A Model for the Regional Variability of Riprap Prices in Alabama

by

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Abstract

Riprap is widely used by departments of transportation (DOTs) for erosion control and slope stabilization activities. Even though DOTs seem to be satisfied with the ability of riprap to fulfill its intended purpose, its cost-effectiveness has been increasingly questioned. Projects, where riprap is not locally available, are affected by long-hauling distances, resulting in high unit prices. This is a concern in some parts of the state of Alabama where the geology does not contain limestone or granite for mining Riprap. Before considering alternative technologies or materials for those locations, the Alabama Department of Transportation (ALDOT) must first understand the behavior of riprap unit prices across the state. A considerable portion of the research efforts conducted under this study was used to gain an understanding of riprap unit prices, which was then applied to facilitate the geographic classification of the riprap market in Alabama. The development of cost classification required the use of advanced data collection and processing techniques, as well as the systematic iterative application of statistical tests. Quantitative research efforts resulted in the identification of four geographic regions that showed statistically significant different riprap pricing levels. The resulting geographic classification was also qualitatively explained and validated through the analysis of the location of riprap producers across the state. Finally, the four different regions were used to model the behavior of the riprap market across the state in the form of a Riprap Location Cost Index (RLCI). All research efforts presented in this thesis were conducted with historical bid data from projects awarded by ALDOT between the years 2006 and 2016.

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List of Abbreviations

AASHTO	Standard Specifications for Transportation Materials and Methods of Sampling and Testing
ANOVA	Analysis of Variance
ACF	Area Cost Factor
ALDOT	Alabama Department of Transportation
CALTRANS	California Department of Transportation
FHWA	Federal Highway Administration
GAO	Government Accountability Office
CCI	City Cost Indexes
LCCA	Life-cycle cost analysis
LCI	Location Cost Index
LSD	Least Significant Difference
MAD	Median Absolute Deviation
MSW	Mean Square Within
PDF	Portable Document Format
QA	Quantitative Analysis
RFP	Request for Proposal
RLCI	Riprap Location Cost Index
USCE	U.S. Army Corps of Engineers

CHAPTER 1: INTRODUCTION

1.1 Introduction

Blodgett and McConaughy (1986) define riprap as an erosion-resistant ground cover of large, loose, and angular stones used to protect channels, shorelines, slopes, stream banks, or other areas affected by water, scour, ice, or wave action. The primary purpose of the riprap is to protect soil from erosion, increasing the surface roughness and slowing the velocity of concentrated runoff. Riprap is also used to prevent damage to slopes due to seepage erosion, applicable in construction sites that contain inlets and outlets of culverts and storm pipes, storm drains, slope drains, and bridges. Types of erosion that can be successfully controlled by riprap include channel degradation, bank erosion, scour, and changes in alinement associated with meandering, branching, and braiding of the stream.

The design of riprap consists of a variety of stone sizes that can be specified by either weight or diameter. Rock riprap resists erosion through a combination of stone size and weight, stone durability, gradation, and thickness of the riprap blanket (British Columbia and Water Management Branch. Public Safety Section 2000).

Many federal and state agencies have adopted the use of riprap to protect public work projects against erosion by flowing water. Riprap, when properly designed and used for erosion protection, has an advantage over rigid structures because it is flexible when subjected to water currents. This structure can remain functioning even if some individual stones are lost and repaired relatively easily. Properly constructed riprap armoring can provide long-term protection if it is inspected and maintained on a periodic basis as well as after flood events (Lagasse et al. 2006).

From 2006 to 2016, the Alabama Department of Transportation (ALDOT) purchased over 2.2 million tons of riprap, with a total cost of $ 74,000,000. Thus, it is reasonable to assume that riprap has a considerable impact on ALDOT's construction program. Though departments of transportation (DOTs) seem to be satisfied with the proper functioning of riprap on their projects, its cost-effectiveness has been increasingly questioned for federal and state transportation agencies. The availability of the material, including the required size and weight, construction site access, and long-haul distances, are some aspects that could increase the cost of riprap substantially. Likewise, price variability between different geographic locations could be attributed to several factors, such as local climate and geological conditions, qualified local labor availability, suppliers, subcontractors, and applicable local regulations (Cuervo and Sui Pheng 2003). This means that two similar projects could have substantially different riprap unit prices at different locations (Xu et al. 2019).

To control the damage caused by the force of water running along the unprotected ground, different alternative technologies could be considered as suitable substitutes riprap. However, the lack of formal studies to better understand the behavior of riprap prices across the state of Alabama is preventing ALDOT from identifying those geographic locations in which alternative technologies would offer better value. This research was aimed to facilitate that required understanding of riprap pricing in Alabama through the development of a Riprap Location Cost Index (RLCI). These indexes would allow the identification of those regions where the implementation of other alternatives could offer competitive cost-effectiveness.

