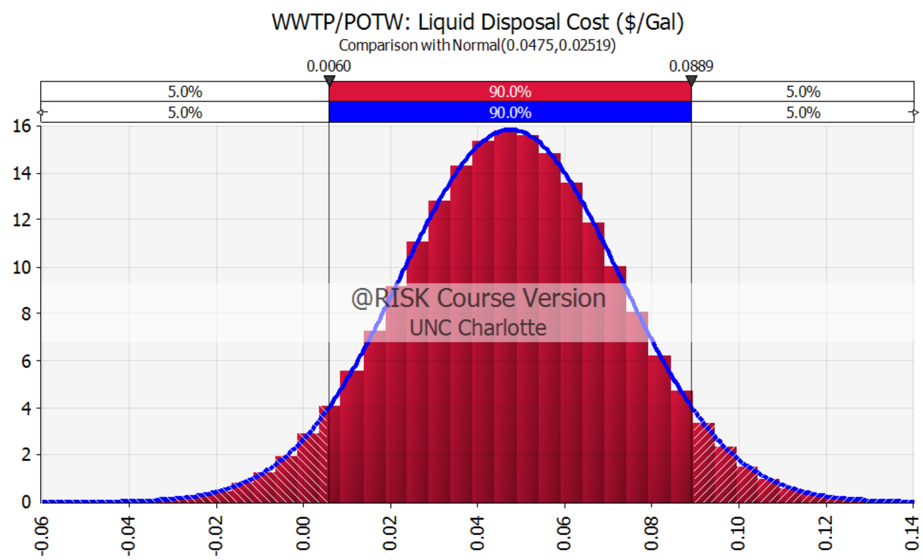


FIGURE 38: Disposal costs at WWTP/POTW throughout North Carolina

4.3 Cost Estimator Design

The spreadsheet was created using a combination of Microsoft Excel and Palisade @Risk 6. The information gathered from the interviews was placed into the spreadsheet to create a model that could be used by a contractor to accurately predict their costs based on industry standard wages, and user inputs based on past experience. The cells in the spreadsheet are highlighted in various colors to represent how that cell will work. The cells that are highlighted in green represent a cell that the user will have to make a selection. The user chooses between preselected options that will define their options further. The cells that are highlighted in blue represent a cell that the user will have to make an input. The user will input quantities and costs that are unique to the project and are based on the contractors experience or preference. This allows the user to maintain a more customized experience while using the cost estimator. The cells that are highlighted in red represent a cell that has been calculated by the model based on user selections and inputs. This allows the user to see the costs or quantities associated with the inputs and selections that they have made in the model.

4.3.1 Assumptions

In the development and evaluation of the spreadsheet, assumptions were required in order to compare the construction operations and their various costs in the same terms to have a realistic and relative comparison. The chosen area to be grinded, grooved, or hydrodemolished was chosen to be 10,000 square yards. This was chosen so there could be a sample with a large enough area to produce a significant amount of residuals.

The construction of the decanting pond, common earth was the selected earth type. The equipment used to excavate the decanting pond was assumed to be the wheel mounted hydraulic excavator with capacity of 0.75 cubic yards, and wheel mounted front-end loader with capacity of 0.75 cubic yards. It was assumed that the equipment would be used at the same time, and would require 2 operators and 2 laborers. For simplicity purposes and based on contractor recommendations, the height of the excavation was chosen to be three feet, or 1 yard. The equipment chosen for backfilling the excavation was assumed to be the same wheel mounted front end loader with capacity of 0.75 cubic yards. This was assumed because it is the same piece of equipment used in the excavation and would therefore already be on site. Lastly the compaction equipment chosen for the comparison was a ride-on sheepsfoot roller, using 12 inch lifts, and making 2 passes.

For the estimation of the Frac tank, it was assumed that the distance from the supplier to the jobsite was 50 miles. The tanks were estimated to be kept for 28 days, or 1 cycle according to the supplier.

For the estimation of the liquid disposal, a 4000 gallon truck attachment was chosen in order to minimize the amount of trips that would have to be made. Minimizing the number of trips would result in a minimization of the cost of delivery of liquid residuals. It was assumed that the pH only needed to be tested once during the project by an environmental consultant. Lastly, it was assumed that the distance from the supplier to the jobsite was 50 miles, for consistency purposes.

It was assumed that during the project, an environmental consultant would only be required to run the paint filter test once, and TCLP once if necessary. For disposal of solids, it was assumed that there would only be one truck making multiple trips with the solid residuals. The truck making those trips was assumed to have a capacity of 10 cubic yards. Lastly, the distance to the disposal facility/reuse location was assumed to be 50 miles for consistency.

4.3.2 Project Information

This section of the Cost-Benefit Model was created so that the user could input very preliminary information to gather details for what would be in store and what they would need to be plan for.

4.3.2.1 Project Information – User Selections

First the user selects the type of construction operation planned, either hydrodemolition, diamond grinding, or diamond grooving. All of these construction operations have different quantities associated with the operations and therefore it was important to differentiate which activity is to be used. Then the user selects the region in which the work is planned. The region affects the cost of disposal for the residuals, as well as limits the contractor in terms of disposal facilities choices.

4.3.2.2 Project Information – User Inputs

The user inputs the square yardage of pavement to be included in the operations into the model. This input value affects the quantity of residuals produced during the project. The larger the area to be grinded/grooved/hydrodemolished, the larger quantity of residuals for the contractor to manage.

4.3.2.3 Project Information - Outputs

Based on the type of construction to be performed and the size (or extent) of the construction area, the model estimates the quantity of slurry to be generated in gallons, expected quantity of solid residuals to be generated, in both tons and cubic yards, and expected liquid residuals generated in gallons. This is important for selecting which type of slurry handling option that the user may select based on the costs of each management method. An example from the spreadsheet can be seen in Figure 38.

	Diamond Grinding
	Project Information
North Carolina Region	Mountain
Area of Operation (SY)	10000
Slurry Generated (Gal)	43333
Volume of Solid Residuals (CY)	61
Weight of Solid Residuals (Tons)	124
Volume of Liquid Residuals (Gal)	30940

FIGURE 39: Project information portion of the CBA model

The Equations used to calculate the project information outputs can be seen below.

$$Slurry\ Gen = Area\ \times SGR \quad \text{(Eq. 4.1)}$$

Where,

- Slurry Gen. = Quantity of Slurry Generated (gallons)
- Area = Area of Pavement to Grind (square yards)

- SGR = Rate at which Slurry is Generated from Grinding (gallons/square yard)

$$Vol. Solids = Slurry\ Gen. \times \left(\frac{1\ CY}{201.974\ Gallons}\right) \times \%Solids \qquad \text{(Eq. 4.2)}$$

Where,

- Vol. Solids = Quantity of Solids Residuals Produced (cubic yards)
- Slurry Gen. = Quantity of Slurry Generated (gallons)
- % Solids = Percentage of Solids in Residual Slurry

$$Wt. Solids = Vol. Solids \times 150 \frac{lbs}{ft^3} \times 27 \frac{ft^3}{yd^3} \times \frac{1\ Ton}{2000\ lbs} \qquad \text{(Eq. 4.3)}$$

Where,

- Wt. Solids = Quantity of Solids Residuals Produced (tons)
- Vol. Solids = Quantity of Solids Residuals Produced (cubic yards)

$$Liquid\ Vol. = Slurry\ Gen. \times (1 - \%Solids) \qquad \text{(Eq. 4.4)}$$

Where,

- Liquid Vol. = Quantity of Liquid Residual Produced (gallons)
- Slurry Gen. = Quantity of Slurry Generated (gallons)
- % Solids = Percentage of Solids in Residual Slurry

4.3.3 Phase I – Slurry Handling Method

Phase I consists of two methods for handling slurry generated from these operations. The user will choose between creating a decanting pond on site to hold the slurry that has been generated, or to rent Frac and liquid holding tanks to deposit the slurry into for separation and management.

4.3.3.1 Option A - Decanting Pond

Option A involves the creation of a decanting pond built on site to deposit slurry from grinding/grooving/hydrodemolition operations into. This phase is split up into four different operations that will affect the overall price of construction. These operations are:

- Excavation,
- Geosynthetic Layering,
- Backfilling, and
- Compaction.

4.3.3.1.1 Decanting Pond – Excavation

The first item considered by the user is the size of the planned excavation. Caltrans (2004) states that the decanting ponds being built for the purpose of handling slurry from concrete operations are not to exceed 75% capacity, which resulted in a safety factor of 1.33 to be included when sizing the decanting pond.

4.3.3.1.1.1 Decanting Pond – Excavation – User Selection

The first selection that the user will make is based on the type of earth they are excavating. The choices are:

- Common Earth and
- Sandy Clay & Loam

The user then chooses the type of equipment they plan to use to excavate. Each piece of equipment has multiple choices for capacity, hourly cost, and output. The user selects which excavator and which loader to be used on the site. The choices are:

- Hydraulic Excavator

    - Crawler Mounted
        - 1 CY,
        - 1.5 CY,
        - 2 CY,
        - 3 CY, and
        - 3.5 CY.
    - Wheel Mounted
        - 0.5 CY and
        - 0.75 CY
- Front-end Loader
    - Track Mounted
        - 1.5 CY,
        - 2.5 CY,
        - 3 CY, and
        - 5 CY.
    - Wheel Mounted
        - 0.75 CY,
        - 1.5 CY,
        - 2.25 CY,
        - 3 CY, and
        - 5 CY.

4.3.3.1.1.2 Decanting Pond – Excavation – User Input

Once the equipment selection has been chosen the user then inputs the quantity of excavators, loaders, operators, and laborers that will be needed to conduct the excavation work. RSMeans recommended that a crew consisting of a laborer and an operator be used. However in the model the user is allowed to select the quantity of laborers and operators that will be used onsite.

4.3.3.1.1.3 Decanting Pond – Excavation – Output

The model provides an output for the hourly rate for the equipment, the hourly output, the daily output, the amount of hours necessary to complete the estimated excavation, and the cost for the equipment based on these hourly rates. Once these inputs and choices have been selected, a total cost for the excavation will computed by the spreadsheet. The excavation portion of the spreadsheet can be seen in Figure 39.

Phase 1 - Slurry Handling & Management	
Slurry Handling Option	(A) Decanting Pond
Excavation Size (CY)	285.3502596
Earth Type	Common Earth
Excavator Type	Excavator Hydraulic, Wheel Mounted
Loader Type	Front end loader, Wheel Mounted
Excavator Capacity (CY)	0.75
Loader Capacity (CY)	0.75
Excavator Quantity (#)	1
Loader Quantity (#)	1
Excavator Hourly Rate ($/hr)	$ 52.16
Loader Hourly Rate ($/hr)	$ 14.96
Excavator Output (CY/hr)	60
Loader Output (CY/hr)	45
Excavator Output (CY/day)	480
Loader Output (CY/day)	360
Excavation Time (hr)	5
Excavation Equipment Cost ($)	$ 335.60
# Laborers	2
Excavation Labor Hourly Rate ($/hr)	$ 14.05
# Operators	2
Excavation Operator Hourly Rate ($/hr)	$ 21.68
Excavation Operator Cost ($)	$ 216.80
Excavation Labor Cost ($)	$ 140.50
Total Excavation Cost ($)	$ 692.90

FIGURE 40: Excavation of decanting pond in CBA model

The equations used to calculate the excavation portion of the decanting pond construction can be seen below.

$$Exc.Size \ = Vol.Solids \times \ F.S. \qquad \text{(Eq. 4.5)}$$

Where,

- Exc. Size = Size of Excavation to be completed (cubic yards)
- Vol. Solids = Quantity of Solids Residuals Produced (cubic yards)
- F.S. = Factor of Safety $\left(\frac{1}{0.75}\right)$

$$Exc.Time = \frac{Exc.Size}{Exc.Output} \qquad \text{(Eq. 4.6)}$$

Where,

- Exc. Time = Time to Complete Excavation (hours)
- Exc. Size = Size of Excavation to be completed (cubic yards)
- Exc. Output = Hourly Output of Excavator (cubic yards/hour)

$$EEC = EHR \times Exc.Time \qquad \text{(Eq. 4.7)}$$

Where,

- EEC = Total Cost of Excavation Equipment ($)
- EHR = Excavation Equipment Hourly Rate ($/hour)
- Exc. Time = Time to Complete Excavation (hours)

$$ELC = LHR \times Exc.Time \times \#L \qquad \text{(Eq. 4.8)}$$

Where,

- ELC = Total Cost of labor used during excavation ($)
- LHR = Labor Hourly Rate ($/hour)
- Exc. Time = Time to Complete Excavation (hours)
- #L = Number of Laborers Used for Excavation (#)

$$EOC = EOHR \times Exc.Time \times \#O \qquad \text{(Eq. 4.9)}$$

Where,

- EOC = Total Cost of Excavation Equipment Operators ($)
- EOHR = Excavation Equipment Operator Hourly Rate ($/hour)
- Exc. Time = Time to Complete Excavation (hours)
- #O = Number of Operators Used for Excavation (#)

$$TCE = EEC + ELC + EOC \qquad \text{(Eq. 4.10)}$$

Where,

- TCE = Total Cost of Excavation ($)

- EEC = Total Cost of Excavation Equipment ($)
- ELC = Total Cost of labor used during excavation ($)
- EOC = Total Cost of Excavation Equipment Operators ($)

4.3.3.1.2 Geosynthetic Layering

The second step in constructing the decanting pond is to layer the excavated area with a geosynthetic layer to keep the slurry from leaching out of the pond.

4.3.3.1.2.1 Geosynthetic Layering – User Inputs

RSMeans suggested that a crew of two laborers be used for this task, however the model allows the user to input the amount of laborers that they would like to use for the given layering operation. The area of the excavation is based on an excavation pond that is 1 yard deep. According to most of the contractors that were contacted, the shallower the pit is the better. A shallower pit will result in more residual liquids to be evaporated, which is less liquid that must be disposed of or beneficially reused. The spreadsheet also allows the user to input the price for the geosynthetic material. The geosynthetic layering portion of the spreadsheet can be seen in Figure 40.

Phase 1 - Slurry Handling & Management	
Geosynthetic Material Cost ($/SY)	0.58
Geosynthetic Layer Area (SY)	285.35
Geosynthetic Labor QTY (#)	2
Geosynthetic Labor Hourly Rate ($/hr)	$ 14.05
Geosynthetic Labor Productivity Rate (SY)	2500
Geosynthetic Layering Time (#)	1
Geosynthetic Material Cost ($)	$ 165.50
Geosynthetic Labor Cost ($)	$ 28.10
Total Geosynthetic Layering Cost ($)	$ 193.60

FIGURE 41: Geosynthetic layering of decanting pond in CBA model

The equations used to calculate the backfilling portion of the decanting pond construction can be seen below.

$$Exc.\,Area = \frac{Exc.\ Size}{Exc.Height} \qquad \text{(Eq. 4.11)}$$

(Note: Height of excavation assumed to be 1 yard)

Where,

- Exc. Area = Geosynthetic Layering Area (Square Yards)
- Exc. Size = Size of Excavation to be completed (Cubic Yards)
- Exc. Height = Height of Excavation (yards)

$$GLPR = 1250\frac{SY}{hr.} \times \#L \qquad \text{(Eq. 4.12)}$$

Where,

- GLPR = Geosynthetic Labor Productivity Rate (Square Yards/hour)
- #L = Number of Laborers Used for Geosynthetic Layering (#)

$$GLT = \frac{GLA}{GLPR} \qquad \text{(Eq. 4.13)}$$

Where,

- GLT = Time to Place Geosynthetic Layer (hours)
- GLA = Geosynthetic Layering Area (Square Yards)
- GLPR = Geosynthetic Labor Productivity Rate (Square Yards/hour)

$$GLC = GLHR \times GLT \times \#L \qquad \text{(Eq. 4.14)}$$

Where,

- GLC = Cost of Labor for Geosynthetic Layering ($)
- GLHR= Hourly Rate for Geosynthetic Laying Laborers ($/hour)
- GLT = Time to Place Geosynthetic Layer (hours)
- #L = Number of Laborers Used for Geosynthetic Layering (#)

$$GMC = GUC \times GLA \qquad \text{(Eq. 4.15)}$$

Where,

- GMC = Cost of Geosynthetic Materials ($)
- GUC = Unit Cost of Geosynthetic Material ($/Square Yard)
- GLA = Geosynthetic Layering Area (Square Yards)

$$TGC = GMC + GLC \qquad \text{(Eq. 4.16)}$$

Where,

- TGC = Total Cost of Geosynthetic Layering ($)
- GMC = Cost of Geosynthetic Materials ($)
- GLC = Cost of Labor for Geosynthetic Layering ($)

4.3.3.1.3 Backfilling

This portion of the decanting pond occurs when the liquid and solids have been taken out of the decanting pond. This section involves backfilling the excavated earth back into the emptied decanting pond. This phase is required by the state to bring the site conditions back to its previous conditions.

4.3.3.1.3.1 Backfilling – User Selection

The user is to select the type of earth that is to be placed into the excavation. The choices are:

- Common Earth,
- Select Granular Fill, and
- Clay, Till, or Blasted Rock

The user will then select the type of equipment to be used in this process. The choices are:

- Front-end Loader
  - Wheel Mounted
    - 0.75 CY,
    - 1.5 CY,
    - 3 CY, and
    - 5 CY.

4.3.3.1.3.2 Backfilling – User Inputs

Once these selections have been made, the user selects the quantity of front-end loading equipment and the amount of operators that they will use.

4.3.3.1.3.3 Backfilling – Outputs

Once the user selections and inputs have been made, the spreadsheet calculates the cost of the equipment, and the daily output of the equipment. Based on the size of the excavation and the daily output of the equipment, the number of hours can be calculated, as well as the cost of using the backfilling equipment for that duration. Based on the equipment costs and operator costs, a total cost of backfilling will be estimated by the spreadsheet. This portion of the model can be seen in Figure 41.

Phase 1 - Slurry Handling & Management		
Backfill Earth Type	Common Earth	
Backfill Equipment Type	Front End Loader, Wheel Mounted	
Backfill Equipment Capacity	0.75	
Backfill Equipment QTY	1	
Backfill Equipment Hourly Rate ($/hr)	$	14.96
Backfill Equipment Output (CY/day)	550	
Backfill Equipment Costs ($)	$	62.09
Backfill Equipment Operator Quantity (#)	1	
Backfill Equipment Operator Cost ($/hr)	$	21.68
Total Backfill Operator Cost ($)	$	89.98
Total Backfill Cost ($)	$	152.08

FIGURE 42: Backfilling of decanting pond in CBA model

The equations used to calculate the backfilling portion of the decanting pond construction are shown below.

$$BFT = \frac{Exc.Size}{BFEO} \times 8\ (\frac{hr}{day}) \qquad \text{(Eq. 4.17)}$$

Where,

- BFT = Time to Backfill Excavation (hours)
- Exc. Size = Size of Excavation to be completed (Cubic Yards)
- BFEO = Output of Backfill Equipment (CY/day)

$$BFEC = BFT \times BFEHR \qquad \text{(Eq. 4.18)}$$

Where,

- BFEC = Cost of Backfill Equipment ($)
- BFT = Time to Backfill Excavation (hours)
- BFEHR = Backfill Equipment Hourly Rate ($/hour)

$$BFOC = BFT \times BFOHR \qquad \text{(Eq. 4.19)}$$

Where,

- BFOC = Cost of Backfill Operator ($)
- BFT = Time to Backfill Excavation (hours)
- BFOHR = Backfill Operator Hourly Rate ($/hour)

$$TBFC = BFEC + BFOC \qquad \text{(Eq. 4.20)}$$

Where,

- TBFC = Total Cost of Backfill ($)
- BFEC = Cost of Backfill Equipment ($)
- BFOC = Cost of Backfill Operator ($)

4.3.3.1.4 Compaction

The compaction portion of the decanting pond is also required to bring the site back to its original condition after the pond has been created, emptied, and backfilled.

4.3.3.1.4.1 Compaction – User Selections

The user is required to make a selection on the type of movement their selected compaction equipment will use, the type of compaction equipment, the size of compaction lifts, and the number of passes that will be made. The user has the following choices in movement and equipment type:

- Riding
    - Sheepsfoot
    - Vibrating Roller

- Walk behind
    - Vibrating Plate
    - Vibrating Roller

The user then selects the size of the compaction lifts. The choices are:

- 6 inch and
- 12 inch

Lastly the user selects the number of passes that the compaction equipment will make. The choices for the number of passes are:

- 2,

- 3, and
- 4.

4.3.3.1.4.2 Compaction – User Inputs

Once these selections have been made, the user selects the quantity of equipment and the amount of operators that they will use.

4.3.3.1.4.3 Compaction – Outputs

Based on the equipment costs, operator costs, and compaction size; a total cost of compaction is estimated by the spreadsheet. This portion of the model can be seen in Figure 42.

Phase 1 - Slurry Handling & Management	
Compaction Movement Type	Riding
Compaction Equipment Type	Sheepsfoot
Compaction Lifts (in.)	12
Compaction Passes (#)	2
Compaction Equipment Output (SY/day)	5200
Compaction Equipment Quantity (#)	1
Compaction Equipment Hourly Rate ($/hr)	$ 104.81
Compaction Time (hrs)	1
Total Compaction Equipment Cost ($)	$ 104.81
Compaction Equipment Operators (#)	1
Compaction Equipment Operator Hourly Rate ($/hr)	$ 21.68
Compaction Operator Total Cost ($)	$ 21.68
Total Compaction Costs ($)	$ 126.49

FIGURE 43: Compaction of decanting pond in CBA model

The equations used to calculate the compaction portion of the decanting pond construction can be seen below.

$$CT = \left(\frac{Exc.Area}{CEO}\right) \times 8\ \frac{hr}{day} \qquad \text{(Eq. 4.21)}$$

Where,

- CT = Time to Complete Compaction of Excavation (hours)
- Exc. Area = Area of Excavation (Square Yards)

- CEO = Compaction Equipment Output (Square Yards/Day)

$$CEC = CEHR \times CT \quad \text{(Eq. 4.22)}$$

Where,

- CEC = Compaction Equipment Cost ($)
- CEHR = Compaction Equipment Hourly Rate ($/hour)
- CT = Time to Complete Compaction of Excavation (hours)

$$COC = COHR \times CT \quad \text{(Eq. 4.23)}$$

Where,

- COC = Compaction Operator Cost ($)
- COHR = Compaction Operator Hourly Rate ($/hour)
- CT = Time to Complete Compaction of Excavation (hours)

$$TCC = CEC + COC \quad \text{(Eq. 4.24)}$$

Where,

- TCC = Total Compaction Cost ($)
- CEC = Compaction Equipment Cost ($)
- COC = Compaction Operator Cost ($)

4.3.3.1.5 Option A Total Cost

When all of the inputs and selections involved with the construction and deconstruction of the decanting pond have been made, all the costs are totaled up, and the sum indicates the costs of Option A. A sample of this can be seen in Figure 43.

Phase 1 - Slurry Handling & Management	
Slurry Handling Option	(A) Decanting Pond
Total Excavation Cost ($)	$ 692.90
Total Geosynthetic Layering Cost ($)	$ 193.60
Total Backfill Cost ($)	$ 152.08
Total Compaction Costs ($)	$ 126.49
Slurry Management Costs ($)	$ 1,165.07

FIGURE 44: Decanting pond total cost estimation

The equations used to calculate the total cost of the decanting pond construction and deconstruction portion of the cost estimator can be seen below.

$$DPC = TCE + TGC + TBFC + TCC \qquad \text{(Eq. 4.25)}$$

Where,

- DCP = Total Cost of Decanting Pond
- TCE = Total Cost of Excavation ($)
- TGC = Total Cost of Geosynthetic Layering ($)
- TBFC = Total Cost of Backfill ($)
- TCC = Total Compaction Cost ($)

4.3.3.2 Option B - Frac Tank & Liquid Storage Tank

Option B involves renting Frac and liquid storage tanks to manage the slurry generated from the construction operations. The purpose of the Frac tank is to deposit the slurry into which will filter the material and separate the solids and liquids. The solids can then be put aside to dry and the liquids can be placed into the liquid storage tank for pH testing. The liquid residuals must be neutralized below the hazardous waste designation before it can be transported.

4.3.3.2.1 Frac & Liquid Storage Tank User Inputs

This portion of the work is less complex than Option A. The user inputs the quantity of tanks that they plan to rent, the duration for which they plan to keep the equipment, and the distance from the delivery site to the work site. The company contacted to support this research study owns multiple delivery warehouses throughout North Carolina to supply this need, and so the contractor would just need to contact the closest location and input the distance to the jobsite to calculate the cost of delivery. This portion of the spreadsheet can be seen in Figure 44.

Phase 1 - Slurry Handling & Management		
Slurry Handling Option	(B) Frac Tank	
Frac Tank Quantity (#)	1	
Water Storage Tank Quantity (#)	1	
Frac Tank Rental Duration(Days)	28	
Water Storage Tank Rental Duration (Days)	28	
Frac Tank Rental Cost ($)	$	1,344.00
Water Storage Tank Rental Cost ($)	$	1,120.00
Tank Delivery Distance (Miles)	50	
Tank Delivery Cost ($)	$	1,265.00
Slurry Management Costs ($)	$	3,729.00

FIGURE 45: Frac tank cost estimation in CBA model

4.3.3.2.2 Frac & Liquid Storage Tank - Outputs

Based on the quantity of tanks, the duration of tank rental, and the distance from the tank company to the jobsite, the spreadsheet calculates the costs for rental and delivery. These outputs are added together to find the total cost of slurry management from Option B.

The equations used to calculate the costs of using a Frac and liquid storage tank for slurry handling and management can be seen below.

$$TRC = TDR \times \#days \qquad \text{(Eq. 4.26)}$$

Where,

- TRC = Tank Rental Cost ($)
- TDR = Daily Rate of Tank Rental ($/day)

$$TDC = TDR \times \#miles \qquad \text{(Eq. 4.27)}$$

Where,

- TDC = Tank Delivery Cost ($)
- TDR = Tank Delivery Rate ($/mile)

$$TTC = TRC + TDC \qquad \text{(Eq. 4.28)}$$

Where,

- TTC = Total Tank Cost ($)
- TRC = Tank Rental Cost ($)
- TDC = Tank Delivery Cost ($)

4.3.4 Phase II – Liquid Residual Management Method

Phase II consists of two methods of liquid residual management. The user selects either depositing the liquid residual at a WWTP/POTW or choosing to land apply the liquid residuals at a NCDOT certified land application site. These options are explored further in the following subsections. Both of these liquid residual management options include at least one pH test performed by a certified operator/tester. If the pH is under the hazardous waste designation, ($pH<12.5$), it is available for transportation.

4.3.4.1. Option A – WWTP/POTW – User Selections

The user first selects the size of truck to haul and transport the liquid residual material to the WWTP/POTW site. The water tank sizes for truck attachment available are:

- 2000 gallons,
- 3000 gallons, and
- 4000 gallons.

4.3.4.2 Option A – WWTP/POTW – User Inputs

The user inputs the quantity of pH testing that must be done. This is based on whether or not the contractor will be using an environmental consultant. If the user is going to handle the testing themselves they will not require additional costs to perform this test, they may input 0 into the quantity of testing.

The user then inputs the distance that the job site is from the disposal site. This determines the costs of delivery for the liquid residual material. The further the jobsite is from the disposal location, the larger the delivery costs will be, and thus the larger the total costs of liquid management will be.

4.3.4.3 WWTP/POTW Outputs

The selection of water tank size will designate the number of trips that must be made based on the quantity of liquid residuals. The cost of the truck driver and the truck were added together and multiplied by the user input distance to the disposal site. The total cost of the liquid delivery cost was computed by multiplying the number of trips by the cost per trip.

The cost of liquid residual disposal was computed by multiplying the quantity of gallons of liquid residual generated by the cost of disposal at the WWTP/POTW. This figure was then added to the cost of liquid delivery to find the total cost of liquid management. This portion of the model is shown in Figure 45.

Phase 2 - Liquid Management	
Liquid pH Test QTY (#)	1
Total pH Testing Costs ($)	$ 750.00
Liquid Disposal/Reuse Option	(A) POTW/WWTP
Size of Tank (Gal)	4000
Number of Trips	8
Tank & Truck Unit Cost ($/mile)	$ 1.34
Distance to Disposal Site (miles)	50
Equipment Operator Cost ($/mile)	$ 0.41
Liquid Transportation to Disposal Site ($)	$ 87.52
Liquid Disposal Cost ($)	$ 1,469.65
Total Liquid Disposal Costs ($)	$ 2,169.84
Liquid Management Costs ($)	$ 2,919.84

FIGURE 46:– POTW/WWTP cost estimation in CBA model

The equations used to calculate the costs of disposing the liquid residual materials in a POTW or WWTP can be seen below.

$$pHTC = pHTR \times \#Tests \qquad \text{(Eq. 4.29)}$$

Where,

- pHTC = Cost of pH Testing ($)
- pHTR = Rate for Conducting pH Test Rate ($/Test)

$$LTT = \frac{Liquid\ Volume}{LTTS} \qquad \text{(Eq. 4.30)}$$

Where,

- LTT = Number of Trips for Liquid Transportation
- Liquid Volume= Quantity of Liquid Residual Produced (Gallons)
- LDTS = Size of Liquid Delivery Tank (Gallons)

$$TTOC = DTS \times \left(\frac{1\, year}{2000\, hrs}\right) \times \left(\frac{1\, hr}{40\, miles}\right) \quad \text{(Eq. 4.31)}$$

Where,

- TTOC = Transportation Truck Operator Cost ($/mile)
- DTS = Delivery Truck Operator Salary ($/year)

$$TTC = TTHR \times \left(\frac{1\, hr}{40\, miles}\right) \quad \text{(Eq. 4.32)}$$

Where,

- TTC = Cost of Transportation Truck ($/mile)
- TTHR = Transportation Truck Hourly Rate ($/hour)

$$LTTC = (TTOC + TTC) \times \#miles \quad \text{(Eq. 4.33)}$$

Where,

- LTTC = Liquid Transportation Trip Cost ($/trip)
- TTOC = Transportation Truck Operator Cost ($/mile)
- TTC = Cost of Transportation Truck ($/mile)

$$LTC = LTTC \times \#Trips \quad \text{(Eq. 4.34)}$$

Where,

- LTC = Liquid Transportation Cost
- LTTC = Liquid Transportation Trip Cost ($/trip)

$$LDC = Vol\ Liquid \times LDR \quad \text{(Eq. 4.35)}$$

Where,

- LDC = Liquid Disposal Cost ($)
- Liquid Volume= Quantity of Liquid Residual Produced (Gallons)
- LDR = Liquid Disposal Rate ($/Gallon)

$$TLDC = LTC + LDC \quad \text{(Eq. 4.36)}$$

Where,

- TLDC = Total Cost of Liquid Disposal ($)
- LTC = Liquid Transportation Cost ($)
- LDC = Liquid Disposal Cost ($)

4.3.4.3 Option B – Land Application

The cost of land application of liquid residual was determined by multiplying the cost at which the land application site would accept and pick up the material by the quantity of liquid residuals. The certified land application sites that were contacted said that they would come to pick up the residuals within a reasonable distance. The cost of land application per gallon is much higher than for deposition in a WWTP/POTW. This portion of the spreadsheet can be seen in Figure 46.

Phase 2 - Liquid Management	
Liquid pH Test QTY (#)	1
Total pH Testing Costs ($)	$ 750.00
Liquid Disposal/Reuse Option	(B) Land Application
Liquid Management Costs ($)	$ 6,938.00

FIGURE 47: Land application cost estimation in CBA model

The equations used to calculate the costs of beneficially reusing liquid residual material via land application can be seen below.

$$LAC = Liquid\ Vol. \times LADR \quad \text{(Eq. 4.37)}$$

Where,

- LAC = Land Application Cost ($)
- Liquid Vol. = Volume of Liquid Residuals (Gallons)
- LADR = Land Application Disposal Rate ($/Gallons)

4.3.5 Phase III – Solid Residual Management Method

Each method of solid residual management started with conducting a Paint Filter Test on the solids to determine the absence of free liquids. This test is to be performed by a qualified employee of the contractor. The cost of this test, and the price of an environmental consultant is taken into account with all methods of solid residual management. If the solid residual material is to be used as a beneficial fill, then the contractor will have to provide at least one TCLP test from a representative sample. This portion of the spreadsheet can be seen in Figures 50-54. The options of solid residual management are:

- MSW Landfill,
- LCID Landfill,
- C&D Landfill,
- Beneficial Fill Onsite, and
- Beneficial Fill Offsite.

4.3.5.1 Solid Residual Disposal/Reuse User Selection

The solids are to be delivered to the solids residual site where disposal of the material is paid for based on the weight, in tons, of the haul. The cost of disposal depends on the type of landfill facility and regional location of the site. The sizes of dump trucks available are:

- 7.5 CY,
- 8.9 CY,
- 10 CY,

- 13.6 CY, and
- 20 CY.

4.3.5.2 Solid Residual Disposal/Reuse – User Inputs

The user inputs the quantity of Paint Filter tests that are to be performed by an environmental consultant. If the user plans on performing that work themselves, they may input 0 into the quantity of tests.

The user then selects the quantity of disposal trucks and operators that they would be using for the solid residual disposal. Generally one truck was used for this disposal operations, but in the case of a time sensitive project, more could be used. Lastly the user inputs the distance from the jobsite to the disposal site. This gives the user a cost for the delivery of this material.

4.3.5.3 Solid Residual Disposal/Reuse – Outputs

The size of the truck determines the number of trips needed to be taken from the jobsite to the disposal site. The total cost of disposal is based on the PDF's previously used to estimate the cost for disposal at these facilities. The distance to all disposal sites was assumed to be 50 miles. This portion of the spreadsheet can be seen in Figures 47-51.

Phase 3 - Solid Management	
Method of Solid Disposal	(A) MSW
Paint Filter/TCLP Test QTY (#)	1
Paint Filter/TCLP Test Cost ($)	$ 750.00
Solid Disposal Cost ($/TON)	$ 55.67
Truck Quantity (#)	1
Disposal Truck Operator Quantity (#)	1
Solid Transportation Vehicle Size (CY)	10
Solid Transportation Truck GVW (lbs)	35000
Solid Transportation Vehicle Cost ($/mile)	$ 1.14
Cost of Operator for Solid Transportation ($/mile)	$ 0.41
Distance to Disposal/Fill Site (miles)	50
Trips (#)	7
Total Cost of Solids Transportation ($)	$ 540.83
Solid Management Cost ($)	$ 8,207.75

FIGURE 48: MSW landfill cost estimation in CBA model

The equations used to calculate the costs of beneficially reusing liquid residual material via land application can be seen below.

$$PFTC = PFTR \times \#T \quad \text{(Eq. 4.38)}$$

Where,

- PFTC = Paint Filter Testing Costs ($)
- PFTR = Paint Filter Test Rate ($/Test)
- #T = Number of Paint Filter Tests Ran

$$SDC = Wt.Solids \times SDR \quad \text{(Eq. 4.39)}$$

Where,

- SDC= Cost of Disposing Solids ($)
- Weight Solids = Quantity of Solids Residuals Produced (Tons)
- SDR = Solid Disposal Rate ($/ton)

$$STT = \frac{Vol.Solids}{SSTT} \quad \text{(Eq. 4.40)}$$

Where,

- STT = Solid Transportation Trips (#)
- Volume Solids = Quantity of Solid Residuals (Cubic Yards)
- SSTT = Size of Solid Transportation Truck (Cubic Yards)

$$STTC = (STOC + STTC) \times Dist. \quad \text{(Eq. 4.41)}$$

Where,

- STTC = Solid Transportation Trip Cost ($/Trip)
- STOC = Solid Transportation Operator Cost ($/mile)
- STTC = Solid Transportation Truck Cost ($/mile)
- Dist. = Number of Miles of Transportation

$$STC = STTC \times \#Trips \quad \text{(Eq. 4.42)}$$

Where,

- STC = Solid Transportation Cost ($)
- STTC = Solid Transportation Truck Cost ($/mile)

$$TSDC = PFTC + STC + SDC \quad \text{(Eq. 4.43)}$$

Where,

- TSDC = Total Solid Disposal Cost ($)
- PFTC = Paint Filter Test Cost ($)
- STC = Solid Transportation Cost ($)
- SDC= Cost of Disposing Solids ($)

Phase 3 - Solid Management	
Method of Solid Disposal	(B) C&D
Paint Filter/TCLP Test QTY (#)	1
Paint Filter/TCLP Test Cost ($)	$ 750.00
Solid Disposal Cost ($/TON)	$ 44.90
Truck Quantity (#)	1
Disposal Truck Operator Quantity (#)	1
Solid Transportation Vehicle Size (CY)	10
Solid Transportation Truck GVW (lbs)	35000
Solid Transportation Vehicle Cost ($/mile)	$ 1.14
Cost of Operator for Solid Transportation ($/mile)	$ 0.41
Distance to Disposal/Fill Site (miles)	50
Trips (#)	7
Total Cost of Solids Transportation ($)	$ 540.83
Solid Management Cost ($)	$ 6,869.93

FIGURE 49: C&D landfill cost estimation in CBA model

Phase 3 - Solid Management	
Method of Solid Disposal	(C) LCID
Paint Filter/TCLP Test QTY (#)	1
Paint Filter/TCLP Test Cost ($)	$ 750.00
Solid Disposal Cost ($/TON)	$ 19.67
Truck Quantity (#)	1
Disposal Truck Operator Quantity (#)	1
Solid Transportation Vehicle Size (CY)	10
Solid Transportation Truck GVW (lbs)	35000
Solid Transportation Vehicle Cost ($/mile)	$ 1.14
Cost of Operator for Solid Transportation ($/mile)	$ 0.41
Distance to Disposal/Fill Site (miles)	50
Trips (#)	7
Total Cost of Solids Transportation ($)	$ 540.83
Solid Management Cost ($)	$ 3,734.53

FIGURE 50: LCID landfill cost estimation in CBA model

Phase 3 - Solid Management	
Method of Solid Disposal	(D) Beneficial Fill (onsite)
Paint Filter/TCLP Test QTY (#)	1
Paint Filter/TCLP Test Cost ($)	$ 750.00
Solid Management Cost ($)	$ 750.00

FIGURE 51: Beneficial fill onsite cost estimation in CBA model

Phase 3 - Solid Management	
Method of Solid Disposal	(E) Beneficial Fill (offsite)
Paint Filter/TCLP Test QTY (#)	1
Paint Filter/TCLP Test Cost ($)	$ 750.00
Truck Quantity (#)	1
Disposal Truck Operator Quantity (#)	1
Solid Transportation Vehicle Size (CY)	10
Solid Transportation Truck GVW (lbs)	35000
Solid Transportation Vehicle Cost ($/mile)	$ 1.14
Cost of Operator for Solid Transportation ($/mile)	$ 0.41
Distance to Disposal/Fill Site (miles)	50
Trips (#)	7
Total Cost of Solids Transportation ($)	$ 540.83
Solid Management Cost ($)	$ 1,290.83

FIGURE 52: Beneficial fill offsite cost estimation in CBA model

The cost of disposal for the solid residuals was determined by multiplying the cost of disposal of solid residual per ton by the quantity, in tons, of solid residuals estimated in the project description portion of the spreadsheet. The distance to the disposal facility was multiplied by the combined cost of the truck and operator to find the disposal cost per trip. The cost of solid residual disposal per trip, is multiplied by the number of trips and then added to the cost of disposal of all the solid residual to determine the total cost of solid residual disposal at the landfill facility. The ranking of costs per disposal, from highest to lowest, is as follows:

1. MSW Landfill
2. C&D Landfill
3. LCID Landfill
4. Beneficial Fill Onsite
5. Beneficial Fill Offsite

4.3.6 Cost Estimation Results

Once all of the information has been input into the cost estimation portion of the spreadsheet, all of the options for phase I, II, and III can be viewed together. This will allow the user the see all the costs associated with each specific options available in each specific phase and find the most cost effective options for managing slurry, liquids, and solids respectively. A portion of this can be seen in Figure 52.

Slurry Handling & Management	Slurry Handling Option	(A) Decanting Pond			(B) Frac Tank	
	Equipment Cost	$ 502.50				
	Labor/Operator Cost	$ 497.06			Rental Costs	$ 2,464.00
	Material Cost	$ 165.50			Delivery Costs	$ 1,265.00
	Slurry Management Costs ($)	$ 1,165.07			Slurry Management Costs ($)	$ 3,729.00
Liquid Management Option	Liquid Management Option	(A) WWTP/POTW			(B) Land Application	
	Testing	$ 750.00			Testing	$ 750.00
	Delivery	$ 87.52			Disposal & Delivery	$ 6,188.00
	Disposal	$ 1,469.65				
	Liquid Management Costs ($)	$ 2,307.17			Liquid Management Costs ($)	$ 6,938.00
Solid Management Option	Method of Solid Disposal	(A) MSW	(B) C&D	(C) LCID	(D) Beneficial Fill (onsite)	(E) Beneficial Fill (offsite)
	Testing	$ 750.00	$ 750.00	$ 750.00	$ 750.00	$ 750.00
	Disposal	$ 6,916.92	$ 5,579.10	$ 2,443.70	$ -	$ -
	Delivery	$ 540.83	$ 540.83	$ 540.83	$ -	$ 540.83
	Solid Management Costs ($)	$ 8,207.75	$ 6,869.93	$ 3,734.53	$ 750.00	$ 1,290.83

Figure 53: Cost estimator side-by-side cost comparisons

4.4 Risk Analysis

This section of the Cost-Benefit Model was created so that the user could view the various risks involved with each individual option of disposal/reuse. Unlike cost, the risks are not dependent upon the region in which it takes place. There are various risks for each option, and the model helps visualize these risks, or lack thereof, of each option so the user can make an informed decision given the listed risks.

The risks, listed in Table 1, for each available option of each available phase for handling slurry, reuse/disposal of residual liquids, and reuse/disposal of residual solids generated from the chosen construction operation.

TABLE 2: Associated risks of available options for handling & reuse/disposal of residuals

Risks	
Decanting Pond	Extra Construction Work
	Increased use of Machinery & labor
	Possibility of precipitation entering pond
	Possibility of Leak/Tear In Lining
Frac Tank	Delays in delivery
	Possibility of damage to rented equipment
	Possible spill risk in transferring from frac tank to water holding tank
WWTP/POTW	Possibility of facility non-acceptance
	Transportation risks
Land App	Possibility of facility non-acceptance
MSW	Transportation risks
	Creation of waste
C&D	Transportation risks
	Possibility of facility non-acceptance
	Creation of waste
LCID	Transportation risks
	Possibility of facility non-acceptance
	Creation of waste
Beneficial Fill Onsite	Possibility of failing TCLP (in existing concrete)
Beneficial Fill Offsite	Transportation risks
	Possibility of failing TCLP (in existing concrete)

The user then provides a risk level for each of the 20 options. Based on these input risk levels, the model and assigns a score to each option based on the assigned risk level, and the maximum risk level listed for all the options. This will give a score that is between zero and one, which will then be put into the benefit cost model for evaluation.

4.5 Environmental Benefit

This section of the Cost-Benefit Model was created so that the user could view the various perceived environmental benefits involved with each individual option of disposal/reuse. Unlike cost, the perceived environmental benefits are not dependent upon the region in which it takes place. There are several environmental benefits identified for each option based on the literature and NCDOT input, and the tool helps to visualize these benefits, or lack thereof, so the user can make an informed decision given the listed benefits.

The environmental benefits (listed in Table 2), for each available option of each phase for handling slurry, reuse/disposal of residual liquids, and reuse/disposal of residual solids generated.

TABLE 3: Perceived environmental benefits

	Environmental Benefit
Decanting Pond	N/A
Frac Tank	Leave Jobsite as is
	Reduced Mechanical Work; save materials
	Low probability of leak/contamination
POTW/WWTP	N/A
Land Application	Beneficial Reuse
	No Burden to Public Works
MSW	N/A
C&D	Reduction in Municipal Waste Stream
LCID	Reduction in Municipal Waste Stream
Beneficial Fill Onsite	No Transportation
	No Burden to Solid Waste Facilities
	Beneficial Reuse
Beneficial Fill Offsite	No Burden to Solid Waste Facilities
	Beneficial Reuse

Once the risks have been quantified for each specific option available, the user will go through and provide a perceived environmental benefit level for each of the 20 options. The model looks at these stated benefit levels, and assigns a score to each option based on the assigned benefit level, and the maximum benefit level listed for all the options. This will give a score that is between zero and one, which is then put into the benefit cost model for evaluation. This score is then inverted since benefits are positive, and the cost and risks are considered negatives.

4.6 Cost Benefit Weights

The next step for the user is to input the weights of importance for each of the three portions of the cost benefit analysis. The sum of these three weights must add up to one. The weight assigned to each portion of the analysis informs the model what the user views as most important, and uses that information to select the most favorable options for the user. This can be seen in Figure 53.

Portion of Analysis	Chosen Weight (greater than 0)
Cost	0.9
Risk	0.05
Environmental Benefit	0.05
	1
	TRUE

Figure 54: CBA model relative weights

4.7 Cost Benefit Analysis Model

The model calculates the most favorable options for disposal and reuse based on what the user views as most important. The model ranks the options based on favorability. The cost items are based on the user selections and inputs from the cost estimation portion of the model. The costs are compared for each option based on the selected region and operation after the cost estimator portion has been finished by the user. The costs are viewed next to each other to give the user the cost of each option available to them.

The user inputs scores for the identified risk items for all the available options listed in the risk portion of the model. Some options have less risks involved, however the ultimate decision for risk comes down to the user. The same method was used for determining the environmental benefits for each option. While some options have more benefits associated with them, it is up to the user to determine the impact that those benefits would have on the decision making process. These options, and their weights and rankings can be seen in Figure 54.