The proposed RLCI is an annual index intended to describe the variability of riprap prices across four regions in Alabama. Historical bid data for projects awarded by ALDOT from 2006 to 2016 were gathered, processed, and analyzed. Different statistical methods to clean and process relevant data were used to ensure the generation of reliable results. In addition to facilitating a comparative cost-effectiveness scenario between riprap and other competitive technologies, RLCI also could be used by ALDOT as a cost estimating

. Location cost indexes allow DOTs to gain an understanding of potential project costs over a specific time period before starting the bidding process. The RLCI presented in this thesis was generated to compare riprap prices across the state of Alabama. However, the overall research approach and analyses could also be implemented for DOTs in other states.

1.2 ALDOT's Riprap Classification

According to the Standard Specifications for Highway Construction by Alabama Department of Transportation (2018) section 814, riprap is classified into five different classes. Class 1 riprap shall consist of graded stones ranging from 10 to 100 pounds with not more than 10% having a weight over 100 pounds and at least 50% having a weight over 50 pounds and not over 10% having a weight under 10pounds. Class 2 riprap shall consist of graded stones ranging from 10 to 200 pounds with not over 10% having a weight over 200 pounds and at least 50% having a weight over 80 pounds and not over 10% having a weight under 10 pounds. Class 3 riprap shall consist of reasonably well-graded stones ranging from 25 pounds to 500 pounds with not over 10% having a weight over 500 pounds, at least 50% having a weight over 200 pounds and not more than 15% having a weight under 25 pounds. Class 4 riprap shall consist of reasonably well-graded stones ranging from 50 to 1000 pounds with not over 25% having a weight over 1000 pounds, at least 50% having a weight over 500 pounds, and not more than 25% having a weight under 50 pounds. Class 5 riprap shall consist of reasonably well-graded stones ranging from 2000 pounds and down with not over 10% having a weight over 2000 pounds, at least 50% having a weight over 1000 pounds and not more than 25% having a weight under 200 pounds.

1.3 Motivation

Riprap is commonly used to protect bridge abutment and pier foundations from scouring, as well as to protect the surface of water channels from erosion (Barkdoll et al. 2007; Suaznabar et al. 2017). Riprap is used extensively in the prevention of river bankline erosion, with the placement of riprap constituting the main part of the construction projects executed for that purpose (Walters 1982). The use of riprap in federal and state public projects is a common practice due to the long-term durability of the material. Riprap is a non-polluting natural material, and under normal river flow conditions, it can provide habitat, hiding, and resting areas for fish and aquatic species (Lagasse et al. 2006).

However, riprap might not be a cost-effectiveness alternative in some geographic locations. The cost of riprap may vary considerably depending on the type of material required and the location of the project. ALDOT has divided its operations across the state of Alabama into five geographic regions: North, East Central, West Central, Southeast, and Southwest. Initial research efforts conducted by this study found that most of the quarries that produce riprap are in the North and East Central regions, which was identified as an early indicator that the cost of riprap prices could be higher in the southern regions.

Further quantitative analysis with historical bid data from projects awarded by ALDOT between 2006 and 2016 was conducted to model the variability of prices across the state. Results from that analysis showed that, on average, the price of riprap in the Southwest region is approximately 39% higher than in the North region. According to this, and based on the location of the quarries, it would be reasonable to assume that long- haul distances influence the total price of riprap substantially. The cost of transportation of the material to the construction site escalates as the distance increases (Odusami and Onukwube 2008).

Previous discussions of this issue with ALDOT’s staff revealed a prior agency knowledge regarding the higher prices of riprap in the southern regions of the state; however, ALDOT does not have the tools or capabilities to needed quantify the regional variability of riprap prices across the state. This economic uncertainty could have a high impact on ALDOT expenses, especially in large-scale projects. Therefore, the primary purpose of this research was to offer ALDOT a reliable index of price variability between different regions of the state in the form of a Riprap Location Cost Index (RLCI). The proposed RLCI was developed between the years 2006 to 2016 to provide an enhanced and more precise understanding of the regional behavior of the riprap market over time.

1.4 Research Objectives

The main objective of this research was to assess and model the behavior of riprap prices across the state of Alabama to provide ALDOT with the means to better evaluate cost-effectiveness in the use of riprap in comparison to other erosion control alternatives. The following three sub-objectives were identified by the author as appropriate steps to accomplish this objective:

- Understand the variability of riprap prices across the state of Alabama. A detailed analysis was performed to quantify differences in Loose Riprap Class 2 prices across the state using ALDOT’s historical bid data;

- Define geographic regions by grouping adjacent counties with similar riprap pricing levels. Various statistical methods and techniques were used to define these regions across all 67 counties in Alabama; and
- Model riprap price differences between geographic regions in the form of a RLCI.