		Cost		Risk		Environmental Benefit		Score	
Diamond Grinding	Option	Cost Weight	0.9	Risk Weight	0.05	EB Weight	0.05		Rank
Mountain Region	1	0.65	0.59	0.50	0.03	1.00	0.05	0.66	13
	2	0.58	0.52	0.60	0.03	0.50	0.03	0.58	10
	3	0.41	0.37	0.80	0.04	0.17	0.01	0.42	4
	4	0.26	0.23	0.10	0.01	0.17	0.01	0.24	1
	5	0.28	0.26	0.30	0.02	0.20	0.01	0.28	2
	6	0.86	0.78	0.60	0.03	0.50	0.03	0.83	18
	7	0.79	0.71	0.60	0.03	0.33	0.02	0.76	16
	8	0.63	0.56	0.30	0.02	0.25	0.01	0.59	11
	9	0.47	0.42	0.30	0.02	0.17	0.01	0.45	6
	10	0.50	0.45	1.00	0.05	0.20	0.01	0.51	7
	11	0.79	0.71	0.90	0.05	0.33	0.02	0.77	17
	12	0.72	0.64	0.50	0.03	0.25	0.01	0.68	14
	13	0.55	0.50	0.40	0.02	0.20	0.01	0.53	8
	14	0.39	0.35	0.20	0.01	0.14	0.01	0.37	3
	15	0.42	0.38	0.80	0.04	0.17	0.01	0.43	5
	16	1.00	0.90	0.70	0.04	0.17	0.01	0.94	20
	17	0.93	0.84	0.40	0.02	0.14	0.01	0.86	19
	18	0.76	0.69	0.50	0.03	0.13	0.01	0.72	15
	19	0.60	0.54	0.10	0.01	0.10	0.01	0.55	9
	20	0.63	0.57	0.40	0.02	0.11	0.01	0.60	12

Figure 55: CBA ranking of options

The costs, risks, and environmental benefits are first normalized by dividing each cost, risk, or environmental benefit by the maximum result in each category. That normalized cost is then multiplied by the cost weight that was previously selected by the user. The resulting score for cost, risk, and environmental benefit are added together and an overall score is computed for each option. The options are then ranked by the model for the user to identify the options that are the most preferable based on the selected inputs.

CHAPTER 5: RESULTS AND LIMITATIONS

In this section the results of the costs estimation of the three construction activities in the three regions of North Carolina are compared, based on the same user selections and inputs to find which disposal/reuse options are most cost effective. These cost values are generated by running a Monte Carlo simulation from the data entered into the cost estimator. Since many of the values in the cost estimator had a range of possibilities, the simulation was run 5000 times to get a large range of possible values that could exist based on the possible values. The box and whisker plots depicted in the following subsections are based on the data found in Appendix D. The box represents a range of the 25th through 75th percentile for cost based on the probability distribution of the 5000 calculations run in the cost simulation. The high extreme is found by subtracting the 50th percentile from the maximum cost value. The low extreme is found by subtracting the minimum cost value from the 50th percentile.

5.1 Results of Cost Data

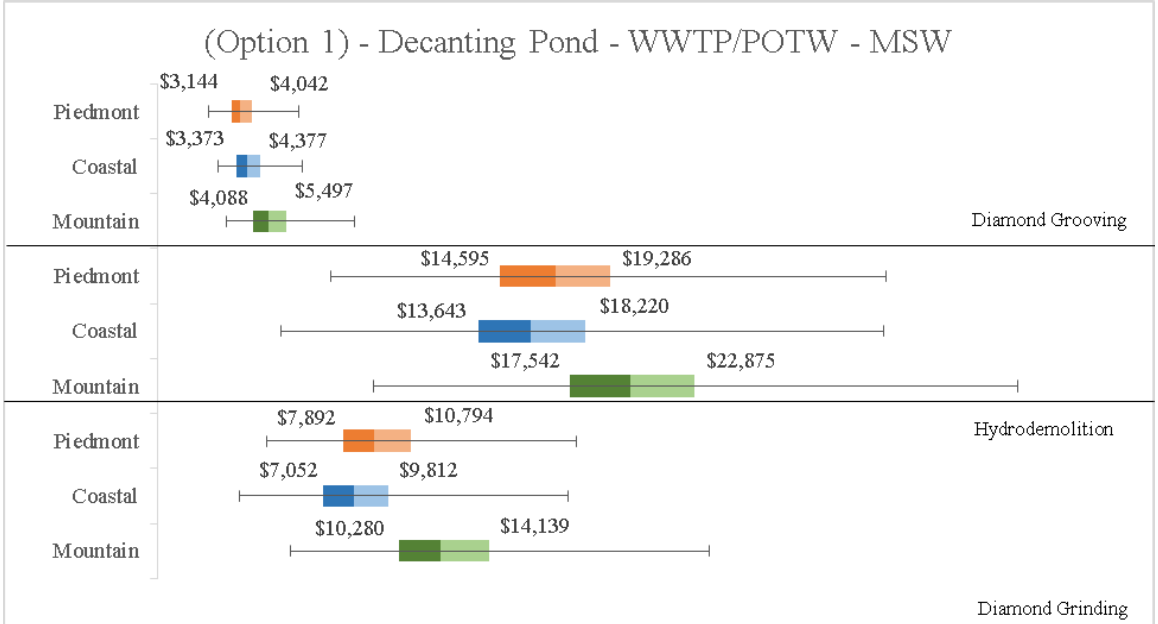


FIGURE 56: Cost simulation results - Option 1

The bar chart for Option 1 can be seen in Figure 52. The immediate trend that emerges depicts the hydrodemolition work being far more expensive than the other two construction activities, followed by diamond grinding, and finally diamond grooving. There is a simple reason for this, as hydrodemolition produces by far the most amount of slurry and liquid residuals, in comparison to diamond grinding and grooving. Hydrodemolition produced a most likely value of 14 gallons per square yard, whereas grinding produced 4.33 gallons per square yard, and grooving which produced just 1 gallon per square yard. The higher the quantity of residual slurry, the more it will cost to dispose of that residual material. Also the trend shows that it is more expensive to dispose of the solid residuals at a MSW landfill in the Mountain region than it is in the Piedmont or Coastal region. The Piedmont is only slightly more expensive on average than the Coastal region. The Coastal region is the cheapest, because the cost data for disposal of solid residual material had the smallest minimum, most likely, and maximum price; $7/ton, $28.70/ton, and $40/ton respectively. The Piedmont region's disposal cost data for the MSW landfill was a minimum of $22/ton, a most likely value of $34.80/ton, and a maximum value of $41/ton. The Mountain region is by far the most expensive as the data in this region ranged from a minimum of $43/ton, a most likely value of $57/ton, and a maximum value of $67/ton.

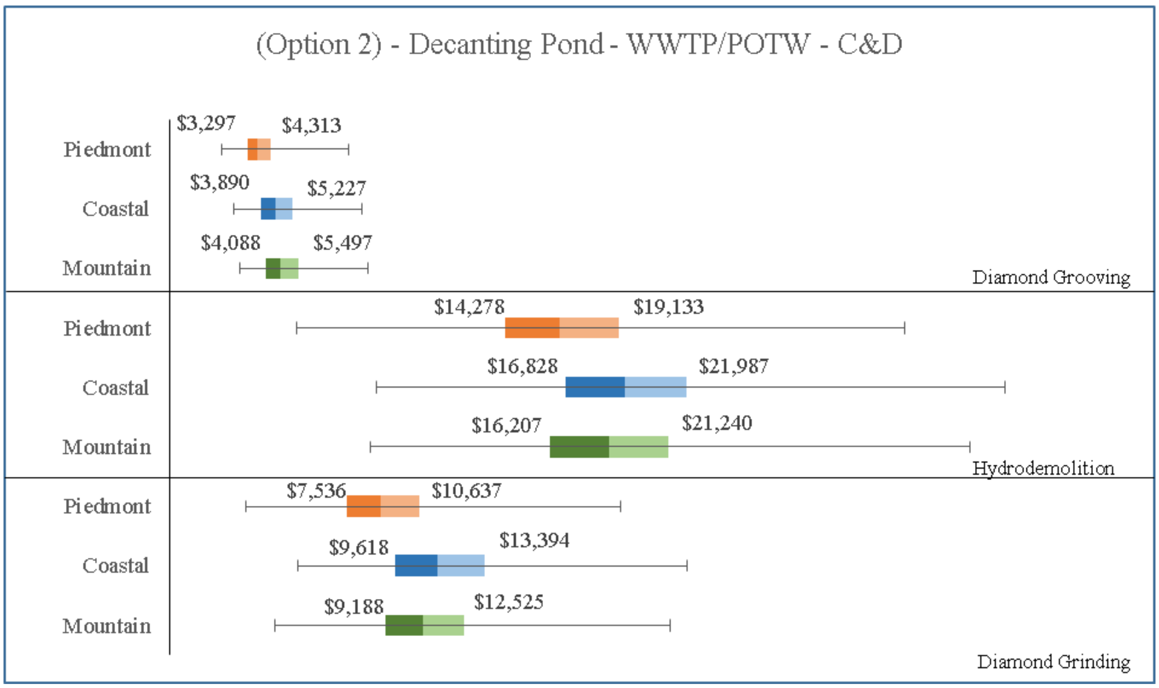


FIGURE 57: Cost simulation results - Option 2

The bar chart for Option 2, as seen in Figure 53. The data also shows that the Coastal region has the most expensive C&D landfills, followed by the Mountain region, and final the Piedmont region. The data for C&D landfill facilities in the Piedmont region was represented as a normal distribution with a mean value of $30.70/ton and a standard deviation of $9.51/ton. The disposal cost data for C&D facilities in the Mountain region ranged from a minimum value of $31/ton, a most likely value of $46.70/ton, and a maximum value of $57/ton. Lastly the disposal cost values for the C&D landfill facilities in the Coastal region ranged from a minimum of $34/ton, to a most likely value of $48/ton, to a maximum value of $68/ton.

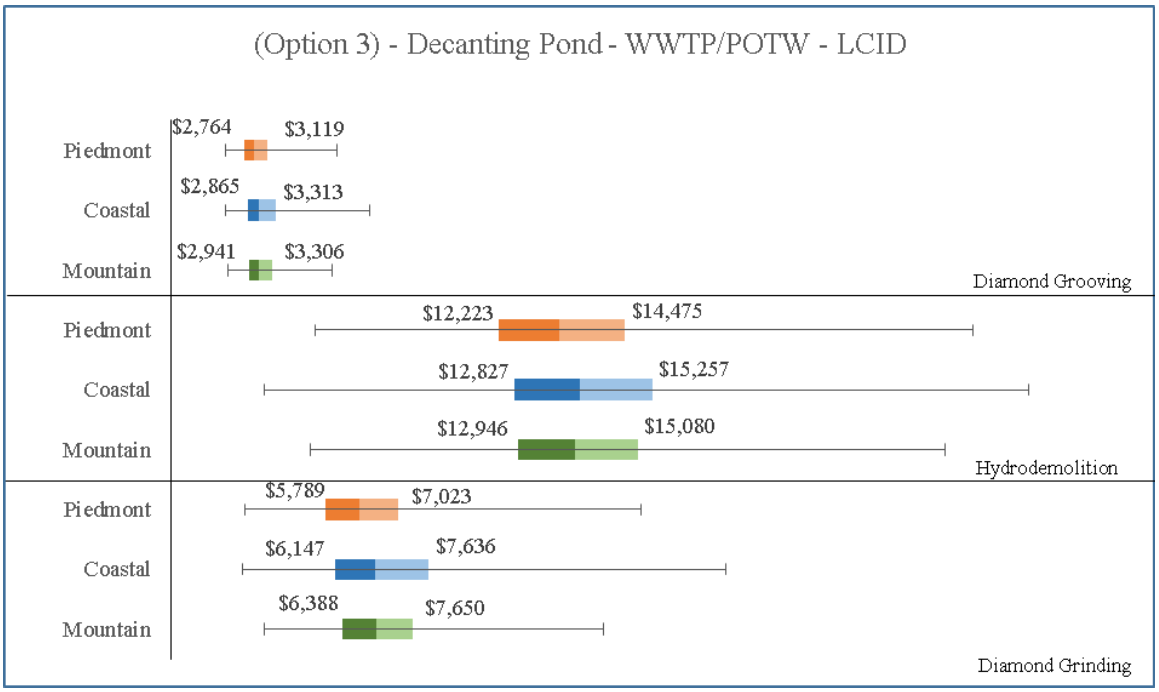


FIGURE 58: Cost simulation results - Option 3

The bar chart for Option 3, as seen in Figure 54. The data shows that the Coastal region has the largest variance in cost. The Piedmont region has the highest likelihood of being the cheapest option. The disposal cost data from LCID facilities in the Piedmont region ranged from a minimum value of $0/ton, a most likely value of $0/ton, and a maximum value of $46/ton. The disposal cost data for the LCID facilities in the Coastal region ranged from a minimum of $0/ton, to a most likely value of $0/ton, to a maximum value of $65/ton. The Piedmont and Coastal LCID facilities had the same most likely value of \$0/ton because a majority of the facilities in that region that provided information stated that they would take the solid residual for free to beneficially reuse at their site. The cost data for LCID facilities in the Mountain region ranged from a minimum of \$0/ton, to a most likely value of \$17/ton, to a maximum value of \$42/ton. The relatively low maximum of the LCID facilities in the Mountain region explains why the variance in cost between the 5th and 95th percentile was smaller than that of the Coastal region.

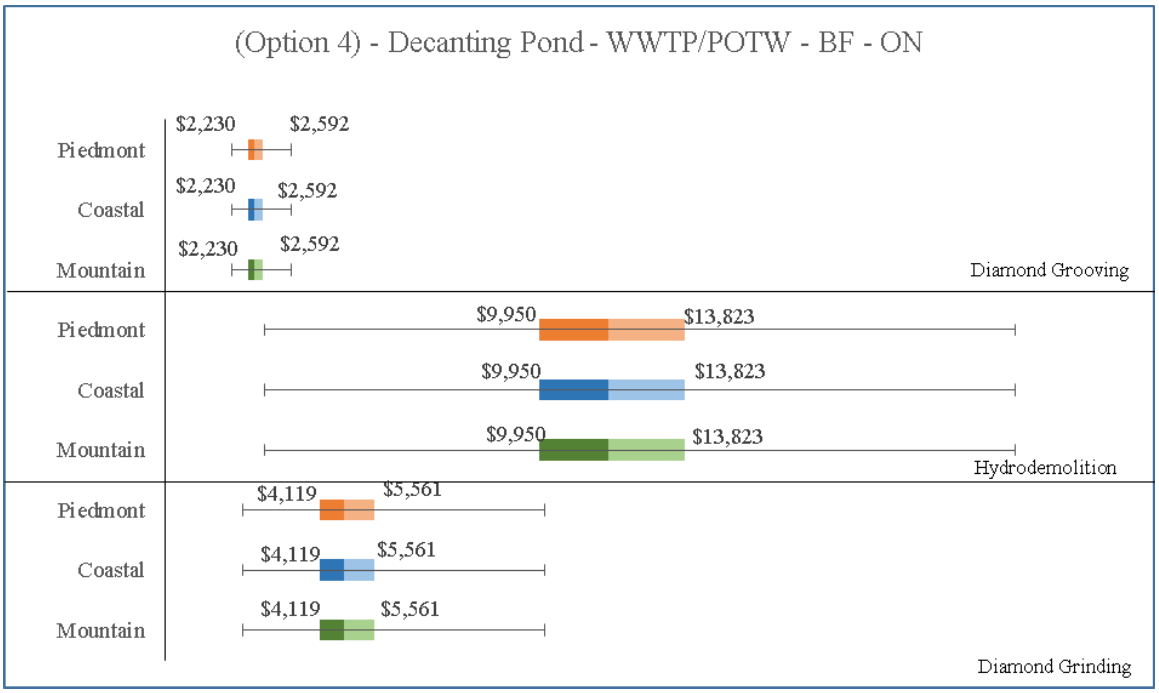


FIGURE 59: Cost simulation results - Option 4

The bar chart for Option 4, as seen in Figure 55, shows that there is no variance in cost between regions for beneficial fill onsite. This is because it does not cost anything to use the solid residuals as beneficial fill on site and therefore no matter what region the operations are occurring in, the disposal of residual solids will have no impact on the cost options.

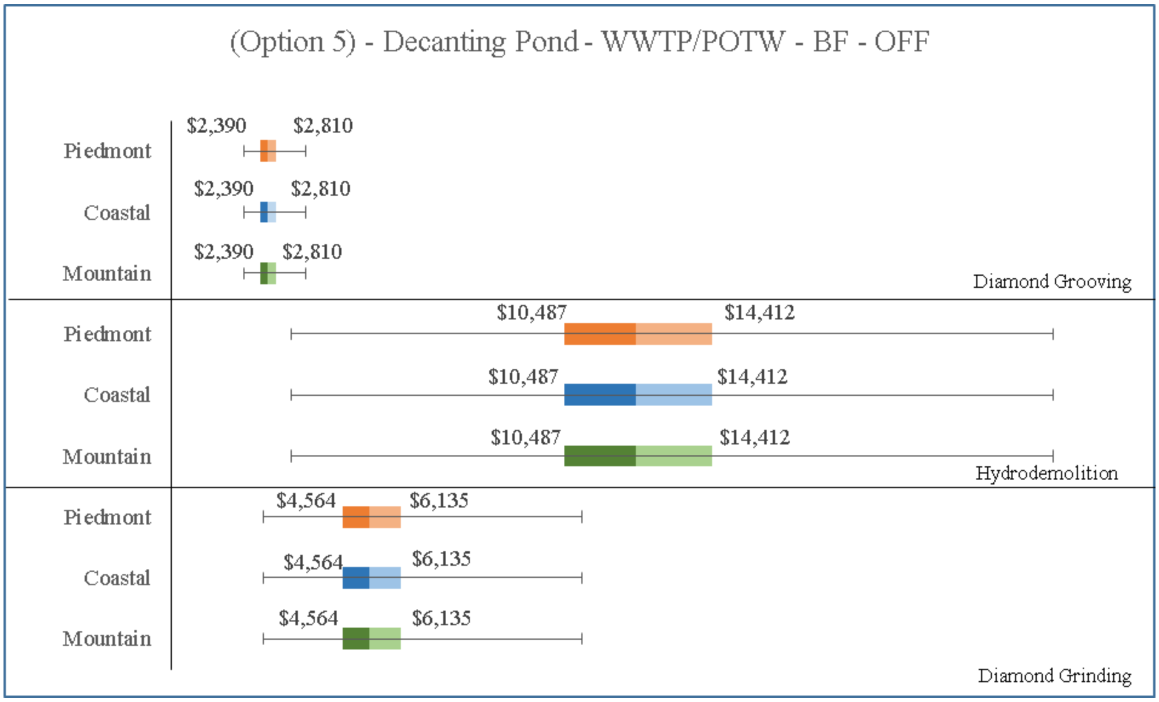


FIGURE 60: Cost simulation results - Option 5

Like the bar chart for Option 4, the bar chart for Option 5, as seen in Figure 56, represents an option where there is no variation in cost between regions. Option 5 is slightly more expensive than Option 4 because the residual solids must be transported from the jobsite to wherever they will be used as beneficial fill. Since there is no cost for disposing this material, there will be no variation amongst regions, and all the cost variation that does exists is from the disposal of the liquid residual and the construction/deconstruction of the decanting pond.

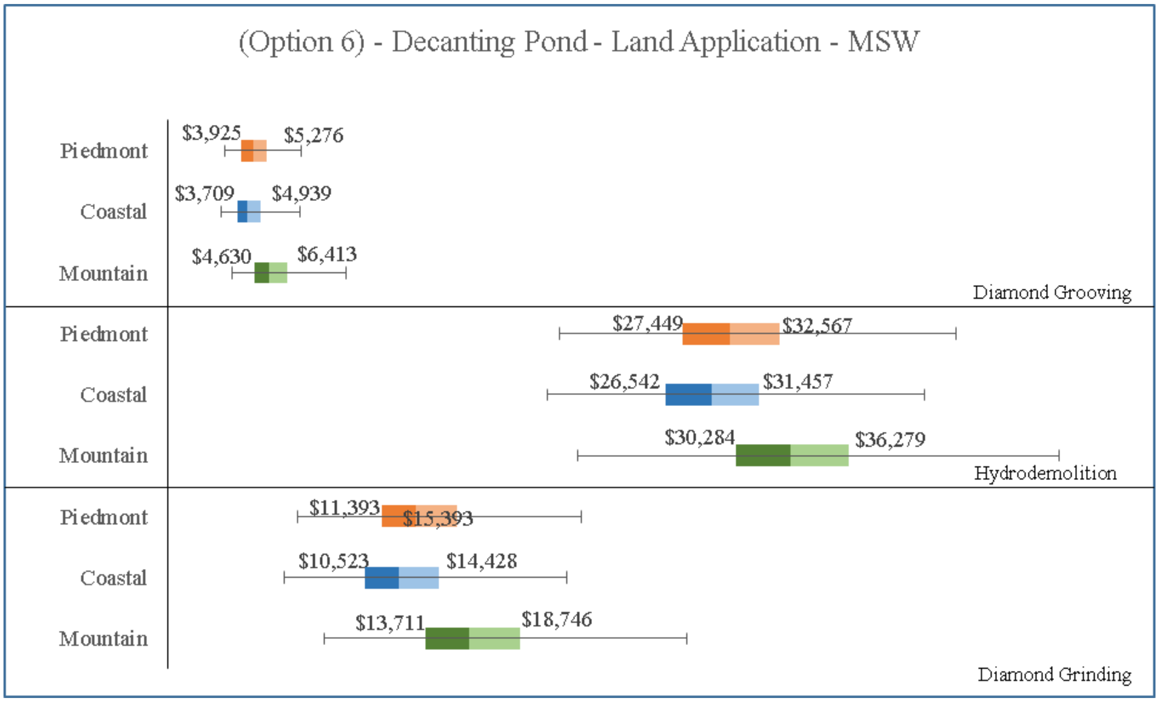


FIGURE 61: Cost simulation results - Option 6

Option 6, as depicted in Figure 57, is directly comparable to Option 1, because the only variation that exists is the used of land application as opposed to using a POTW/WWTP for disposal/reuse of the liquid residuals. Land application of the liquid residual materials is clearly more expensive than disposal at a WWTP/POTW. Land Application could be a favorable option for diamond grinding, since it does not generate a large quantity of liquid residuals. However, for the operations that generate a comparably larger quantity of liquid residuals, diamond grooving and hydrodemolition, land application would not be a favorable option as it would cause costs to be dramatically greater than disposal via WWTP/POTW. Options 7, 8, 9, and 10, as seen in Figures 58-61, further depict these claims in comparison to Options 2, 3, 4, and 5 respectively.

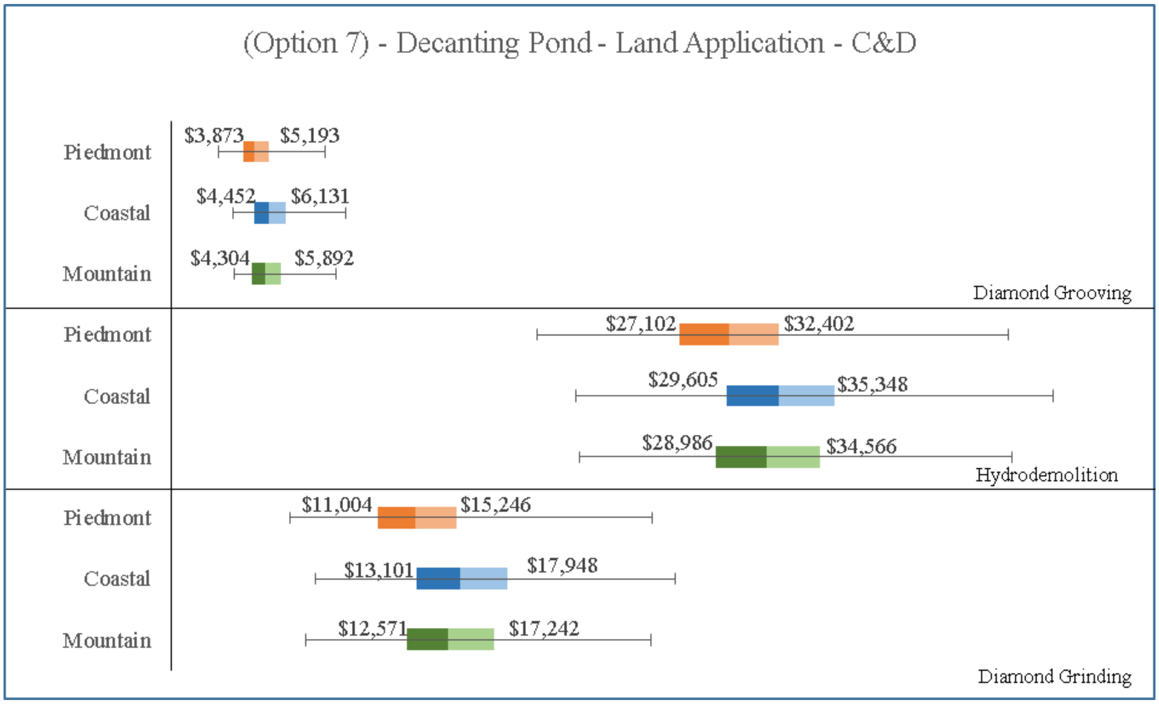


FIGURE 62: Cost simulation results - Option 7

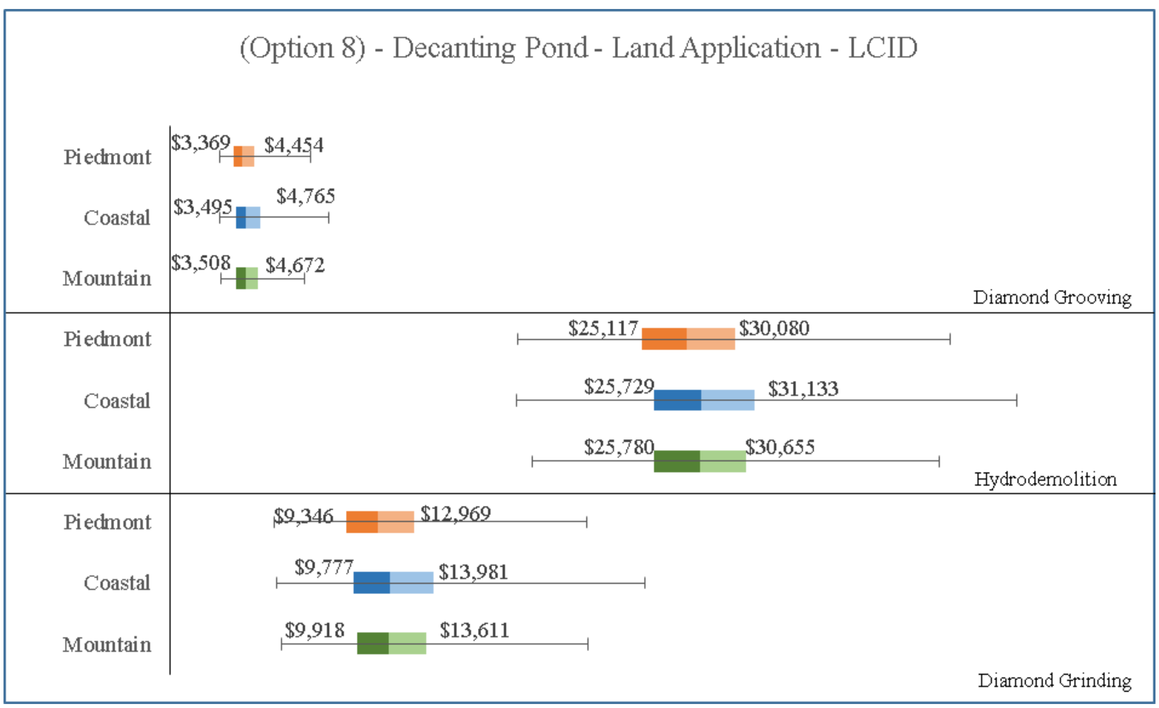


FIGURE 63: Cost simulation results - Option 8

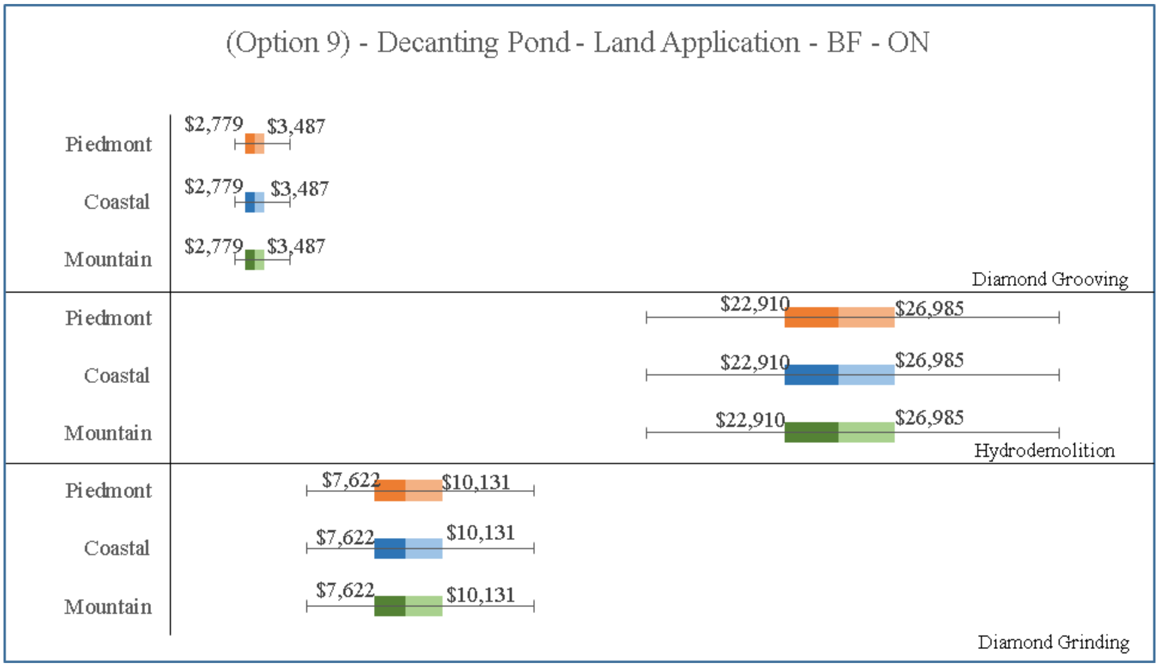


FIGURE 64: Cost simulation results - Option 9

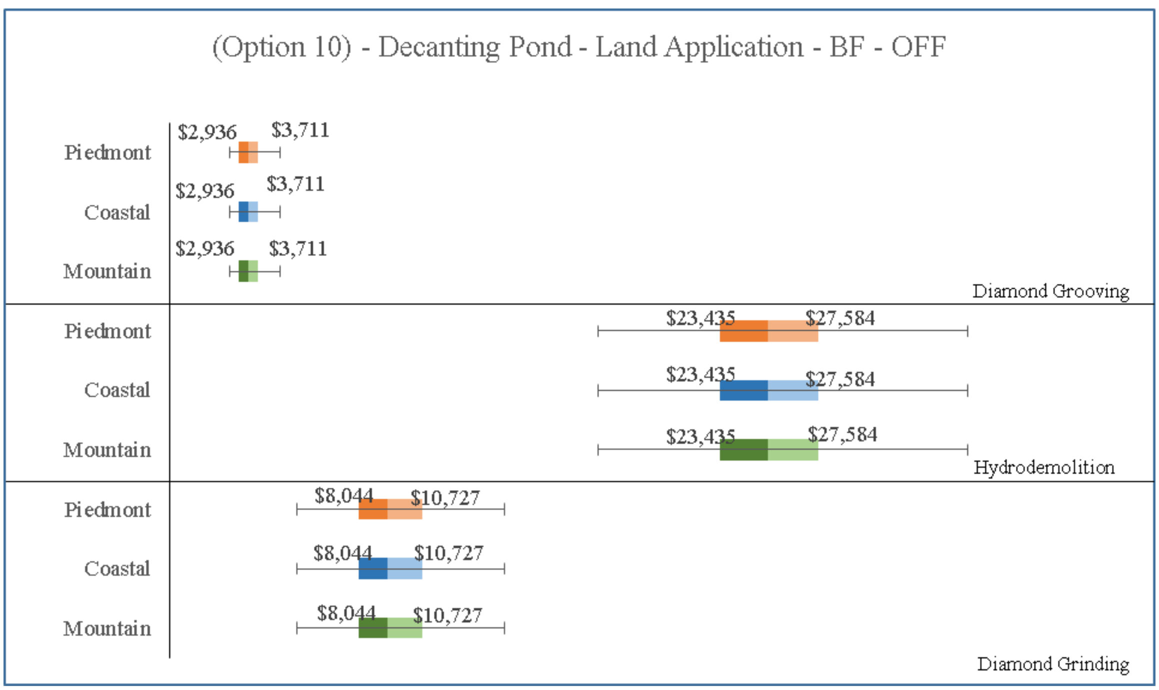


FIGURE 65: Cost simulation results - Option 10

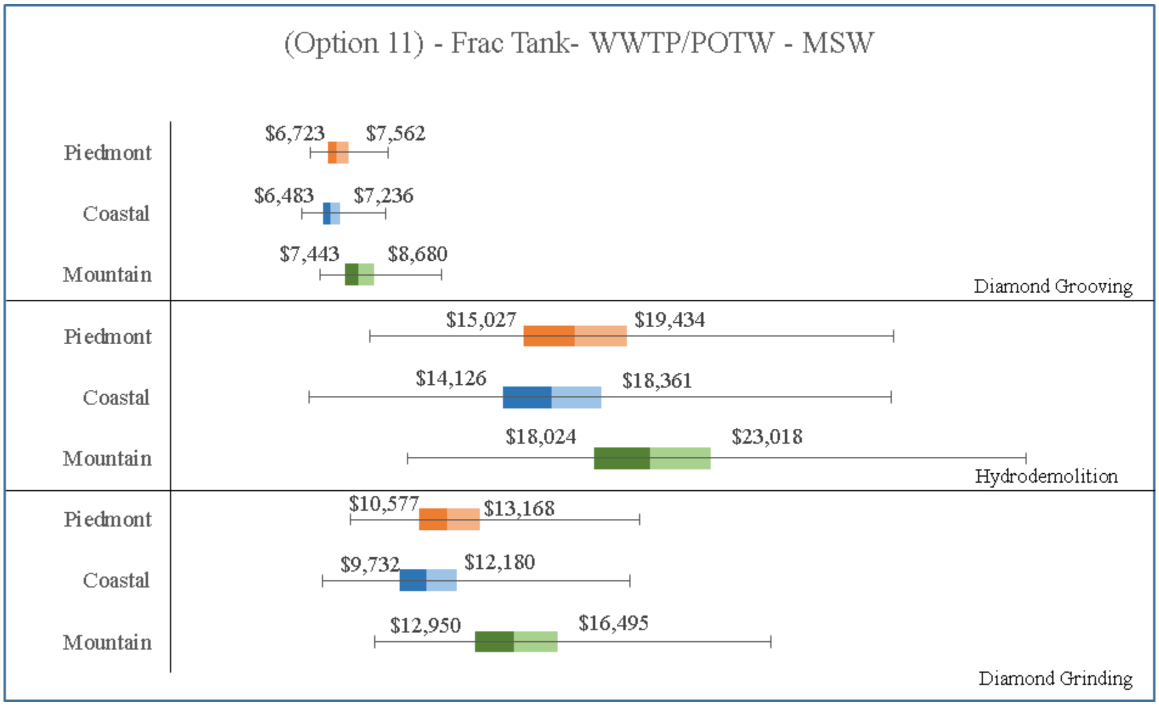


FIGURE 66: Cost simulation results - Option 11

Option 11, as seen in Figure 62, is the first option to use Frac tanks as the method of slurry handling. The following ten options (Options 11-20) use a Frac tank as the chosen method of slurry handling. In comparison to constructing a decanting pond for slurry management, and all other things held equal, the Frac tank was more expensive. This is especially true for diamond grinding and diamond grooving. However using a Frac tank as the method of slurry handling for hydrodemolition is shown to be nearly as cost effective as constructing and deconstructing a decanting pond onsite. Using a Frac tank to manage slurry from hydrodemolition in the three regions, equated to an average cost increase of just $552. This is because hydrodemolition produces a large quantity of slurry, which will require a large excavation, which will drive up cost for construction and deconstruction. The previously stated trends exist for the rest of the following cost simulation graphs; Options 12 – 20, and can be seen in Figures 63-71.