1.5 Organization of Research

This thesis has been divided into five chapters to detail the process for the development of the RLCI. Following this introductory chapter, *Chapter Two - Literature review and Background*, summarizes the information available from several sources about cost estimating, factors affecting riprap pricing, and geographic considerations in construction cost estimating. *Chapter Three - Methodology*, describes the research approach designed for the development of the RLCI. This chapter explains the different statistical tests and quantitative techniques used to clean and process the available data. *Chapter Four - Data Analysis and Results* provides the results obtained from the research methodology presented in Chapter Three. A discussion of the results is offered to interpret and define the significance of the findings. *Chapter Five - Conclusions and Recommendations*, summarizes the findings, conclusions, contributions, and future recommendations associated with the research problem. This chapter outlines the potential impacts of this research on future studies.

CHAPTER 2: LITERATURE REVIEW AND BACKGROUND

2.1 Introduction

Currently, transportation agencies are becoming more careful in estimating the total cost of projects. The accuracy of cost estimates is fundamental in effectively planning and is a common metric to determine the overall achievement or failure of a construction project. As the first step in the planning phase, estimates help owners and contractors evaluate the financial feasibility of intended projects. Those early estimates are commonly prepared with the aid of historical data and later adjusted to consider specific project characteristics such as project location, size, and anticipated level of competition, among others (Migliaccio et al. 2009).

The location component has a significant impact on overall construction costs due to the regional variability in the price of materials, labor, and equipment. Likewise, according to Seely (1996), costs in construction projects are dependent not only on the geographic location of the project but also on the specific job site conditions. Local characteristics such a climate, topography, terrain type, and environmental factors have a bearing on the cost of executing work. In a global study, Ling (2005) found that in many countries project location has a significant impact on contractor's profits. The cost of the construction project varies from place to place, even if projects have identical designs. This variation could increase the total cost of a project by as much as a third from one location to another (Stallworthy and Kharbanda 1983). Several researchers, including Akintoye (2000) and An et al. (2007), have ranked location among the significant factors that influence construction price estimates.

In existing construction-cost-engineering literature, a cost index is commonly defined as the ratio between the cost of a given commodity or construction activity at a given time or place and the cost of a similar facility at a base time or place. Cost indexes that represent construction price changes over time are usually called construction cost indexes (CCIs). Those indexes comparing prices among geographic regions, like the one presented in this thesis, are called location costs indexes (LCIs) or location cost factors. Taking this definition into consideration, a CCI is intended as the factor that allows the generation of a project cost estimate based on the cost of a similar project at a different point in time (Migliaccio et al. 2013). On the other hand, the adjustment of construction costs by location is performed with location cost factors (Migliaccio et al. 2009). Contractors could also use LCIs to prepare rough feasibility cost estimates based on their cost knowledge from different geographic regions (Aibinu et al. 2008).

2.2 Design of riprap revetments

The use of riprap for erosion control should be durable and composed of the appropriate size of stones to guarantee stability under the hydraulic design loading. The design of riprap revetments is based on the nature of the streambank and the hydraulic characteristics of the stream at the design flood (British Columbia and Water Management Branch. Public Safety Section 2000). Many procedures for the design of riprap have been prepared by several agencies, such as Federal Highway Administration (FHWA), U.S. Bureau of Reclamation (USBR), U.S. Army Corps of Engineers (USCE), and California Department of Transportation (CALTRANS). To have a better understanding of project characteristics, it is essential to carry out preliminary inspections of the conditions of the job sites. That includes examinations of the banks and river channel, possible erodible materials, and behavior of the river near to the protection site. Also, maps, air photographs, channel surveys, and previous studies could be considered to ensure an optimum design of riprap revetments.

A hydraulic analysis is essential to determine design water levels, depth conditions, and maximum velocities. A key aspect of the hydraulic analysis is to predict the maximum average velocity that occurs along the channel and, by extension, the bank where protective works are to be constructed (British Columbia and Water Management Branch. Public Safety Section 2000). Industry recognized standard specifications, such as the "Standard Specifications for Transportation Materials and Methods of Sampling and Testing" (AASHTO,2003) or the "Annual Book of ASTM Standards" (ASTM, 2003a, b), describe the quality and characteristics of the riprap material recommended for a specific installation. Specifications for rock used as riprap typically include a range of sizes or weights, shape, density, water absorption, and durability. Geotextiles or aggregate underlayers are used to maintain permeability and provide a free flow of water through the materials. Design considerations and the specific characteristics of the base soil determine the requirement of filter layers. Some situations call for a composite filter consisting of both a granular layer and a geotextile (Lagasse et al. 2006).

Riprap revetments inspections are recommended to be performed in a bi-annual period or after every major storm (Walters 1982). Frequent inspections detect minor damages and specific repairs before further damages can take place.