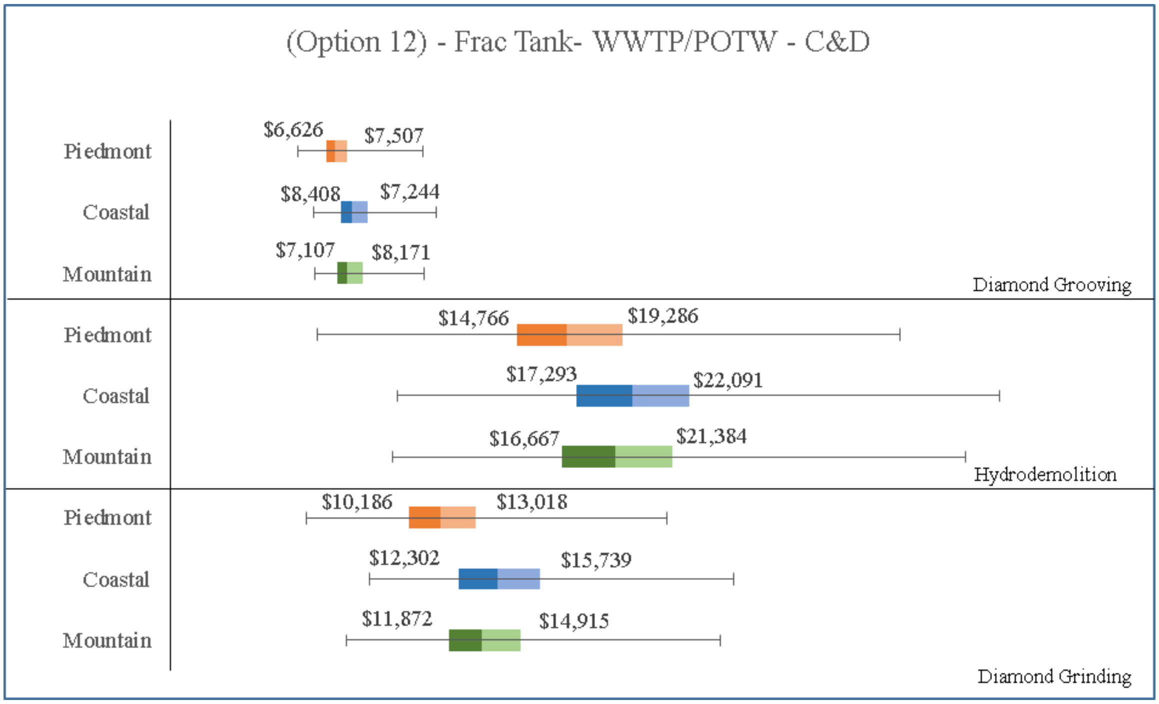


FIGURE 67: Cost simulation results - Option 12

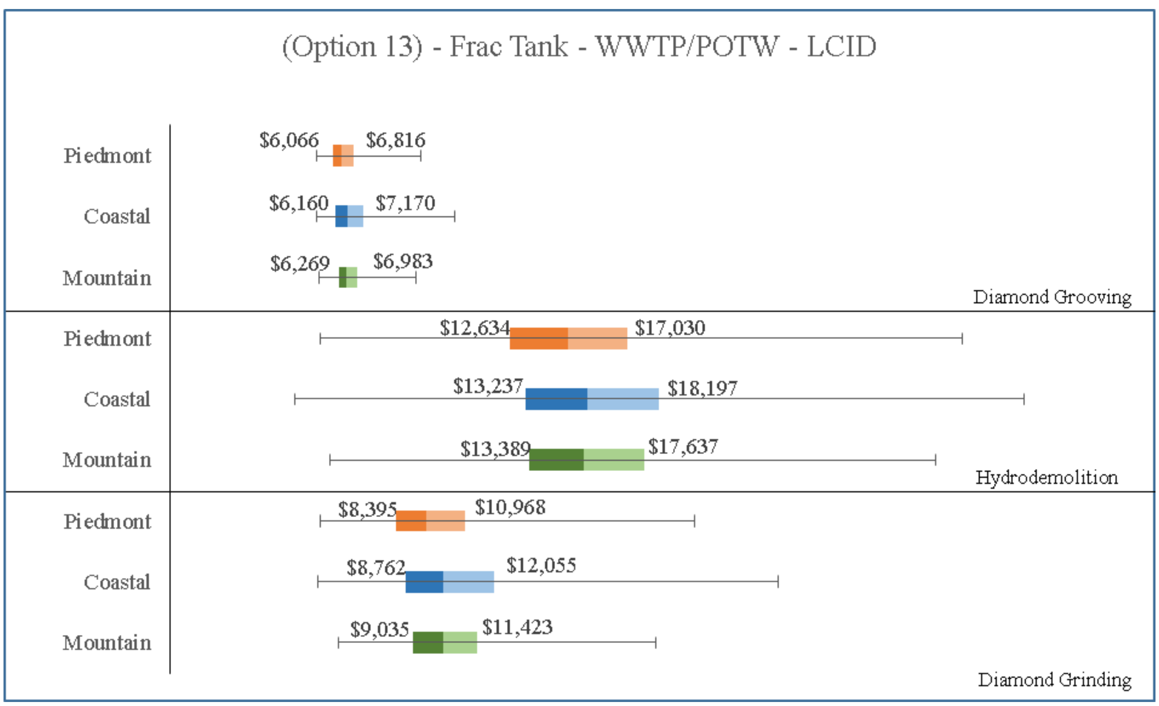


FIGURE 68: Cost simulation results - Option 13

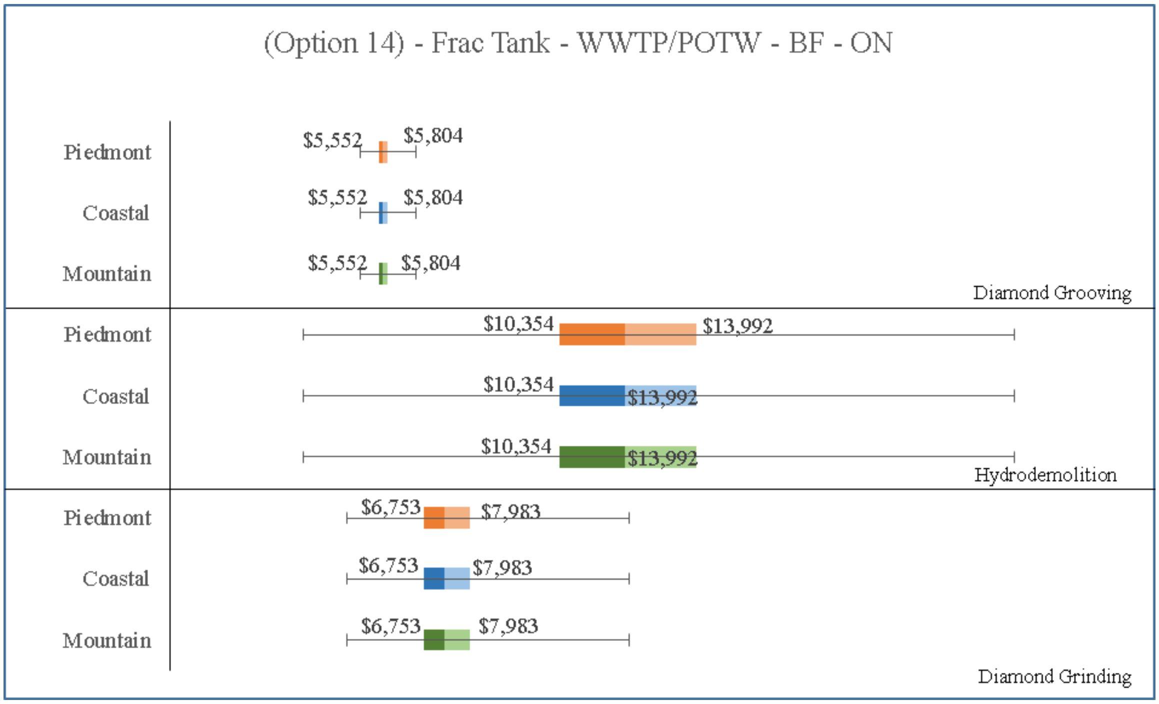


FIGURE 69: Cost simulation results - Option 14

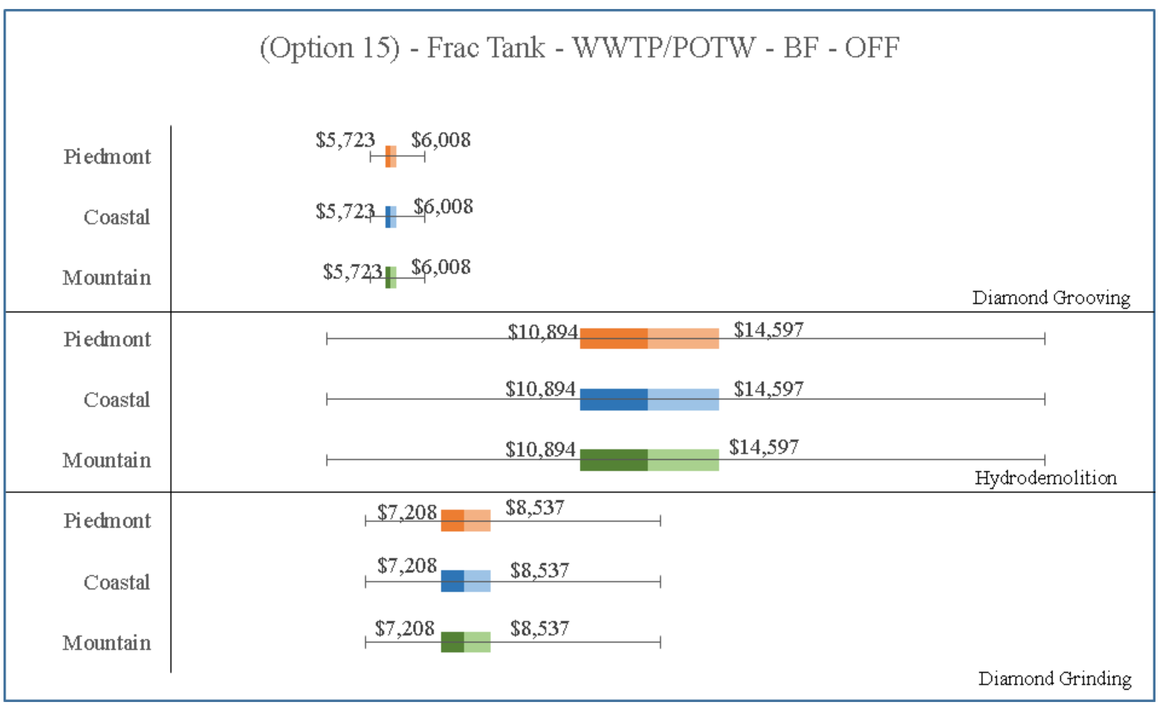


FIGURE 70: Cost simulation results - Option 15

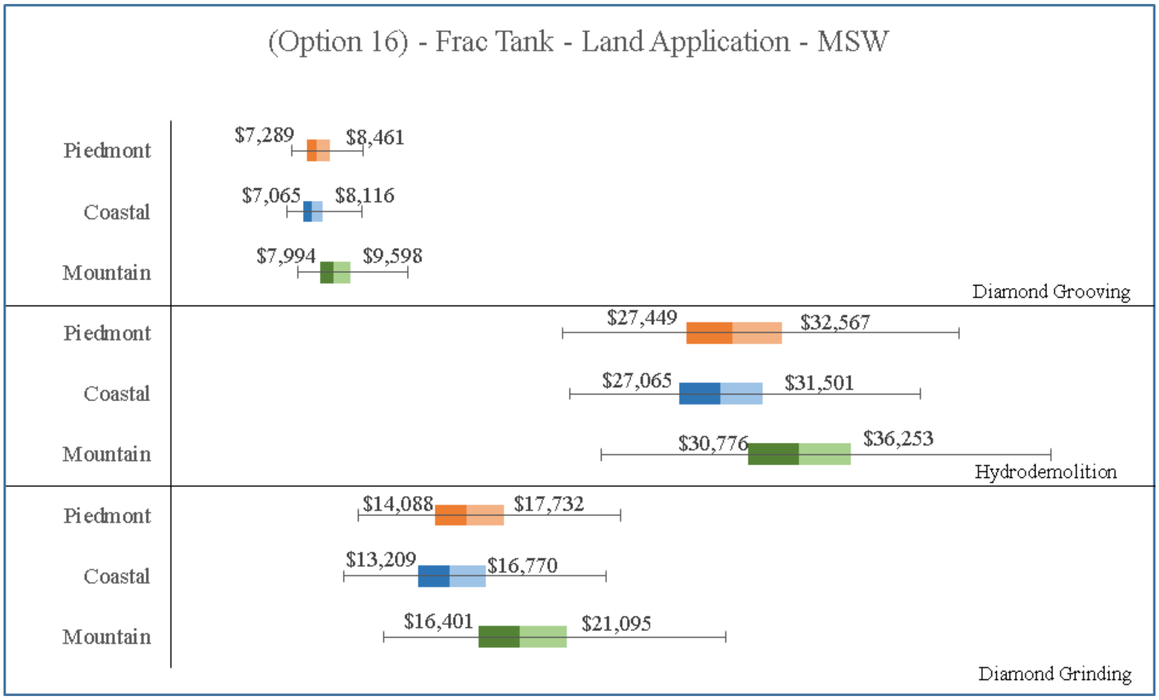


FIGURE 71: Cost simulation results - Option 16

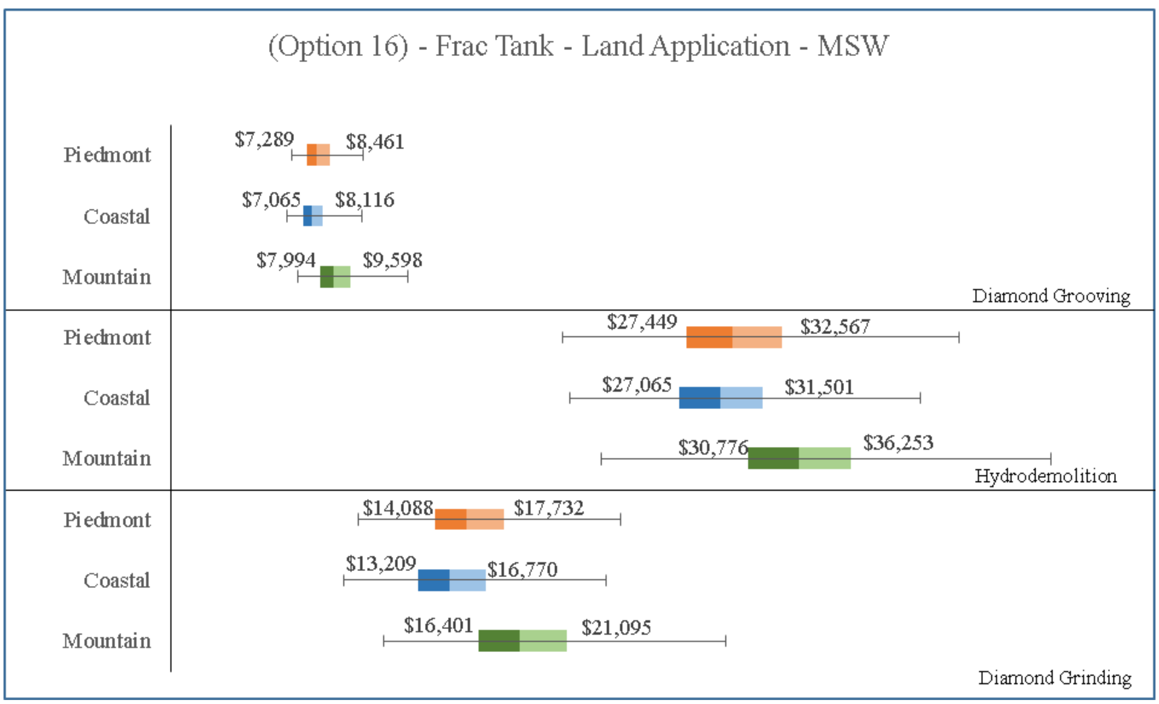


FIGURE 72: Cost simulation results - Option 17

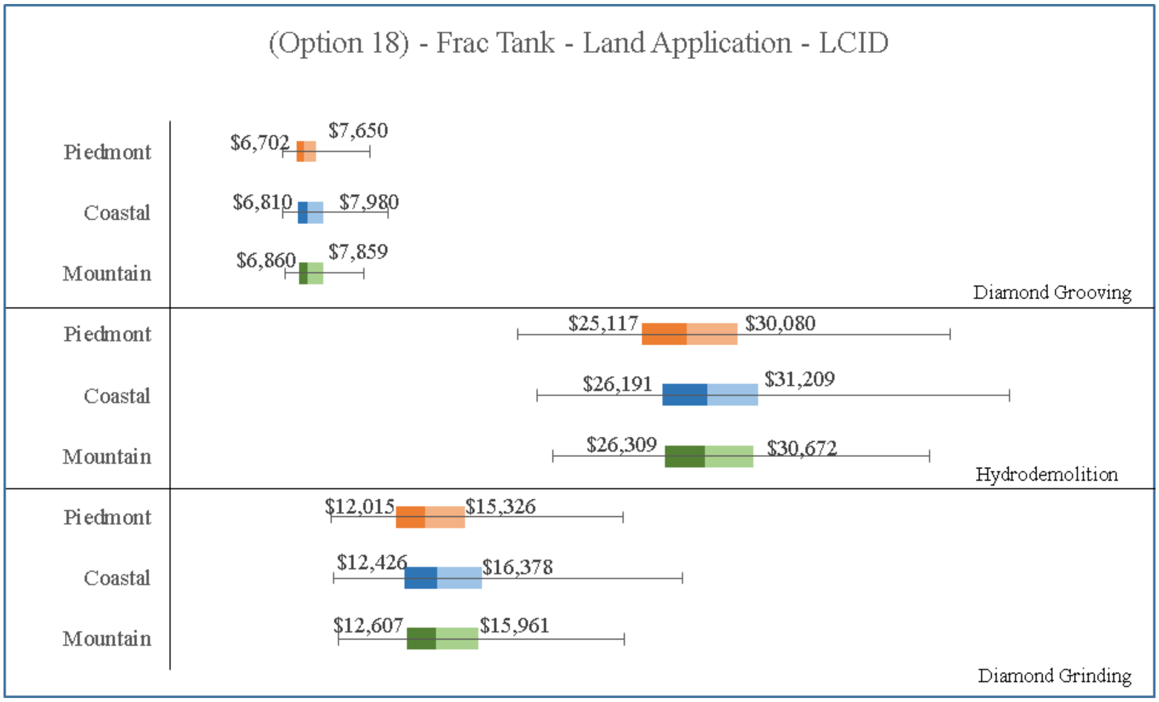


FIGURE 73: Cost simulation results - Option 18

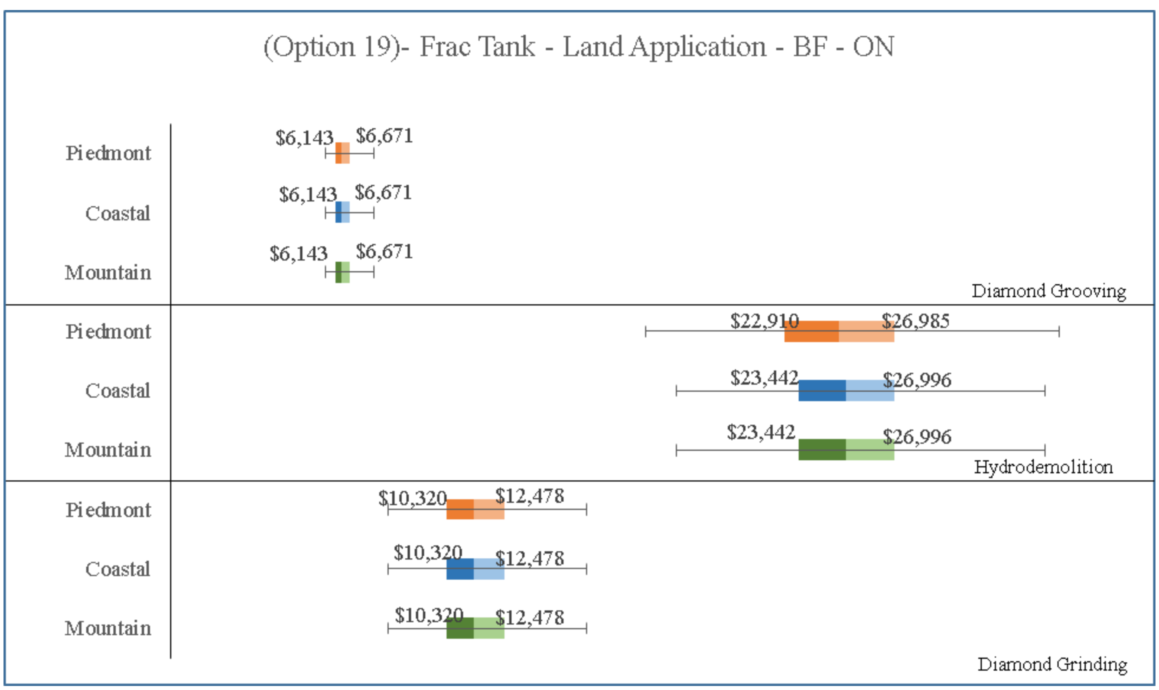


FIGURE 74: Cost simulation results - Option 19

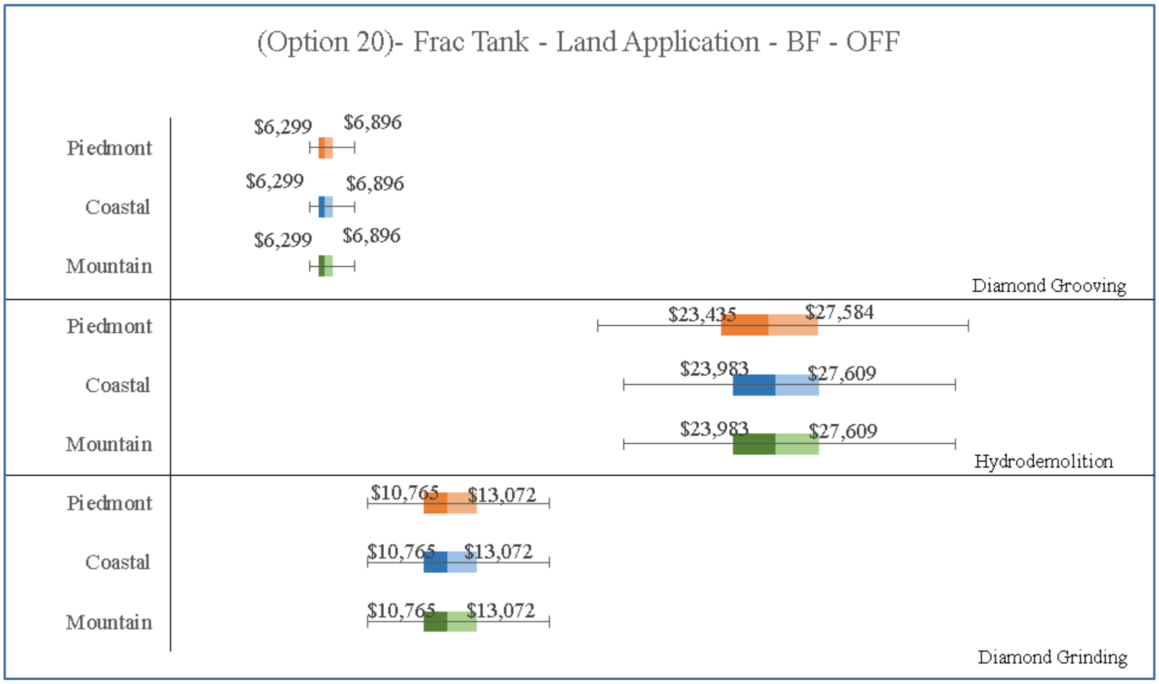


FIGURE 75: Cost simulation results - Option 20

5.1.1 Mountain Region Cost Data

In this subsection, the costs of the three construction activities and the various reuse/disposal options when the work is being done within the Mountain region of North Carolina are compared.

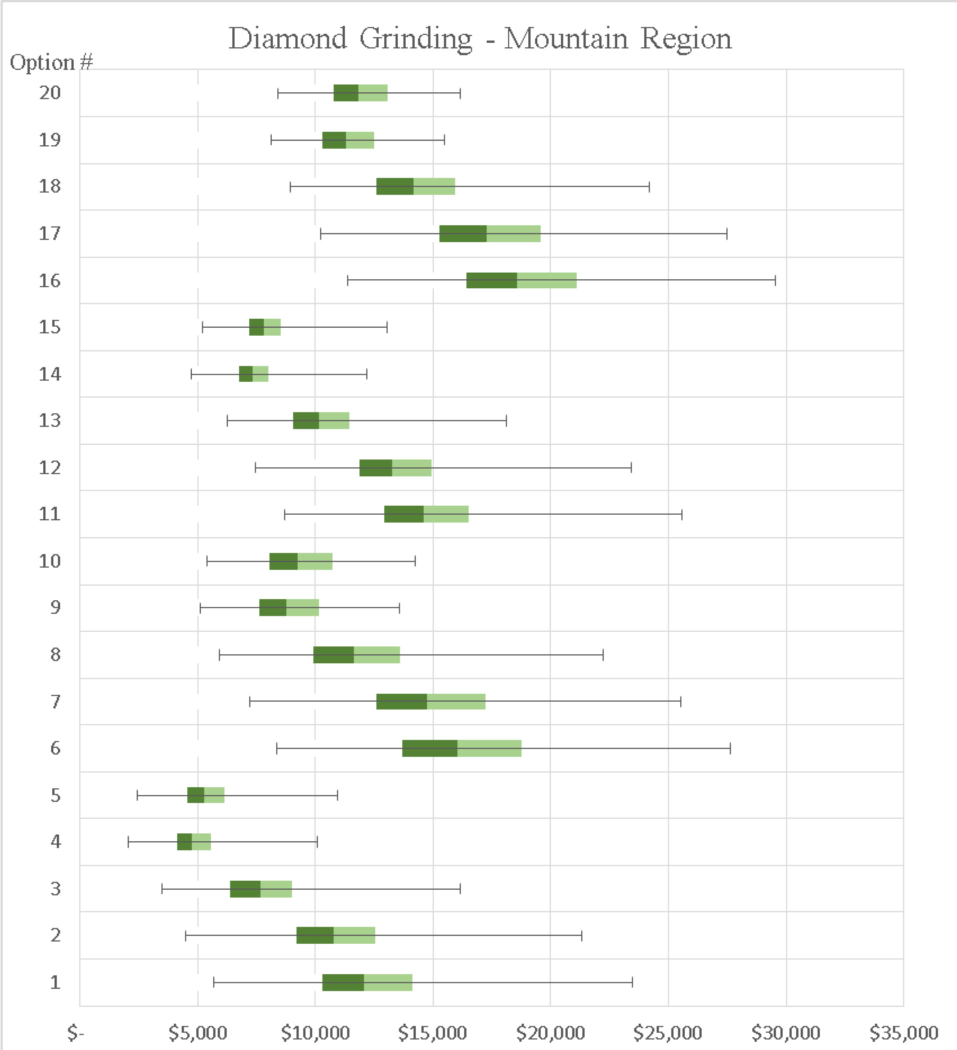


FIGURE 76: Cost simulation results diamond grinding in the Mountain region

The data seen in Figure 72 shows that for diamond grinding in the Mountain region, the decanting pond is more cost effective than the Frac tank as a method of slurry handling. Options 1-10 when compared to Options 11-20 is on average more than $2835 cheaper. On a cost basis, the preferred method of liquid residual management is clearly POTW/WWTP when compared to Land Application. This is shown by the cost increase from Options 1-5/Options 11-15 when compared to Options 6-10/Options 16-20 respectively. The trend for solid residual management within the Mountain region is consistent no matter what slurry/liquid management options are chosen. From least to most expensive, the preferred method of solid residual management is beneficial fill onsite, beneficial fill offsite, LCID landfill, C&D landfill, and finally MSW landfill.

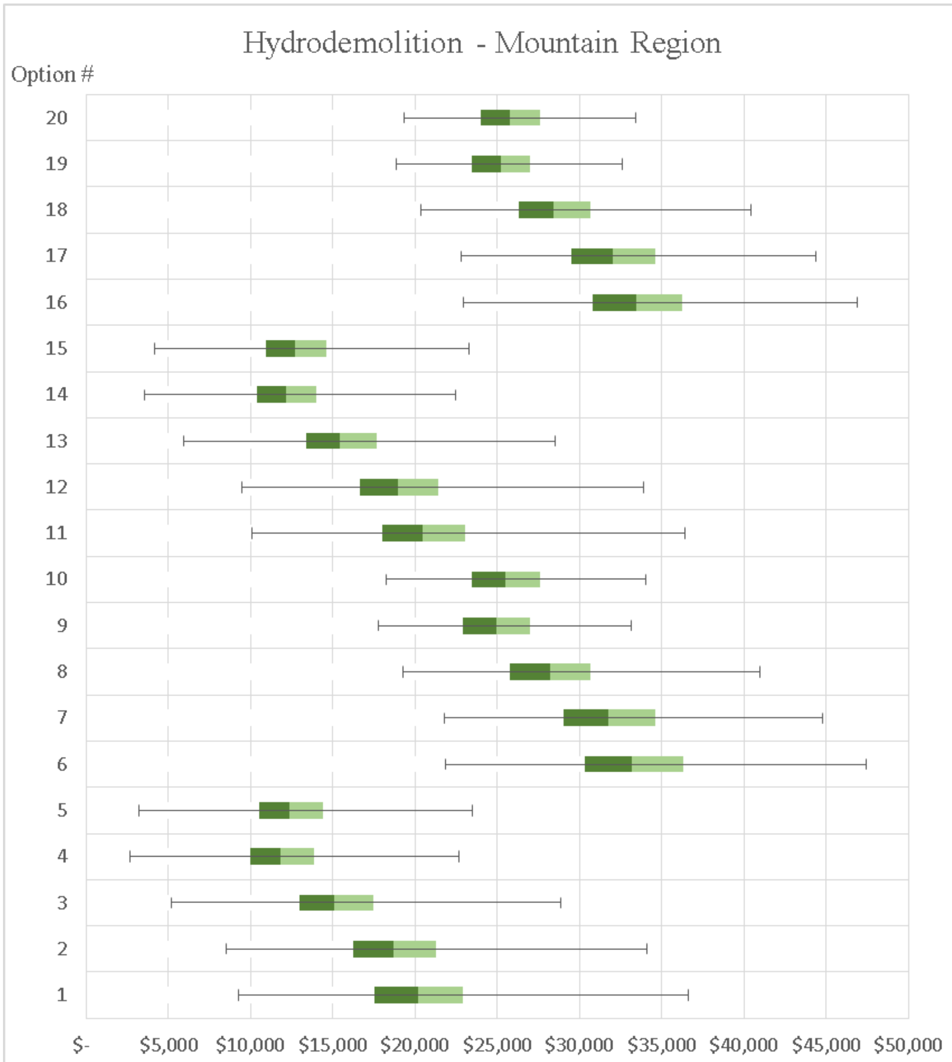


FIGURE 77: Cost simulation results for hydrodemolition in the Mountain region

In terms of solid and liquid disposal/reuse the same trends exist in Figure 72 and Figure 73. However due to the high quantity of slurry produced from hydrodemolition, there is less economic advantage for using for using the decanting pond over the Frac tank, as is shown by the small difference in costs when comparing Options 1-5 and Options 11-15, or Options 6-11 and Options 16-20.