2.3 Cost Estimating

The U.S. Government Accountability Office (GAO) defines cost estimates as "the summation of individual cost elements, using established methods and valid data to estimate the future costs of a program, based on what is known today" (Leonard 2009). In construction, cost estimating is the determination of quantities and the prediction of the costs required to construct and commission a facility within a defined scope (Migliaccio et al. 2013). Cost estimates have two general purposes: (1) to help managers evaluate affordability and performance against plans, as well as the selection of alternative systems and solutions, and (2) support the budget process by providing estimates of the funding required to efficiently execute a program (Leonard 2009). The program should address the agency’s mission, goals, and strategic objectives.

Cost estimating is a critical part of the construction process and has a significant impact on decision making during the early project phases. Reasonable cost estimates required both science and judgment. During estimating, cost estimators often face different challenges like poorly defined assumptions, unreliable data or supporting documentation, inadequate data collection, and inappropriate estimating methods. Estimators or cost analysts must understand the process and know how to use the appropriate tools to predict reliable values. Table 2.1 describes nine basic characteristics of credible cost estimates according to 1972 GAO’S report: Theory and Practice of Cost Estimating for Major Acquisitions (GAO 1972).

Table 2.1: GOA's 1972 Version of the Basic Characteristics of Credible Cost Estimates

Characteristic	Description
Clear identification of task	The estimator must be provided with the system description, ground rules, and assumptions, and technical and performance characteristics Estimate's constraints and conditions must be clearly identified to ensure the preparation of a well-documented estimate
Broad participation in preparing estimates	All stakeholders should be involved in deciding mission needs and requirements and defining system parameters and other characteristics. Data should be independently verified for accuracy, completeness, and reliability
Availability of valid data	Numerous sources of suitable, relevant, and available data should be used. Relevant; historical data should be used from similar systems to project costs of new systems; these data should be directly related to the system's performance characteristics
Standardized structure for the estimate	A standard work breakdown structure, as detailed as possible, should be used, refining it as the cost estimate matures, and the system becomes more defined. The work breakdown structure ensures that no portions of the estimate are omitted and makes it easier to make comparisons to similar systems and programs
Provision for program uncertainties	Uncertainties should be identified, and allowance developed to cover the cost effect. Known costs should be included, and unknown costs should be allowed for
Recognition of inflation	The estimator should ensure that economic changes, such as inflation, are properly and realistically reflected in the life-cycle cost estimate
Recognition of excluded costs	All costs associated with a system should be included; any excluded costs should be disclosed and given a rationale
Independent review of estimates	Conducting an independent review of an estimate is crucial to establishing confidence in the estimate; the independent reviewer should verify, modify, and correct an estimate to ensure realism, completeness, and consistency
Revision of estimates for significant program changes	Estimates should be updated to reflect changes in a system's design requirements. Large changes that affect costs can significantly influence program decisions

2.2.1 Data for cost estimating

Data collection efforts as part of cost estimating procedures is a complex, lengthy, and time-consuming process. Data needs are not always clear at the assignment's beginning, and data requirements often evolve during project development phases (NASA Executive Cost Analysis

Steering Group 2008). There are different sources and ways to collect supporting data for cost estimating processes, such as surveys or questionnaires, interviews, historical databases for past projects, focus groups, engineering build-up estimating analyses, among others. Once the data has been collected, the next step is to clean it. That means that data must be analyzed and adjusted to make it consistent and reliable. There are three main types of data: cost data, schedule or program data, and technical data (Leonard 2009). Cost data implies labor cost, material and overhead cost, facilities capital cost of money, and profit. The schedule or program data provide parameters as delivery dates, start and duration of activities, initial operational capability dates, contract type, and multiyear procurement that directly influence the overall cost. Finally, technical data define physical and performance characteristics, technology descriptors, the operational environment, major design changes, and performance metrics. Other data sources for this data include previous contracts and cost proposals, engineering specifications and drawings, technical databases, and project management plans, among others.

2.4 Factors affecting Riprap unit price

2.4.1 Riprap Placement Methods

Riprap is the most widely used material and the most preferred type of revetment in the United States (Brown and Clyde 1989). Riprap can be placed using two different methods: hand-placed or dumped riprap (Brewer and Officials, 2007).

- Hand-placed riprap: This method involves laying stones by hand following a previously defined pattern. This patter contains voids between the large rocks filled with smaller rocks, to create a continuous uniform surface. Hand-placed riprap produces a tidy appearance and reduces flow turbulence, as shown in Figure 2.1.a. The advantages associate with this method include a neat surface appearance and the reduction of flow turbulence at the water-revetment interface. Likewise, the hand-placement method can significantly reduce blanket thickness, resulting in the use of less material. On the other hand, this is a very labor-intense approach, increasing the cost of installation, and resulting in a less resilient revetment that could easily fail with the movement of the base material. Repairs could also be more expensive.

- Dumped riprap: This method refers to the dumping of graded stone in a prepared slope in a way that segregation would not take place, as shown in Figure 2.1.b. Crane, dragline, or some form of dumping bucket, are some of the common mechanisms to place riprap. Some advantages of this method are that local damage or loss can be repaired easily by the placement of more rock, and vegetation can grow through the rocks when riprap is exposed to freshwater, serving as additional natural protection from erosion. The construction process could be done faster, resulting in higher labor productivity and fewer labor hours. The main disadvantage of this method in comparison with hand-placed riprap is a larger amount of riprap required per unit of area, as well as the greater risk for material segregation due to the dumping process.

a. Hand-placed riprap b. Dumped riprap

Figure 2.1: Riprap placing methods (Bureau of Reclamation 2001)

2.4.2 Equipment

Different types of equipment can be used to place riprap adequately, preventing damage to the geotextile or to the surface to be protected. The skills of the operator and the proper handling of the equipment are essential to spreading riprap directly on the geotextile, without damaging it. Heavy equipment may not be used on the geotextile without a bedding layer to protect the geotextile. It is highly recommended to position the equipment on top of the slope to allow the operator a wide view of the work area. According to the U.S Army Corp of Engineers (1984), the mechanically articulated “claws” or “orange peel grabs” (shown in Figure 2.2) work best in placing the riprap directly on the geotextile. Conventional backhoes do not work very well because the downward pressure of the bucket cannot be appropriately controlled. Goods results are obtained with equipment such as skip pans and backhoes (shown in Figure 2.3) when protective beddings are placed over the geotextile (U.S. Army Corps of Engineers 1984). The selection of the appropriate type and size of construction equipment has a clear, direct impact on the job-site productivity of riprap installation procedures. The type of equipment and its productivity are also aspects that could affect riprap installation costs.

Figure 2.2: Equipment Operator 3rd Class Clayton Dalrymple (Yan Kennon 2010)

Figure 2.3: Sacramento Riverbank Protection(Nevins 2011)

2.4.3 Material

In general, riprap must be hard, dense, and durable. It should be free from overburden, spoil, and organic material, and resistant to weathering (British Columbia and Water Management Branch. Public Safety Section 2000). Riprap is commonly produced from granite and limestone soils. The decision between these two types of riprap is driven by availability, haul distance, cost, operation, and maintenance, among others.

Limestone riprap is a sturdy rock, and it’s commonly used for shorelines, ditches, and channels due to the material is not affected by rainy conditions. There are four types of limestone riprap according to the rock size, offering different advantages. Limestone Type A is an excellent choice for steep slopes for the ability to stay in place while stacked. Useful for protecting or restore large areas susceptible to drainage issues. Rocks from 18 to 30 in are suitable for this type. Limestone

Type B is appropriate for high-velocity slopes with rocks between 12 to 24 in. It has the same use as Type A, just is adequate for areas that suffer less erosion. Limestone Type C is the most popular type of riprap used to moderate-velocity slopes such as retaining walls, creeks, and riverbanks. Its measurement is between 6 to 18 in. Finally, Limestone Type D is the smallest type of riprap with rocks from 4 to 12 in. Usually, it is used as a base in ditches or bonds (Bureau of Reclamation 2001).

Granite Riprap also has the same use as limestone protecting slopes in creeks, ditches, rivers, and shorelines. Its colors range from grays to pinks to hues of iron rust. This type of riprap is a good option to control erosion around culverts.

2.5 Geographic considerations in construction projects

In this thesis, geographic considerations refer to project attributes associated with the location of a construction project, which usually has an impact on final project costs. The location of the project, whether in an urban or rural setting, must be factored into the estimation of construction costs. All components of the cost estimate (materials, equipment, and labor) may be affected by project-specific geographic considerations (Akanni et al. 2015; Cuervo and Sui Pheng 2003).

The cost of projects that require large amounts of borrow or disposal materials, such as projects using large amounts of riprap, are heavily impacted by the distance between the material sources/disposal sites and the project locations. Nearby material sources or disposal sites may considerably reduce hauling costs (Washington State Department of Transportation, 2015). Hauling costs vary greatly depending on the type of transportation mode involved and the conditions of trade routes.

2.5.1 Location Cost Indexes and Location Adjustment Factors

DOTs usually face different types of challenges and project requirements depending on the geographic location of the intended projects, resulting in different pricing levels for the same commodity in different regions (Xu 2018; Abeysinghe 2010). These differences in price from one location to another can be measured by location cost indexes (LCIs) (Humphreys 2004). An LCI is an indicator of the price of a given commodity or service at a given place, compared to the price for the same commodity or service at a benchmark location (Humphreys 2004).