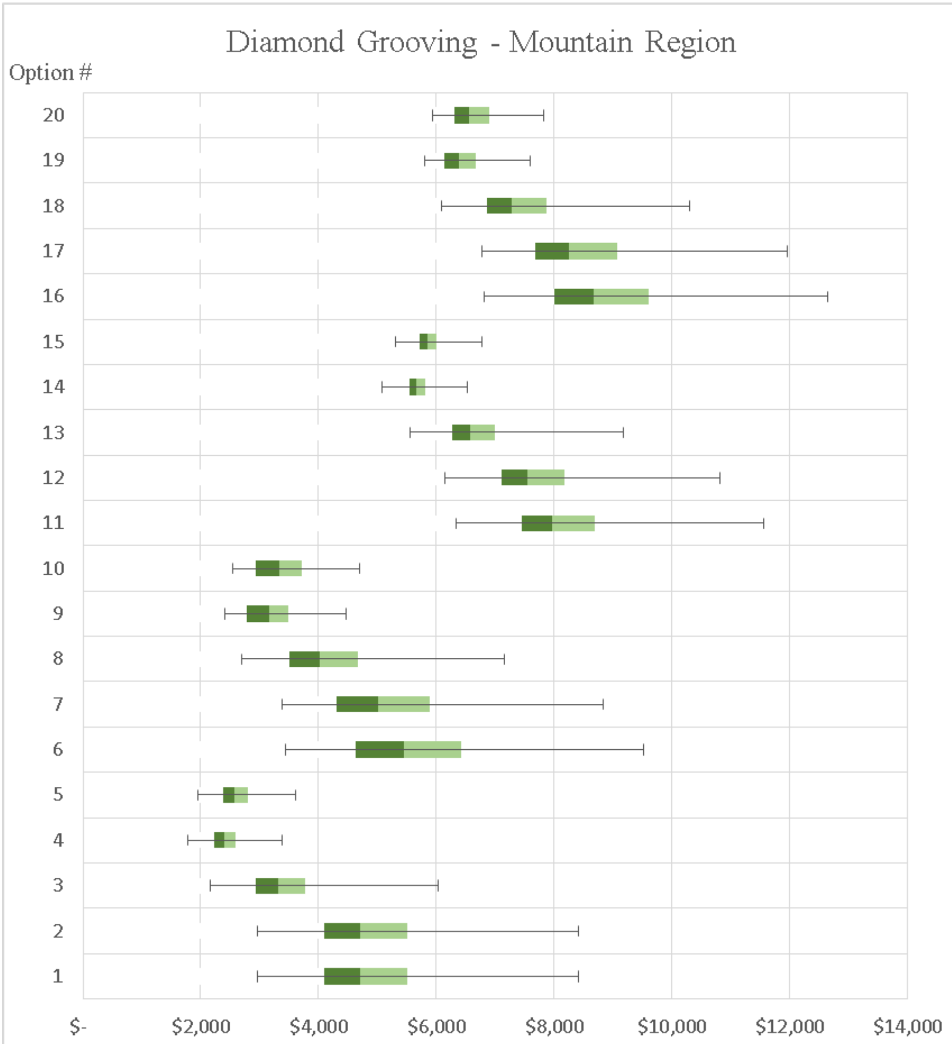


FIGURE 78: Cost simulation results for diamond grooving in the Mountain region

In terms of slurry and solid residual management, the same trends exist in Figure 72 and Figure 74. However when it comes to liquid residual management for diamond grooving, disposal at a WWTP/POTW holds less of an economic advantage than land application because of the small amount of liquid residual that is created from this process.

5.1.2 Piedmont Region Cost Data

This subsection, the costs of the three construction activities and the various reuse/disposal options when the work is being done within the Piedmont region of North Carolina are compared.

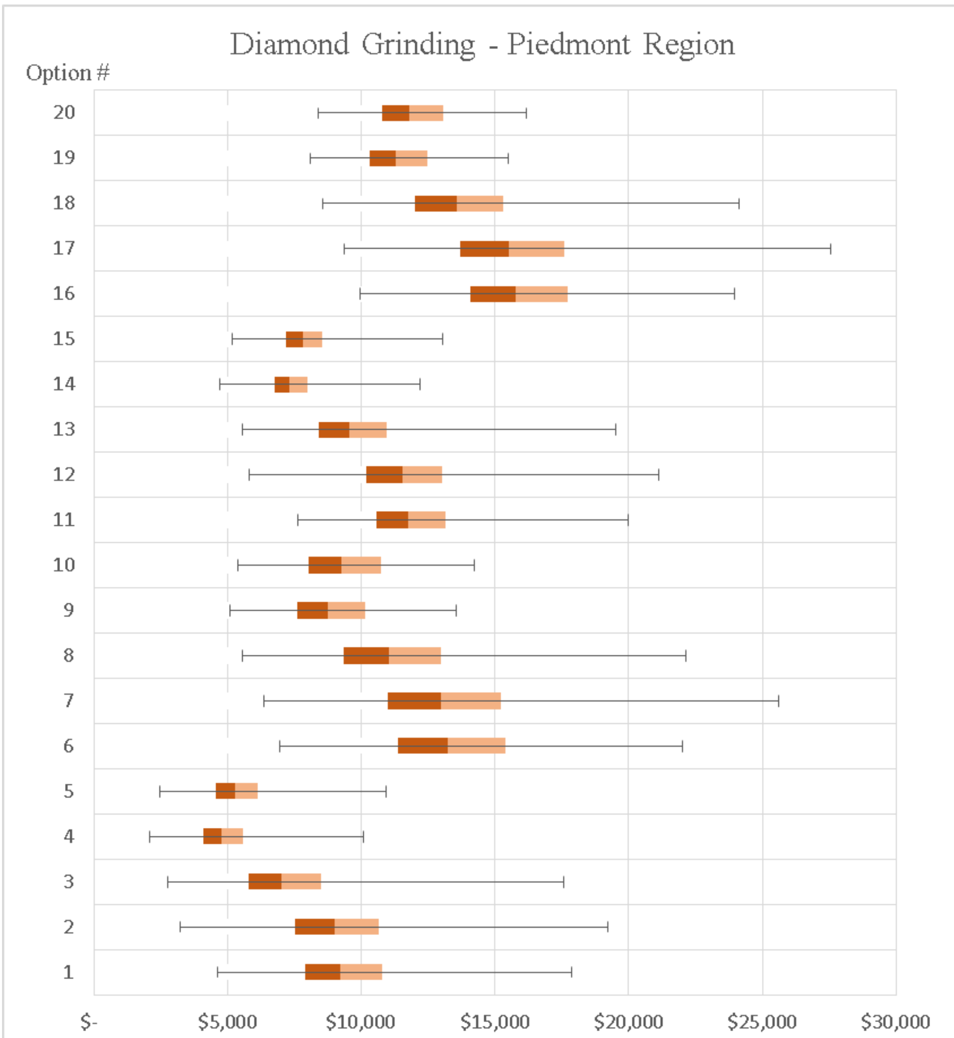


FIGURE 79: Cost simulation results for diamond grinding in the Piedmont region

The data, as depicted by Figure 75, shows that for diamond grinding in the Piedmont region, the decanting pond is the least costly method of slurry handling over the use of a Frac tank. Options 1-10 when compared to Options 11-20 is on average more than $2831 cheaper. The preferred method of liquid residual management is clearly POTW/WWTP when compared to Land Application. This is shown by the cost increase from Options 1-5/Options 11-15 when compared to Options 6-10/Options 16-20 respectively. The trend for solid residual management within the Piedmont region is consistent no matter what slurry/liquid management options are chosen. From least to most expensive, the preferred method of solid residual management is beneficial fill onsite, beneficial fill offsite, and LCID landfill. The choice is less clear between the C&D landfill and the MSW landfill, the C&D landfill option within the Piedmont region has a lower minimum, but also a large maximum than the MSW landfill.

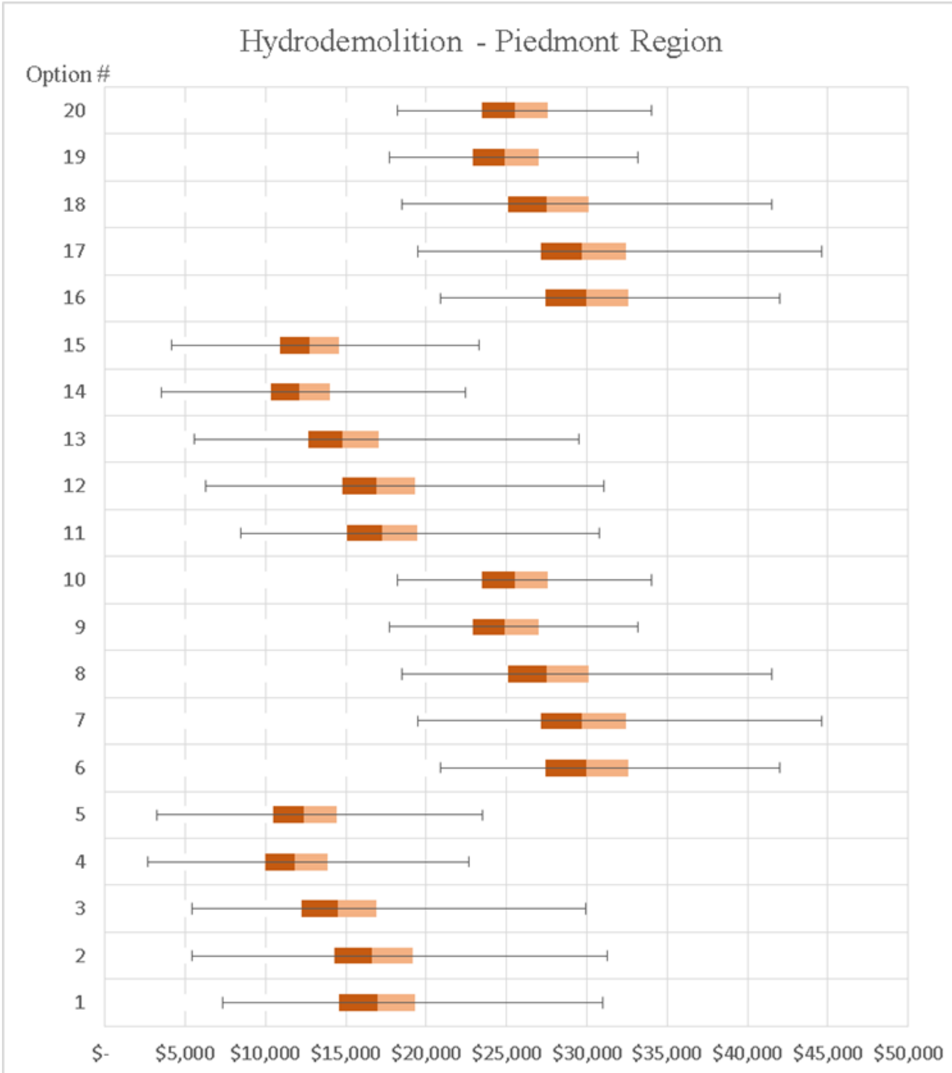


FIGURE 80: Cost simulation data for hydrodemolition in the Piedmont region

The cost data for hydrodemolition within the Piedmont region shows similar trends to hydrodemolition in the Mountain region. In terms of solid and liquid disposal/reuse the same trends exist in Figure 75 and Figure 76. However due to the high quantity of slurry produced during hydrodemolition, there is less of an economic advantage for using the decanting pond over the Frac tank, as by shown by the small difference in costs when comparing Options 1-5 and Options 11-15, or Options 6-11 and Options 16-20 as depicted in Figure 76.

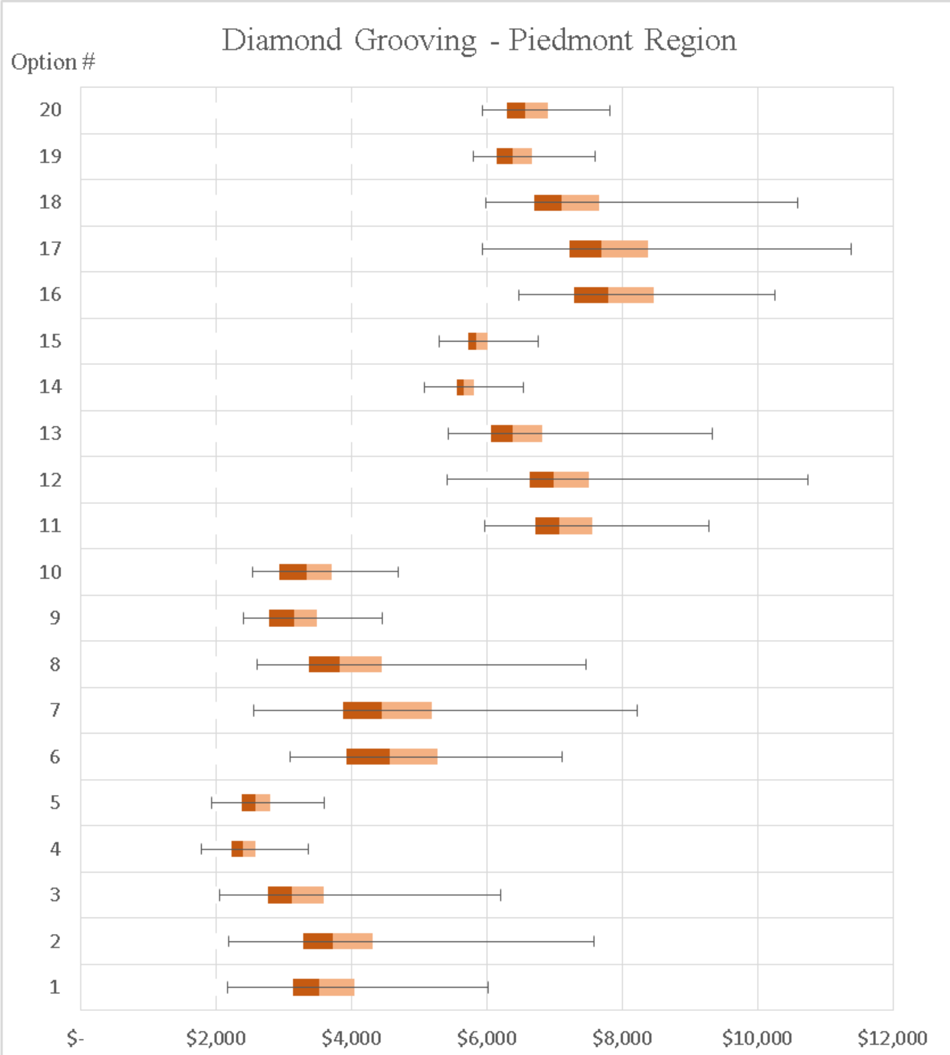


FIGURE 81: Cost simulation results for diamond grooving in the Piedmont region

The cost data for diamond grooving in the Piedmont region follows a similar trend to that shown in the Mountain region. In terms of slurry and solid residual management, the same trends exist in Figure 75 and Figure 77. However when it comes to liquid residual management for diamond grooving, disposal at a WWTP/POTW holds less of an economic advantage than land application because of the small amount of liquid residual that is created from this process.

5.1.3 Coastal Region Cost Data

In this subsection, the costs of the three construction activities and the various reuse/disposal options when the work is being done within the Coastal region of North Carolina are compared.

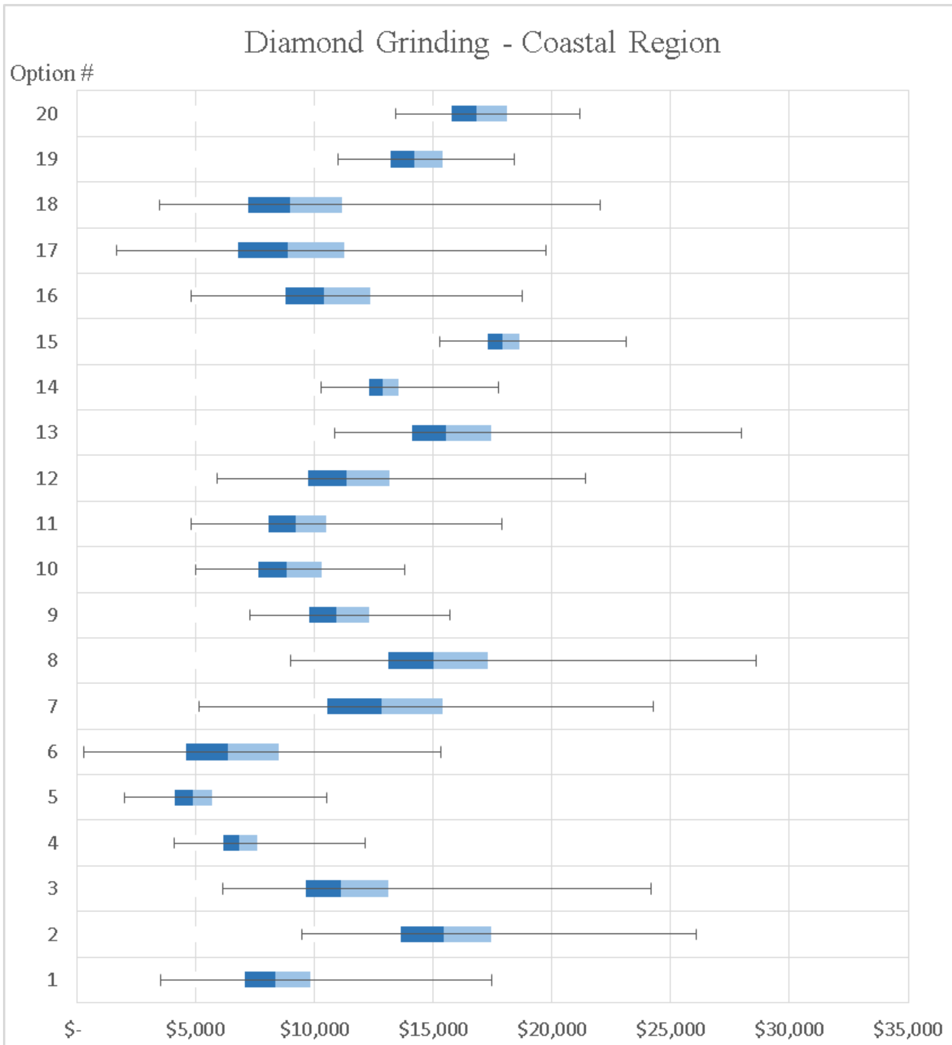


FIGURE 82: Cost simulation results for diamond grinding in the Coastal region

The data shows that for diamond grinding in the Coastal region, the decanting pond is the preferred method of slurry handling over the use of a Frac tank. Options 1-10 when compared to Options 11-20 are on average more than $2823.9 cheaper. The preferred method of liquid residual management is clearly POTW/WWTP when compared to Land Application. This is shown by the cost increase from Options 1-5/Options 11-15 when compared to Options 6-10/Options 16-20 respectively as depicted in Figure 81. The trend for solid residual management within the Coastal region is consistent regardless of the slurry/liquid management options chosen. From least to most expensive, the preferred method of solid residual management is beneficial fill onsite then beneficial fill offsite. The choice is less clear between a LCID landfill, a C&D landfill, and a MSW landfill. A LCID landfill option within the Coastal region has the next lowest minimum, however its maximum exceeds that of a MSW landfill option. A C&D landfill option within the Coastal region is the most expensive option.

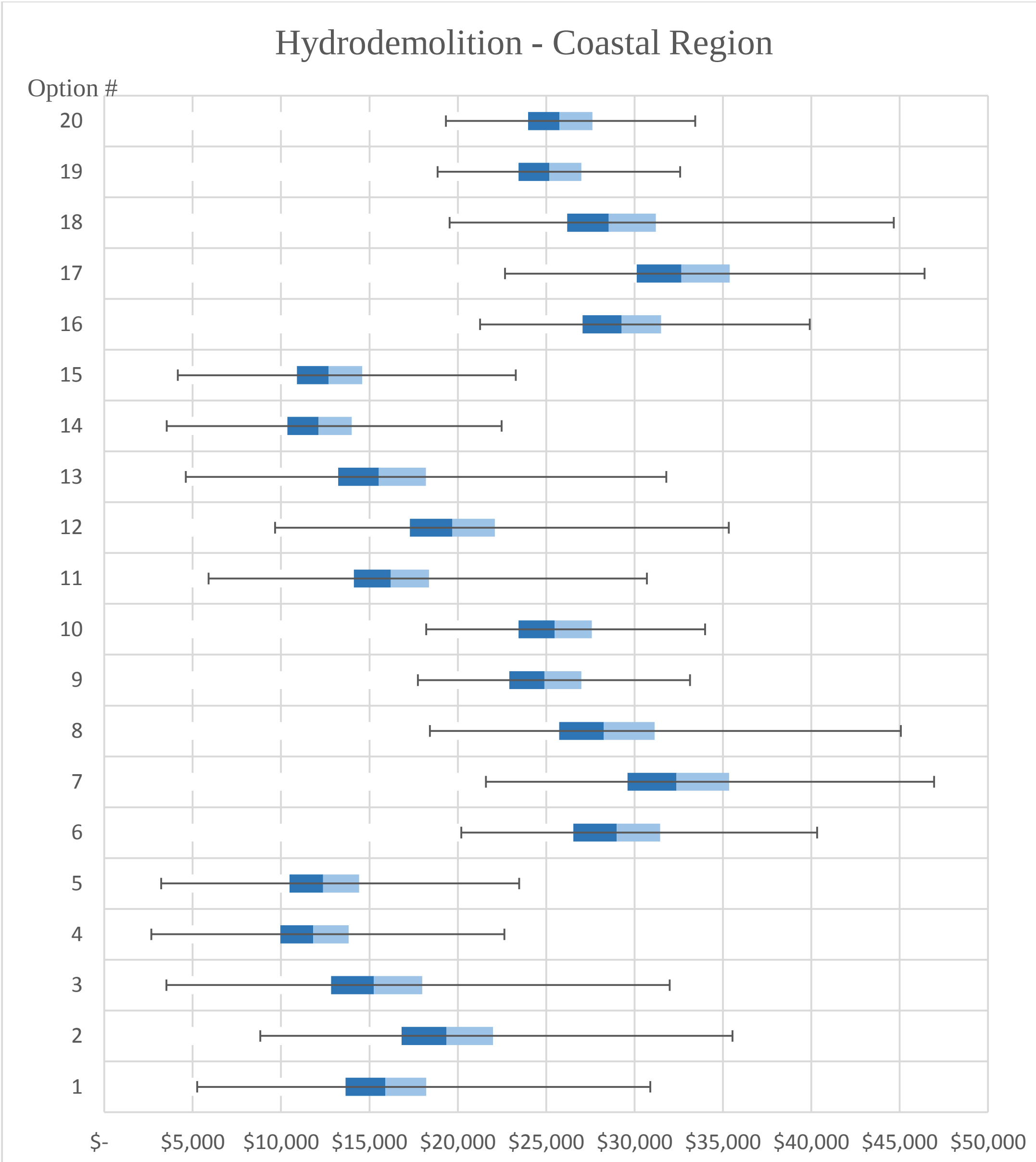


FIGURE 83: Cost simulation results for hydrodemolition in the Coastal region

The cost data for hydrodemolition within the Coastal region shows similar trends to hydrodemolition in the Mountain and Piedmont region. In terms of solid and liquid disposal/reuse the same trends exist in Figure 78 and Figure 79. However due to the high quantity of slurry produced from hydrodemolition, there is less economic advantage for using the decanting pond over the Frac tank, as is shown by the small difference in costs when comparing Options 1-5 and Options 11-15, or Options 6-11 and Options 16-20 as depicted in Figure 79.