The concept of location adjustment factor was introduced by Johannes et al. (1985) as the construction cost in an area relative to the cost in another area. A location adjustment factor can be calculated just as the ratio between the LCI values of the two regions under consideration, as shown in Equation 1. The location adjustment factor in this equation is intended to adjust construction prices from Location B to represent prices for Location A. The adjustment calculation is shown in Equation 2.

$$Location\ Adjustment\ Factor_{from\ B\ to\ A} = LAC_{BA} = \frac{Index\ for\ City\ A}{Index\ for\ City\ B} \qquad \textbf{Eq. 1}$$

$$LAC_{BA} x\ Cost\ in\ City\ B = Cost\ in\ City\ A \qquad \textbf{Eq. 2}$$

In other words, a location adjustment factor is an instantaneous overall total project factor for translating all the project cost elements of a defined construction scope of work from one geographic location to another. This factor recognizes differences in productivity and costs for labor, engineered equipment, commodities, freight, duties, taxes, procurement, engineering, design, and project administration, as applicable (Pietlock 1996). The following are three examples of LCIs and location adjustment factors found in the literature: the Area Cost Factor (ACF) Indexes used by the Department of Defense (DOD); the City Cost Indexes published and maintained by the RSMeans, and an LCI for hot mix asphalt developed by Xu (2018) for ALDOT.

Area Cost Factor Indexes – Department of Defense

ACF Indexes were first approved by Office of the Assistant Deputy Under Secretary of Defense (Energy and Engineering) on May 28, 1997. These indexes are used for the development of construction cost estimates for military family houses (Chapman and Thompson 1981). The ACF reflects a relative comparison on the combination of local construction costs of labor, material, and equipment, and other factors such as weather, climate, seismic, mobilization, overhead and profit, labor availability, and labor productivity for each location versus an ACF of 1.00 for the national average of 96 base cities (two cities per state in the continental US) (Chapman and Thompson 1981). Table 2.2 is an example of the 2019 ACF index for Alabama. ACF indexes are calculated by a specific software that computes and integrates the cost of 8 labor crafts, 18 construction materials, and 4 equipment items identified as representative inputs in the construction of most military facilities in the U.S.

The overall statewide ACF value in Table 2.2 should be used when the location of the project does not have a specific AFC value. Alternatively, the ACF for the closest location could be used when market conditions such as material prices, labor rates, climate, labor availability, among others, are deemed similar. Table 2.2 shows that, on average, the construction cost of military family houses in Alabama is about 16% lower than the national average, with this percentage ranging between 13% and 18% among the eight specific locations listed in Table 2.2.

Table 2.2: Area Cost Factors 16 May 2019 PDF (Chapman and Thompson 1981)

DOD Area Cost Factors - CONUS		
PAX Newsletter, dated 5/16/2019 - National Average 1.00		
CONUS Installations by STATE	**Service**	**ACF Official**
Alabama		**0.84**
Anniston Army Depot	Army	0.83
Fort McClellan	Army	0.83
Fort Rucker	Army	0.84
Maxwell Air Force Base	Air Force	0.87
Mobile	Army	0.83
Mobile Area	Navy	0.85
Montgomery	Army	0.85
Redstone Arsenal	Army	0.82

City Cost Indexes – RSMeans

RSMeans' City Cost Indexes are convenient when estimators want to compare costs from city to city and region to region. They contain average construction cost indexes for over 200 cities in the United States and Canada, covering over 930 three-digit zip code locations (Waier 2010). However, the application of these City Cost Indexes should be limited to vertical construction projects rather than transportation and infrastructure construction since they are calculated with building construction data from nine different types of buildings. That includes pricing data from 66 construction materials, wage rates for 21 trades, and different types of construction equipment.

The RSMeans database provides over 85,000 unique line items, calculated based on location. As known in the construction industry, the differences in the prices of labor, equipment, and material, can vary greatly depending on location. Each of these factors may impact the overall cost of construction projects substantially. For that reason, RS Means can adjust construction data based on location, providing more accurate estimates according to current market prices. The material costs contain fasteners, which are generated from manufactures' recommendations and engineering best practices. In the case of labor costs, RSMeans presents this factor for either union labor or non-union labor, calculated base on the national average for construction labor costs or from union agreements. Finally, for equipment, RSMeans data includes average rental costs and also operating costs. Operating costs contain parts that are affected by normal wear and tear and even the cost associate with the repair. The cost to move the equipment to the job site is not included.

Table 2.3 shows the City Cost Indexes for the five city Alabamian cities considered by the RSMeans, as well as the national average location index calculated with 30 major cities across the country.

Table 2.3: RSMeans Alabama City Cost Index(Hale and R.S. Means Company 2019)

Year	**National 30 City Average**	**Alabama**				
		Birmingham	**Huntsville**	**Mobile**	**Montgomery**	**Tuscaloosa**
2020	239.1	201.9	201.5	198.7	201.2	201.4
2019	229.6	198.1	197.7	195.0	197.4	197.6
2018	217.7	186.4	185.6	183.0	185.1	186.2
2017	209.4	178.6	178.3	177.9	178.5	179.6
2016	207.7	185.6	184.2	184.1	183.5	186.3
2015	204.0	184.8	182.1	185.4	182.7	184.5

<u>*Hot Mix Asphalt Location Cost index – Alabama Department of Transportation*</u>

Hot Mix Asphalt (HMA) Location Cost Index developed by Keren XU (2018) presents a three-dimensional HMA cost estimating system based on historical bid data for projects awarded by ALDOT between the years 2011 to 2016. The LCI provides ALDOT a better understanding of the main factors influencing cost estimating in asphalt paving projects. Likewise, this is an essential tool for decision-making in different management levels and helps to improve ALDOT’s budget control capabilities and resource allocation procedures.