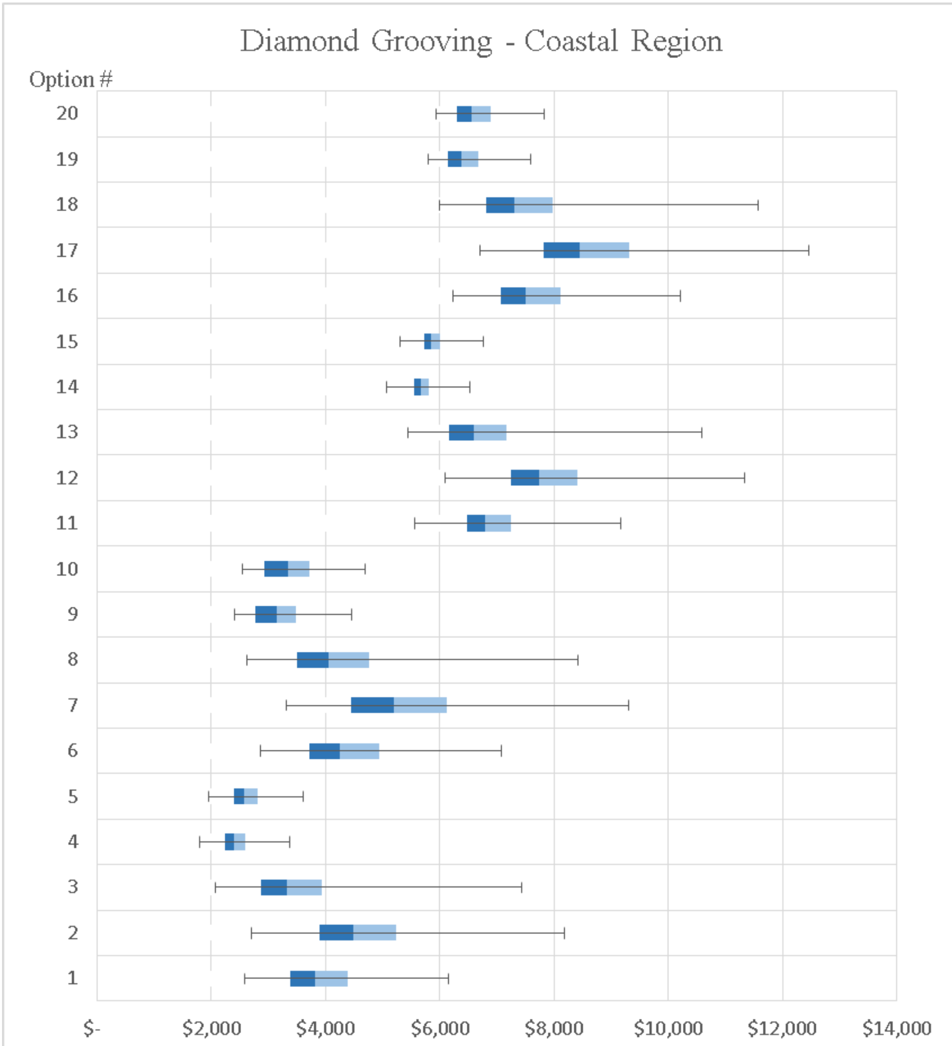


FIGURE 84: Cost simulation data for diamond grooving in the Coastal region

The cost data for diamond grooving in the Coastal region follows a similar trend to that shown in the Mountain and Piedmont region. In terms of slurry and solid residual management, the same trends exist in Figure 78 and Figure 80. However when it comes to liquid residual management for diamond grooving, disposal at a WWTP/POTW holds less of an economic advantage than land application because of the small amount of liquid residual that is created from this process.

5.2 Risk Results

No matter which option is chosen, there are unique risks associated with the operations and disposal techniques utilized in these activities that generate concrete residuals. However the risk assessment included in this model is subjective, and is dependent upon the user to assign a score for the risks associated with each option. This creates a system for ranking the options that provides the user insight into which options would be preferable based on the user input scores for risk. The weight given to risk overall, which is dependent upon a user input value, is the overall defining factor of how strongly the model will interpret the choice of option depending upon its associated risks.

5.3 Environmental Benefit

The environmental benefits portion of the model is also subjective, however some methods of handling slurry, liquids, and solids potentially hold environmental benefits over the others. For methods of slurry handling, the use of the Frac tank likely holds an environmental benefit over the construction/deconstruction of the decanting pond because there is less disruption to the natural land as well as less energy expended in hauling. For the method of liquid residual management, beneficial reuse via land application very likely holds a potential advantage over disposal via POTW/WWTP. For the method of solids management, the ranking of choices in terms of environmental benefit is as follows: beneficial fill onsite, beneficial fill offsite, disposal at an LCID landfill, disposal at a C&D landfill, and finally disposal at a MSW landfill.

The effect of the environmental benefits within the model, no matter how advantageous, will depend upon the given weight that the user has given in the hypothetical model. The given weight will determine how strongly the model will weigh environmental benefits in its final calculation of which options are most preferable

CHAPTER 6: CONCLUSIONS, LIMITATIONS, RECOMMENDATIONS, AND FUTURE WORK

6.1 Conclusions

The model can be used to estimate the cost of the given work associated with production, handling, and disposal of concrete residuals for diamond grinding, grooving, and hydrodemolition activities performed on North Carolina highways, and can be used to provide the user with insight into various options that they may not have known about. The model will help the user to choose an option to mitigate risk, as well as maximize potential environmental benefit.

The model simulation results showed that the most cost effective method of slurry handling was to create a decanting pond, unless the user is conducting hydrodemolition work and there will be a large amount of concrete slurry. In the case of hydrodemolition, use of a Frac tank may be more cost effective due to the large quantity of liquid residuals created. The Frac tank is the more environmentally friendly of the two options, as well as the least risky option because this is method has the smallest possibility of releasing residuals to the environment.

The model simulation results showed that deposition of the liquid residuals at a POTW/WWTP is far more cost effective than land application, unless the user is conducting diamond grooving operations. If the overall quantity of liquid is relatively small, land application can be just as cost effective. Based on feedback from NCDOT, land application is also perceived to be the less risky and more environmentally friendly option of liquid residual management.

The results for model simulations for solid residual management showed that no matter what the region the work was being conducted, beneficial fill onsite is the most cost effective, least risky, and likely most environmentally friendly option available for solids residual management. The second most cost effective, second most risk adverse, and second most environmentally friendly option was beneficial offsite. The third best option in most cases is disposal at an LCID landfill for all regions, however in the Coastal region, LCID landfills had a higher ceiling than MSW landfill. However the LCID landfill is likely more environmentally friendly and more risk averse than a MSW landfill according to North Carolina Administrative Code, which states that MSW landfills should only be used as a last case scenario.

The rest of the simulation results varied dependent upon which region the work was being conducted. As previously stated, the LCID landfill has a higher ceiling than the MSW landfill in the Coastal region. However in the Mountain region disposal via a C&D landfill is the fourth best option in terms of cost, and perceived environmental friendliness than disposal at a MSW landfill. In the Piedmont region, disposal via C&D landfill has a lower minimum cost than disposal at a MSW landfill, however the maximum cost of disposal at a C&D facility exceeds the maximum cost of disposal at a MSW landfill facility by roughly $124. In the Coastal region, disposal at a C&D facility is by far the most expensive option of disposal.

6.2 Limitations

This research is fairly comprehensive in terms of scale, however it also has its limitations. The data for cost was heavily dependent upon data given from landfills, WWTP's/POTW's, and land application facilities. The overall number of data points from WWTP/POTW and land application sites were very low. Owners of a number of land application sites were not comfortable sharing their cost data for research. Also a large limitation that existed was that many POTW/WWTP's were unsure as to whether their facility would accept the liquid residual material, and were not familiar with the material. Many stated that they would need a representative sample from the contractors before they could give a definitive answer as to whether or not they would accept the material. This is contrary to the typical work structure which states that the contractor should define where the residuals will be disposed/deposited before the start of work.

A major limitation that the research team had run into was the fact that many wastewater facilities, especially within the Piedmont region, would not be able to provide a price unless they could first test the material.

It should also be noted that this model is only applicable within the state of North Carolina. Other states may have different regulations that could alter costs, risks, and environmental benefit.

6.3 Recommendations

Based on the research performed, NCDOT should consider the following recommendations. Since land application was the most preferred method of residual management per NCDOT personnel, the agency should consider ways to increase the attractiveness of this disposal method as an option to private sector firms performing the majority of diamond grinding, diamond grooving, and hydrodemolition activities. This can be done by creating more land application sites throughout the state, and especially distributing them more evenly throughout the regions. This would decrease the cost of land applying residuals.

NCDOT should also look for possible ways to subsidize land application costs, since this is perceived as the agency's most environmentally friendly option, and does not add to the loading of current solid/liquid waste facilities. If private firms could see land application as a more economically viable option, this environmentally friendly option could also be the most favorable option. The agency should also try to encourage private firms to treat/handle residuals to help other companies streamline the process.

6.4 Future Work

The model should be expanded beyond North Carolina to other states in order to provide a state-to-state comparison of the most economically and environmentally friendly options to see which options work best based on location. This could also create a system that allows states to collaborate to increase use of more environmentally friendly options in ways that would be most economical. A national set of standards for treatment of the residual materials would also be helpful in working towards finding the best ways to handle and treat the material.

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APPENDIX A: STATE LITERATURE RESEARCH

STATE	Hydrodemolition	Grinding	Grooving
Alabama (ALDOT, 2012)	N/A	1-Lane, self-propelled equipment Removed continuously; not to flow onto lanes or into drainage structures	All residue, slurry, or other waste to be continuously removed Waste to be disposed in earthwork; if approved by an engineer If not approved by engineer; dispose according to applicable laws
Alaska (ADOT&PF, 2011; Green, 2004)	Must submit WTP; Method of collection, filtration, storage, and disposal. Debris disposed at DEC approved landfill	Equipment must limit slurry generated, and maximize slurry captured	N/A
Arizona (ADOT, 2008)	N/A	CGR to be removed by vacuum prior to re-opening lane Removed continuously; not to flow on lanes or into drainage structures Dry Residue to be picked up with "power broom"	Slurry/residue removed continuously Not to flow across shoulder, into other lanes, or drainage facilities Dry residue to be picked up with "power broom"
Arkansas (AHTD, 2014)	N/A	Self-propelled equipment Contractor to remove grinding residue; Solids removed immediately; Slurries/liquids not to flow on lane or into drainage facilities	Self-propelled equipment Contractor to remove grinding residue; Solids removed immediately; Slurries/liquids not to flow on lane or into drainage facilities
California	Remove HOS immediately by vacuum; not to flow	Remove CGR immediately by vacuum; not to flow	CGR to be removed by vacuum and

(Caltrans, 2003, 2008, 2010)	onto lanes or into drainage facilities/gutters. Slurry can be deposited into onsite temporary concrete washout facilities Liquid to be decanted and reused until end of useful life; then taken to non-sewage waste treatment facility Solid CGR can be incorporated in embankment	onto lanes or into drainage facilities/gutters. Slurry can be deposited into onsite temporary concrete washout facilities Liquid to be decanted and reused until end of useful life; then taken to non-sewage waste treatment facility Solid CGR can be incorporated in embankment	disposed at approved facility Solid CGR can be incorporated in embankment Slurry can be placed in impoundment Liquid to be decanted and reused until end of useful life; then taken to non-sewage waste treatment facility
Colorado (CDOT, 2011)	HOS to be handled, stockpiled, & disposed without discharge to state waters Contractor to submit pollutant containment plan	CGR to be handled, stockpiled, & disposed without discharge to state waters Contractor to submit pollutant containment plan	CGR to be handled, stockpiled, & disposed without discharge to state waters Contractor to submit pollutant containment plan
Connecticut (ConnDOT, 2011; E. B. Smith, 2006)	Contractor to submit plan for filtration, containment, and disposal of HOS No residual release to the environment	Contractor to submit plan for filtration, containment, and disposal of CGR Solids settled in sedimentation basin; removed at end of work	All residuals to be removed in an environmentally friendly manner
Delaware	N/A	N/A	N/A
District of Columbia	N/A	N/A	N/A
Florida (FDOT, 2010)	Control & maintain all residuals throughout Measure residuals for safe contaminant levels before discharge	Solids removed before re-opening lane Slurry not to flow onto lanes, or into drainage facilities/sewers No residuals to enter bodies of water	N/A

Georgia (GDOT, 2013)	N/A	Self-propelled equipment Remove CGR immediately; not to flow onto lanes or into drainage facilities/gutters. Waste not to enter any bodies of water Transport residuals without leaks/spills Regulated solid waste deposited in C&D landfill	Self-propelled equipment Remove CGR immediately; not to flow onto lanes or into drainage facilities/gutters. Waste not to enter any bodies of water Transport residuals without leaks/spills Regulated solid waste deposited in C&D landfill
Hawaii (CCHDES, 2011)	Remove HOS immediately by vacuum; not to flow onto lanes or into drainage facilities/gutters. Allow liquids to dry in a sedimentation pit, or pump water to sanitary sewer Solids from HOS can be incorporated in embankment	Remove CGR immediately by vacuum; not to flow onto lanes or into drainage facilities/gutters. Allow liquids to dry in a sedimentation pit, or pump water to sanitary sewer Solid CGR can be incorporated in embankment	Remove CGR immediately by vacuum; not to flow onto lanes or into drainage facilities/gutters. Allow liquids to dry in a sedimentation pit, or pump water to sanitary sewer Solid CGR can be incorporated in embankment
Idaho (IDT, 2012)	All residuals collected and disposed by land application off-site May store in lined collection pond	N/A	N/A
Illinois (Associates, 2009; IDOT, 2012)	Liquid not to flow onto lanes or into drainage facilities Solids used in fills or embankments Solids may be disposed in licensed landfill	CGR to be disposed of in a licensed landfill, or otherwise recycled/reused Continuously remove all CGR from surface; must not flow into drainage structures or onto lanes	Residuals removed continuously by vacuum Surfaces flushed with water Liquids to be held in facilities
Indiana (Associates, 2009; INDOT, 2014)	Water must be potable. Not allowed to be	Continuously remove all CGR from surface; must not flow into drainage	Remove residue immediately from surface using vacuum/brooms

	discharged into bodies of water	structures or onto lanes Removed from site in tanker truck	
Iowa (IowaDOT, 2012a, 2012b)	N/A	All CGR removed from surface continuously; kept from flowing onto lanes, or into drainage facilities CGR may be spread on foreslopes for disposal	All CGR removed from surface continuously; kept from flowing onto lanes, or into drainage facilities CGR may be spread on foreslopes for disposal
Kansas (KDOT, 2007a, 2007b)	Submit protected area map, and wastewater handling plan	CGR removed continuously by vacuum; not to flow onto lanes, into drainage facilities, or bodies of water	Reside removed continuously by vacuum; not to flow onto lanes, into drainage facilities, or bodies of water
Kentucky (KYTC, 2012)	N/A	CGR to be cleaned from surface; not to flow onto lanes, or into drainage structures Submit wastewater treatment plan	CGR to be cleaned from surface; not to flow onto lanes, or into drainage structures Submit wastewater treatment plan
Louisiana	N/A	N/A	N/A
Maine	N/A	N/A	N/A
Maryland	N/A	N/A	N/A
Massachusetts	N/A	N/A	N/A
Michigan (MDOT, 2012)	N/A	Develop residual management and disposal plan Disposal may take place on roadway side slopes	Develop residual management and disposal plan Disposal may take place on roadway side slopes
Minnesota (Druschel, 2012; MnDOT, 2012)	N/A	In rural areas. CGR may be deposited on vegetated side slopes CGR must be vacuumed continuously	In rural areas. CGR may be deposited on vegetated side slopes CGR must be vacuumed continuously

		May place in settlement pond; water to evaporate, while solids to be used as fill material or recycled aggregate	May place in settlement pond; water to evaporate, while solids to be used as fill material or recycled aggregate
Mississippi (MDOT, 2004)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures
Missouri (Wenzlick, 2002)	Slurry may be dispersed inside ROW No HOS to be discharged into state waters	CGR slurry is allowed to be discharged onto vegetated side slopes Slurry can be pumped into tankers and hauled offsite Solid CGR can be used as fill in embankments	CGR slurry is allowed to be discharged onto vegetated side slopes Slurry can be pumped into tankers and hauled offsite Solid CGR can be used as fill in embankments
Montana	N/A	N/A	N/A
Nebraska (NDOR, 2007; World, Water Resources Congress, & Water Resources, 2006)	N/A	CGR to be removed from surface before it spreads	CGR to be removed from surface before it spreads
Nevada (NDOT, 2014)	N/A	CGR to be disposed of in authorized Class I or II landfill or permitted Class III landfill	CGR to be disposed of in authorized Class I or II landfill or permitted Class III landfill
New Hampshire	N/A	N/A	N/A
New Jersey (N.J.A.C., 2012; N.J.S.A, 2014; NJDOT, 2007)	N/A	CGR disposed/recycled according to Solid Waste Management Act	CGR disposed/recycled according to Solid Waste Management Act

		CGR is a Class B recyclable material; must be approved before storage, processing, and transferring to recycle center	CGR is a Class B recyclable material; must be approved before storage, processing, and transferring to recycle center
New Mexico (NMDOT, 2014)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures
New York (NYSDOT, 2014)	Must develop comprehensive plan for filtration and disposal of HOS HOS not to enter bodies of water		
North Dakota (NDDOT, 2014)	N/A	CGR continually removed; disposed through beneficial use Disposed at permanent waste management facility; may be disposed as an inert waste	CGR continually removed; disposed through beneficial use Disposed at permanent waste management facility; may be disposed as an inert waste
Ohio (ODOT, 2012)	Wastewater pH not to exceed 11.5 Wastewater must be recycled at an appropriate facility If pH adjusted to 5-9, may dispense residuals on side of road	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures
Oklahoma (ODOT, 2009)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures
Oregon	N/A		

(ODOT, 2015)		CGR must be recycled/reused; solids can be used as beneficial fill or in basements	CGR must be recycled/reused; solids can be used as beneficial fill or in basements
Pennsylvania (PennDOT, 2014)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures
Rhode Island (RIDOT, 2010)	HOS will be collected in containment system; either lined pit or man-made container Liquid to be removed/discharged after settling period; not to enter drainage facilities Solids to be collected from bottom of basin and disposed of properly	N/A	N/A
South Carolina	N/A	N/A	N/A
South Dakota (SDDOT, 2001)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures Slurry must be filtered; can use sedimentation basin	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures Slurry must be filtered; can use sedimentation basin
Tennessee (TDOT, 2006)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures

		CGR may be disposed on roadway slopes; if vegetative cover and slopes conditions are met	CGR may be disposed on roadway slopes; if vegetative cover and slopes conditions are met
Texas	N/A	N/A	N/A
Utah (UDOT, 2012)	HOS is to be collected in retention basins/sediment traps All water used is to be cleaned before being returned to streams	N/A	N/A
Vermont	N/A	N/A	N/A
Virginia (VDOT, 2007)	N/A	CGR to be disposed in sanitary landfill, or licensed industrial landfill Liquid material is to be taken to a POTW	CGR to be disposed in sanitary landfill, or licensed industrial landfill Liquid material is to be taken to a POTW
Washington (WSDOT, 2014; Yonge. David, 2005)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures
West Virginia (WVDOH, 2010)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures
Wisconsin	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures CGR to be disposed of at authorized disposal site	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures CGR to be disposed of at

			authorized disposal site
Wyoming (WYDOT, 2010)	N/A	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures CGR to be disposed of at authorized disposal site	CGR must be collected and removed continuously; not to flow onto lanes or into drainage structures CGR to be disposed of at authorized disposal site

APPENDIX B: QUESTIONAIRE FOR CONTRACTORS

Types of material

1. What types of materials do you have experience of disposing?
2. What kinds of projects did these material come from? (hydrodemolition/grinding/grooving/road/bridge)
3. Describe the methods and equipment used for collecting and storing these material. Please provide any pictures you have.
    a. How many of each equipment?
    b. Types of equipment?
    c. Capacity of equipment?
4. Who performed the work for grinding/grooving/hydrodemolition?
    a. Types of contract was used? Were there any pre-bid qualifications considered?
    b. What was included in the work? (Please provide all phases and steps)
    c. What were the responsibilities of each party involved? (Available contracts?)
5. What were the risks associated with performing the work? Storage of the material?
    a. How was that risk mitigated?
    b. What precautionary measures did you take?
    c. Were there any extra cost items associated?
6. What options did you consider for disposing of the materials?
7. What did you end up deciding to do?

Tests Performed (Paint Filter Test)

1. Were the tests performed?
2. Who performed the paint filter test?
3. How was it performed?
4. How many tests were performed?
5. What are the costs associated with the tests?

Disposal of Solids

1. For the solids associated with the disposal in your project, what method of disposal/reuse did you decide to use?
2. Why did you make that choice?
3. Where was it disposed?
4. How were the solids transported? Who transported them?
    a. Additional associated safety costs?
5. Rates of generation of debris? Volume per area of hydrodemolition?
6. Who performed the disposal?

7. What was the costs/benefits realized from disposal?
8. Can the transportation logs be obtained?
9. Were there any unforeseen costs that surfaced?
10. Any attempts to amend the original contract for the DOT with change orders?

Solids (Beneficial Use)

1. What beneficial use did you decide to use?
2. Why did you make that choice?
3. What were the costs/benefits associated with these disposal methods?
4. What was the hauling distance? Where were they disposed? Who transported the material?
5. Who performed the disposal?
6. Were there any other hidden costs?

Alternate Daily Cover (ADC)

1. What ADC performed?
2. How was it performed?
3. Where did that happen?
4. Who transported the material?
5. Were there any acceptance costs for using as ADC?

Land Application

1. Tests Performed (Who? / How many? / How often?):
    a. Nitrates
    b. Agronomic rates
    c. Set back
    d. pH Tests
    e. Corrosivity
    f. Chemical Oxygen Demand (COD)
2. Any other tests?
3. Legal fees?
4. Hidden Costs?
5. Costs Associated with the Spill Control Plan?
    a. Measures taken to perform spill control plan
    b. Risks associated with spill control plan
    c. Is the spill control plan product specific?
6. Are there any other factors that influence costs in Land Application?
7. Are there any other risks associated with Land Application?
8. Are there costs associated with reporting of information and tests?
9. Were there any costs associated with the creation and submission of the annual report?

Disposal of Liquids

Publicly Owned Treatment Works/Wastewater Treatment Plant (POTW/WWTP)

1. Did you have any materials disposed of at POTW's/WWTP's?
2. Why did you choose this option?
3. Who performed the disposal?
4. How was the material transported?
5. What are our costs factors associated with this disposal method?
6. What are the risks associated with this disposal method, if so how were these risks mitigated?

Beneficial Use – Reclaimed Water

1. Effluent Standards
    a. How many tests were performed?
    b. Who performs the tests?
    c. How frequent were the tests?
    d. Are there any other costs factors associated with the tests?
2. How was the material stored at the site?
    a. Any costs associated with storage?
    b. Any risks associated with storage? Risk mitigation?
3. Were there any setback requirements
4. Operations & Maintenance Plan
    a. Are there costs to certification?
    b. Any other costs?
    c. Any other costs due to weather or other delays?
5. Monitoring requirements?
6. Safety Requirements?
7. Any other risks? Mitigation techniques?

APPENDIX C: PROBABILITY DISTRIBUTION FUNCTION DATA

Piedmont - LCID				Beneficial Reuse		
Location ID #	$/TON	County Regulation	Out County Price	Road Base	ADC	Resell
1	0			x	x	
2	0	x		x		
3	0	x	15	x	x	
4	0			x		
5	0			x		
6	0			x		
7	0			x		
8	0			x		
9	0			x		
10	5			x		
11	5			x		
12	6			x		
13	9.75					
14	9.75			x		
15	10			x		x
16	29.5					
17	30					
18	31					
19	39					
20	46					

Piedmont - MSW			
Location ID #	$/TON	County Regulation	Out County Price
1	22	x	
2	23		
3	32		
4	33		
5	34.4	x	43
6	35		
7	36	x	41
8	41		

Piedmont - C&D			
Location ID #	$/TON	County Regulati	Out County Pri
1	5		
2	20		
3	21.55		
4	23		
5	24		
6	26		
7	29.5		
8	29.93		
9	29.93		
10	30		
11	31		
12	31		
13	32		
14	34		
15	36		
16	39		
17	40		
18	40	x	42
19	45.31		
20	46		

Coastal - LCID		Beneficial Reuse		
Location ID #	$/TON	Road Base	ADC	Resell
1	0			
2	0	x		
3	0	x		
4	0			
5	7.5			
6	10	x	x	
7	15			
8	19			
9	20			
10	52			
11	65			

Coastal - MSW	
Location ID #	$/TON
1	7
2	39
3	40

Coastal C&D	
Location ID #	$/TO
1	34
2	34
3	40
4	41
5	52
6	59
7	65
8	68

Mountain - LCID		Beneficial Reuse		
Location ID #	$/TON	Road Base	ADC	Resell
1	0	x	x	
2	0	x		
3	10	x		
4	20			
5	30			
6	42			

Mountain - MSW	
Location ID #	$/TON
1	43
2	43
3	57
4	57
5	62
6	66

Mountain - C&D	
Location ID #	$/TO
1	31
2	52
3	57

Contractor ID #	Grinding Slurry Generation Rate (gal/sy)			Percent Solids
	Min	Avg	Max	
1	2	3.75	7	
2	2.43		4.26	
3		5		
4	2		4	
5	3.5		4	20
6	3.33		7	33.3
7	3.26		6.75	30
8	2.7		6.75	

Contractor ID #	Grooving Slurry Generation Rate (gal/sy)			Percent Solids
	Min	Avg	Max	
1	0.47	0.53	0.65	50
2		1.2		40
3	0.72		1.8	30

Contractor ID #	Hydrodemolition Slurry Generation Rate (gal/sy)			Percent Solids		
	Min	Avg	Max	Min	Avg	Max
1	10	14	18	5	10	15

WWTP/POTW Location ID #	Price per gallon
1	.05-.1
2	0.015
3	0.05
4	0.055
5	0.04
6	0.02
7	0.013
8	0.065
9	0.05
10	0.1
11	.03-.06
12	0.042

Land Application Location ID #	Price per Gallon
1	0.25
2	N/A

APPENDIX D: BOX AND WHISKER PLOT DATA TABLES

Option 1

Grinding	Min	25%	50%	75%	Max
Mountain	$ 5,674	$ 10,280	$ 12,074	$ 14,139	$ 23,473
Coastal	$ 3,510	$ 7,052	$ 8,346	$ 9,812	$ 17,463
Piedmont	$ 4,634	$ 7,892	$ 9,237	$ 10,794	$ 17,856
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 9,222	$ 17,542	$ 20,144	$ 22,875	$ 36,634
Coastal	$ 5,254	$ 13,643	$ 15,894	$ 18,220	$ 30,896
Piedmont	$ 7,354	$ 14,595	$ 16,948	$ 19,286	$ 30,995
Grooving	Min	25%	50%	75%	Max
Mountain	$ 2,957	$ 4,088	$ 4,713	$ 5,497	$ 8,413
Coastal	$ 2,588	$ 3,373	$ 3,817	$ 4,377	$ 6,144
Piedmont	$ 2,178	$ 3,144	$ 3,532	$ 4,042	$ 6,012

Option 2

Grinding	Min	25%	50%	75%	Max
Mountain	$ 4,465	$ 9,188	$ 10,758	$ 12,525	$ 21,316
Coastal	$ 5,458	$ 9,618	$ 11,405	$ 13,394	$ 22,048
Piedmont	$ 3,236	$ 7,536	$ 8,998	$ 10,637	$ 19,207
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 8,521	$ 16,207	$ 18,693	$ 21,240	$ 34,084
Coastal	$ 8,820	$ 16,828	$ 19,363	$ 21,987	$ 35,540
Piedmont	$ 5,399	$ 14,278	$ 16,617	$ 19,133	$ 31,270
Grooving	Min	25%	50%	75%	Max
Mountain	$ 2,957	$ 4,088	$ 4,713	$ 5,497	$ 8,413
Coastal	$ 2,710	$ 3,890	$ 4,482	$ 5,227	$ 8,187
Piedmont	$ 2,198	$ 3,297	$ 3,721	$ 4,313	$ 7,590

Option 3

Grinding	Min	25%	50%	75%	Max
Mountain	$ 3,489	$ 6,388	$ 7,650	$ 9,022	$ 16,156
Coastal	$ 2,675	$ 6,147	$ 7,636	$ 9,621	$ 20,683
Piedmont	$ 2,752	$ 5,789	$ 7,023	$ 8,484	$ 17,555
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 5,192	$ 12,946	$ 15,080	$ 17,427	$ 28,847
Coastal	$ 3,509	$ 12,827	$ 15,257	$ 17,981	$ 31,998
Piedmont	$ 5,397	$ 12,223	$ 14,475	$ 16,907	$ 29,921
Grooving	Min	25%	50%	75%	Max
Mountain	$ 2,161	$ 2,941	$ 3,306	$ 3,774	$ 6,028
Coastal	$ 2,062	$ 2,865	$ 3,313	$ 3,942	$ 7,441
Piedmont	$ 2,055	$ 2,764	$ 3,119	$ 3,588	$ 6,197

Option 4

Grinding	Min	25%	50%	75%	Max
Mountain	$ 2,070	$ 4,119	$ 4,775	$ 5,561	$ 10,099
Coastal	$ 2,070	$ 4,119	$ 4,775	$ 5,561	$ 10,099
Piedmont	$ 2,070	$ 4,119	$ 4,775	$ 5,561	$ 10,099
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 2,667	$ 9,950	$ 11,812	$ 13,823	$ 22,641
Coastal	$ 2,667	$ 9,950	$ 11,812	$ 13,823	$ 22,641
Piedmont	$ 2,667	$ 9,950	$ 11,812	$ 13,823	$ 22,641
Grooving	Min	25%	50%	75%	Max
Mountain	$ 1,790	$ 2,230	$ 2,394	$ 2,592	$ 3,374
Coastal	$ 1,790	$ 2,230	$ 2,394	$ 2,592	$ 3,374
Piedmont	$ 1,790	$ 2,230	$ 2,394	$ 2,592	$ 3,374

Option 5

Grinding		Min		25%		50%		75%		Max
Mountain	$	2,456	$	4,564	$	5,296	$	6,135	$	10,949
Coastal	$	2,456	$	4,564	$	5,296	$	6,135	$	10,949
Piedmont	$	2,456	$	4,564	$	5,296	$	6,135	$	10,949
Hydrodemolition		Min		25%		50%		75%		Max
Mountain	$	3,208	$	10,487	$	12,379	$	14,412	$	23,473
Coastal	$	3,208	$	10,487	$	12,379	$	14,412	$	23,473
Piedmont	$	3,208	$	10,487	$	12,379	$	14,412	$	23,473
Grooving		Min		25%		50%		75%		Max
Mountain	$	1,945	$	2,390	$	2,581	$	2,810	$	3,605
Coastal	$	1,945	$	2,390	$	2,581	$	2,810	$	3,605
Piedmont	$	1,945	$	2,390	$	2,581	$	2,810	$	3,605

Option 6

Grinding		Min		25%		50%		75%		Max
Mountain	$	8,373	$	13,711	$	16,038	$	18,746	$	27,623
Coastal	$	6,247	$	10,523	$	12,300	$	14,428	$	21,256
Piedmont	$	6,964	$	11,393	$	13,219	$	15,393	$	22,023
Hydrodemolition		Min		25%		50%		75%		Max
Mountain	$	21,837	$	30,284	$	33,185	$	36,279	$	47,430
Coastal	$	20,205	$	26,542	$	28,987	$	31,457	$	40,324
Piedmont	$	20,854	$	27,449	$	29,939	$	32,567	$	41,976
Grooving		Min		25%		50%		75%		Max
Mountain	$	3,432	$	4,630	$	5,440	$	6,413	$	9,507
Coastal	$	2,850	$	3,709	$	4,242	$	4,939	$	7,083
Piedmont	$	3,090	$	3,925	$	4,561	$	5,276	$	7,116

Option 7

Grinding		Min		25%		50%		75%		Max
Mountain	$	7,202	$	12,571	$	14,738	$	17,242	$	25,541
Coastal	$	7,710	$	13,101	$	15,378	$	17,948	$	26,863
Piedmont	$	6,371	$	11,004	$	12,997	$	15,246	$	25,632
Hydrodemolition		Min		25%		50%		75%		Max
Mountain	$	21,740	$	28,986	$	31,730	$	34,566	$	44,762
Coastal	$	21,584	$	29,605	$	32,379	$	35,348	$	46,953
Piedmont	$	19,487	$	27,102	$	29,703	$	32,402	$	44,613
Grooving		Min		25%		50%		75%		Max
Mountain	$	3,389	$	4,304	$	5,018	$	5,892	$	8,829
Coastal	$	3,317	$	4,452	$	5,189	$	6,131	$	9,313
Piedmont	$	2,567	$	3,873	$	4,443	$	5,193	$	8,227

Option 8

Grinding		Min		25%		50%		75%		Max
Mountain	$	5,908	$	9,918	$	11,630	$	13,611	$	22,227
Coastal	$	5,662	$	9,777	$	11,684	$	13,981	$	25,295
Piedmont	$	5,541	$	9,346	$	11,049	$	12,969	$	22,155
Hydrodemolition		Min		25%		50%		75%		Max
Mountain	$	19,266	$	25,780	$	28,207	$	30,655	$	40,946
Coastal	$	18,414	$	25,729	$	28,268	$	31,133	$	45,065
Piedmont	$	18,473	$	25,117	$	27,486	$	30,080	$	41,497
Grooving		Min		25%		50%		75%		Max
Mountain	$	2,701	$	3,508	$	4,026	$	4,672	$	7,157
Coastal	$	2,614	$	3,495	$	4,045	$	4,765	$	8,426
Piedmont	$	2,606	$	3,369	$	3,830	$	4,454	$	7,457

Option 9

	Min	25%	50%	75%	Max
Grinding	Min	25%	50%	75%	Max
Mountain	$ 5,099	$ 7,622	$ 8,746	$ 10,131	$ 13,559
Coastal	$ 5,099	$ 7,622	$ 8,746	$ 10,131	$ 13,559
Piedmont	$ 5,099	$ 7,622	$ 8,746	$ 10,131	$ 13,559
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 17,740	$ 22,910	$ 24,905	$ 26,985	$ 33,140
Coastal	$ 17,740	$ 22,910	$ 24,905	$ 26,985	$ 33,140
Piedmont	$ 17,740	$ 22,910	$ 24,905	$ 26,985	$ 33,140
Grooving	Min	25%	50%	75%	Max
Mountain	$ 2,409	$ 2,779	$ 3,154	$ 3,487	$ 4,463
Coastal	$ 2,409	$ 2,779	$ 3,154	$ 3,487	$ 4,463
Piedmont	$ 2,409	$ 2,779	$ 3,154	$ 3,487	$ 4,463

Option 10

	Min	25%	50%	75%	Max
Grinding	Min	25%	50%	75%	Max
Mountain	$ 5,408	$ 8,044	$ 9,244	$ 10,727	$ 14,224
Coastal	$ 5,408	$ 8,044	$ 9,244	$ 10,727	$ 14,224
Piedmont	$ 5,408	$ 8,044	$ 9,244	$ 10,727	$ 14,224
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 18,204	$ 23,435	$ 25,479	$ 27,584	$ 33,989
Coastal	$ 18,204	$ 23,435	$ 25,479	$ 27,584	$ 33,989
Piedmont	$ 18,204	$ 23,435	$ 25,479	$ 27,584	$ 33,989
Grooving	Min	25%	50%	75%	Max
Mountain	$ 2,545	$ 2,936	$ 3,341	$ 3,711	$ 4,694
Coastal	$ 2,545	$ 2,936	$ 3,341	$ 3,711	$ 4,694
Piedmont	$ 2,545	$ 2,936	$ 3,341	$ 3,711	$ 4,694

Option 11

	Min	25%	50%	75%	Max
Grinding	Min	25%	50%	75%	Max
Mountain	$ 8,680	$ 12,950	$ 14,619	$ 16,495	$ 25,582
Coastal	$ 6,478	$ 9,732	$ 10,871	$ 12,180	$ 19,572
Piedmont	$ 7,641	$ 10,577	$ 11,771	$ 13,168	$ 19,966
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 10,086	$ 18,024	$ 20,416	$ 23,018	$ 36,430
Coastal	$ 5,903	$ 14,126	$ 16,213	$ 18,361	$ 30,702
Piedmont	$ 8,461	$ 15,027	$ 17,229	$ 19,434	$ 30,801
Grooving	Min	25%	50%	75%	Max
Mountain	$ 6,340	$ 7,443	$ 7,971	$ 8,680	$ 11,553
Coastal	$ 5,560	$ 6,483	$ 6,801	$ 7,236	$ 9,165
Piedmont	$ 5,974	$ 6,723	$ 7,074	$ 7,562	$ 9,283

Option 12

	Min	25%	50%	75%	Max
Grinding	Min	25%	50%	75%	Max
Mountain	$ 7,472	$ 11,872	$ 13,275	$ 14,915	$ 23,426
Coastal	$ 8,460	$ 12,302	$ 13,925	$ 15,739	$ 24,004
Piedmont	$ 5,803	$ 10,186	$ 11,527	$ 13,018	$ 21,145
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 9,447	$ 16,667	$ 18,965	$ 21,384	$ 33,890
Coastal	$ 9,652	$ 17,293	$ 19,693	$ 22,091	$ 35,337
Piedmont	$ 6,278	$ 14,766	$ 16,910	$ 19,286	$ 31,076
Grooving	Min	25%	50%	75%	Max
Mountain	$ 6,150	$ 7,107	$ 7,543	$ 8,171	$ 10,807
Coastal	$ 6,094	$ 7,244	$ 7,745	$ 8,408	$ 11,330
Piedmont	$ 5,415	$ 6,626	$ 6,989	$ 7,507	$ 10,736

Option 13

Grinding	Min	25%	50%	75%	Max
Mountain	$ 6,258	$ 9,035	$ 10,165	$ 11,423	$ 18,095
Coastal	$ 5,477	$ 8,762	$ 10,175	$ 12,055	$ 22,622
Piedmont	$ 5,562	$ 8,395	$ 9,546	$ 10,968	$ 19,512
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 5,940	$ 13,389	$ 15,381	$ 17,637	$ 28,488
Coastal	$ 4,616	$ 13,237	$ 15,537	$ 18,197	$ 31,804
Piedmont	$ 5,573	$ 12,634	$ 14,789	$ 17,030	$ 29,510
Grooving	Min	25%	50%	75%	Max
Mountain	$ 5,544	$ 6,269	$ 6,573	$ 6,983	$ 9,164
Coastal	$ 5,440	$ 6,160	$ 6,585	$ 7,170	$ 10,593
Piedmont	$ 5,438	$ 6,066	$ 6,387	$ 6,816	$ 9,337

Option 14

Grinding	Min	25%	50%	75%	Max
Mountain	$ 4,723	$ 6,753	$ 7,314	$ 7,983	$ 12,209
Coastal	$ 4,723	$ 6,753	$ 7,314	$ 7,983	$ 12,209
Piedmont	$ 4,723	$ 6,753	$ 7,314	$ 7,983	$ 12,209
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 3,537	$ 10,354	$ 12,119	$ 13,992	$ 22,471
Coastal	$ 3,537	$ 10,354	$ 12,119	$ 13,992	$ 22,471
Piedmont	$ 3,537	$ 10,354	$ 12,119	$ 13,992	$ 22,471
Grooving	Min	25%	50%	75%	Max
Mountain	$ 5,074	$ 5,552	$ 5,667	$ 5,804	$ 6,533
Coastal	$ 5,074	$ 5,552	$ 5,667	$ 5,804	$ 6,533
Piedmont	$ 5,074	$ 5,552	$ 5,667	$ 5,804	$ 6,533

Option 15

Grinding	Min	25%	50%	75%	Max
Mountain	$ 5,186	$ 7,208	$ 7,817	$ 8,537	$ 13,059
Coastal	$ 5,186	$ 7,208	$ 7,817	$ 8,537	$ 13,059
Piedmont	$ 5,186	$ 7,208	$ 7,817	$ 8,537	$ 13,059
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 4,156	$ 10,894	$ 12,690	$ 14,597	$ 23,279
Coastal	$ 4,156	$ 10,894	$ 12,690	$ 14,597	$ 23,279
Piedmont	$ 4,156	$ 10,894	$ 12,690	$ 14,597	$ 23,279
Grooving	Min	25%	50%	75%	Max
Mountain	$ 5,305	$ 5,723	$ 5,848	$ 6,008	$ 6,764
Coastal	$ 5,305	$ 5,723	$ 5,848	$ 6,008	$ 6,764
Piedmont	$ 5,305	$ 5,723	$ 5,848	$ 6,008	$ 6,764

Option 16

Grinding	Min	25%	50%	75%	Max
Mountain	$ 11,375	$ 16,401	$ 18,592	$ 21,095	$ 29,563
Coastal	$ 9,254	$ 13,209	$ 14,832	$ 16,770	$ 23,195
Piedmont	$ 9,974	$ 14,088	$ 15,782	$ 17,732	$ 23,967
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 22,916	$ 30,776	$ 33,445	$ 36,253	$ 46,880
Coastal	$ 21,259	$ 27,065	$ 29,280	$ 31,501	$ 39,913
Piedmont	$ 20,854	$ 27,449	$ 29,939	$ 32,567	$ 41,976
Grooving	Min	25%	50%	75%	Max
Mountain	$ 6,818	$ 7,994	$ 8,677	$ 9,598	$ 12,641
Coastal	$ 6,234	$ 7,065	$ 7,496	$ 8,116	$ 10,219
Piedmont	$ 6,476	$ 7,289	$ 7,789	$ 8,461	$ 10,256

Option 17

Grinding	Min	25%	50%	75%	Max
Mountain	$ 10,209	$ 15,267	$ 17,296	$ 19,564	$ 27,471
Coastal	$ 10,712	$ 15,787	$ 17,902	$ 20,296	$ 28,793
Piedmont	$ 9,376	$ 13,682	$ 15,532	$ 17,615	$ 27,570
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 22,816	$ 29,503	$ 32,018	$ 34,590	$ 44,351
Coastal	$ 22,663	$ 30,129	$ 32,653	$ 35,386	$ 46,402
Piedmont	$ 19,487	$ 27,102	$ 29,703	$ 32,402	$ 44,613
Grooving	Min	25%	50%	75%	Max
Mountain	$ 6,771	$ 7,668	$ 8,253	$ 9,077	$ 11,962
Coastal	$ 6,702	$ 7,814	$ 8,457	$ 9,315	$ 12,456
Piedmont	$ 5,940	$ 7,225	$ 7,699	$ 8,377	$ 11,374

Option 18

Grinding	Min	25%	50%	75%	Max
Mountain	$ 8,914	$ 12,607	$ 14,151	$ 15,961	$ 24,165
Coastal	$ 8,662	$ 12,426	$ 14,187	$ 16,378	$ 27,258
Piedmont	$ 8,542	$ 12,015	$ 13,577	$ 15,326	$ 24,117
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 20,362	$ 26,309	$ 28,440	$ 30,672	$ 40,396
Coastal	$ 19,533	$ 26,191	$ 28,542	$ 31,209	$ 44,666
Piedmont	$ 18,473	$ 25,117	$ 27,486	$ 30,080	$ 41,497
Grooving	Min	25%	50%	75%	Max
Mountain	$ 6,085	$ 6,860	$ 7,282	$ 7,859	$ 10,293
Coastal	$ 5,995	$ 6,810	$ 7,307	$ 7,980	$ 11,577
Piedmont	$ 5,994	$ 6,702	$ 7,099	$ 7,650	$ 10,597

Option 19

Grinding	Min	25%	50%	75%	Max
Mountain	$ 8,105	$ 10,320	$ 11,311	$ 12,478	$ 15,509
Coastal	$ 8,105	$ 10,320	$ 11,311	$ 12,478	$ 15,509
Piedmont	$ 8,105	$ 10,320	$ 11,311	$ 12,478	$ 15,509
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 18,858	$ 23,442	$ 25,178	$ 26,996	$ 32,589
Coastal	$ 18,858	$ 23,442	$ 25,178	$ 26,996	$ 32,589
Piedmont	$ 17,740	$ 22,910	$ 24,905	$ 26,985	$ 33,140
Grooving	Min	25%	50%	75%	Max
Mountain	$ 5,793	$ 6,143	$ 6,379	$ 6,671	$ 7,593
Coastal	$ 5,793	$ 6,143	$ 6,379	$ 6,671	$ 7,593
Piedmont	$ 5,793	$ 6,143	$ 6,379	$ 6,671	$ 7,593

Option 20

Grinding	Min	25%	50%	75%	Max
Mountain	$ 8,414	$ 10,765	$ 11,813	$ 13,072	$ 16,165
Coastal	$ 8,414	$ 10,765	$ 11,813	$ 13,072	$ 16,165
Piedmont	$ 8,414	$ 10,765	$ 11,813	$ 13,072	$ 16,165
Hydrodemolition	Min	25%	50%	75%	Max
Mountain	$ 19,322	$ 23,983	$ 25,752	$ 27,609	$ 33,439
Coastal	$ 19,322	$ 23,983	$ 25,752	$ 27,609	$ 33,439
Piedmont	$ 18,204	$ 23,435	$ 25,479	$ 27,584	$ 33,989
Grooving	Min	25%	50%	75%	Max
Mountain	$ 5,933	$ 6,299	$ 6,557	$ 6,896	$ 7,824
Coastal	$ 5,933	$ 6,299	$ 6,557	$ 6,896	$ 7,824
Piedmont	$ 5,933	$ 6,299	$ 6,557	$ 6,896	$ 7,824