For the development of this system, five factors were taken into consideration: 1) project scale, 2) time, 3) geographic location, 4) estimating uncertainty, and 5) level of competition. A different number of factors and quantitative procedures, including non-linear regression, were integrated for the suitable performance of this study. The effectiveness of the system was demonstrated using the Moving-Window Cross Validation approach and several test methods to assess the results. Table 2.4 shows the HMA Location Cost Index in Alabama between 2011to 2016.

Table 2.4: HMA Location Cost Index in Alabama (Xu 2018)

Year	State	North	Central	South
2011	100.00	95.15	102.56	100.21
2012	100.00	97.53	106.98	96.35
2013	100.00	102.02	104.51	94.93
2014	100.00	97.12	106.75	97.37
2015	100.00	97.80	105.70	94.22
2016	100.00	98.46	110.25	92.42

2.6 Summary

Cost estimating is essential in the planning process, useful to prepare cost at the early phases of the projects. During the design, the estimate is used to establish a preliminary construction budget, and present appropriate information for agencies to contemplate project feasibility and further development. Likewise, estimates will anticipate cost overruns before starting the bidding process to consider alternate designs, materials, or technologies. The effort for the estimator is to understand the project scope to evaluate the cost of materials, equipment, and labor, taking into consideration the geographic location of projects. The results of the cost estimate are a crucial part of decision-making.

However, the cost estimate could be prepared based on available information on previously completed projects. Historical data can be used as the basis to develop more accurate budgets for future projects. Many companies realize that much more focus is needed in the area of benchmarking and the development of associated historical metrics that can be used to estimate and validate their future projects (Pickett and Elliott 2007). The use of data from previous projects will not be consistent unless an adjustment factor is applied to represent the difference in costs between particular locations. Location Cost Indexes and Location Adjustment Factors measure the change in the price level to translate the cost of one location to another.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter describes the methodology followed to develop the annual RLCI proposed in this thesis. The methodology includes methods used to collect, process, and analyze historical bid data. To start data collection, all projects awarded by ALDOT between the years 2006 and 2016 using riprap were taken into consideration. This information was extracted from ALDOT's bid tabulations website. Once the data was collected and organized, an exploratory analysis was conducted to select the most significant riprap pay item used in ALDOT projects. This item determined the initial price database used for the development of the RLCI. Two outlier detection methods were applied to clean the available data to create a consistent and reliable dataset. Figure 3.1 illustrates the steps followed in conducting this research. ALDOT's regions were considered as an initial partition of the state for the calculation of the RLCI. However, a series of statistical tests were used to define a more effective partition of the state into geographic regions that represent different riprap market conditions given by their statistically significantly different pricing levels.

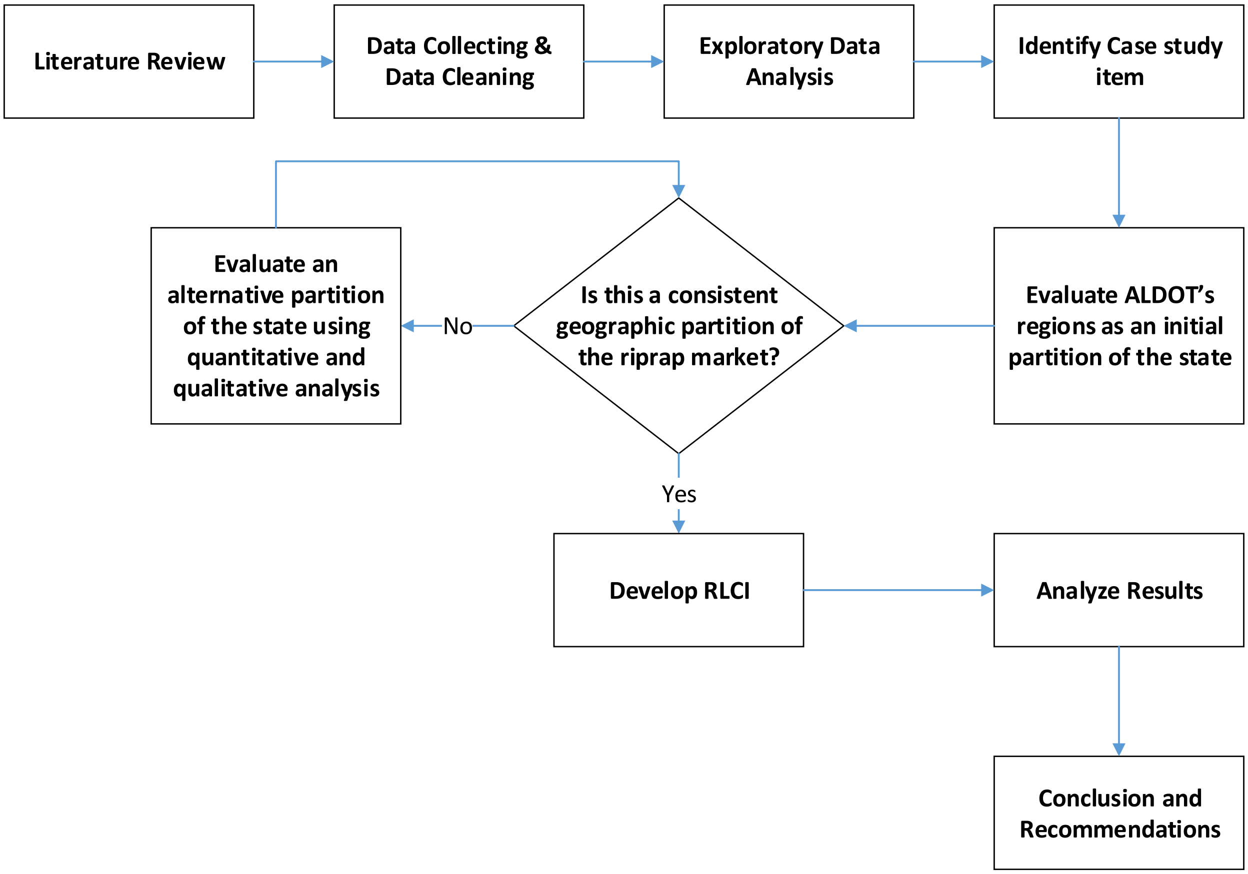
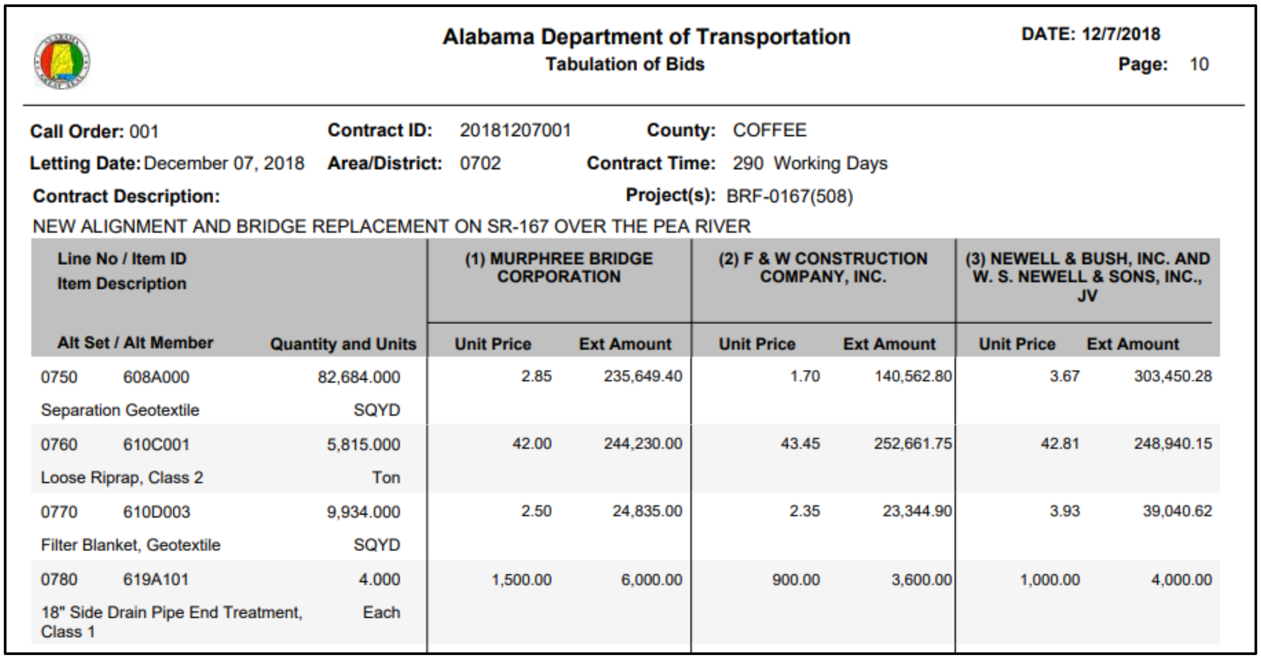


Figure 3.1: Methodology Flow chart of the research

3.2 Data Collection and cleaning

The first step to develop this research was seeking a suitable source of pricing data to ensure the generation of reliable results. The author decided to use historical bid data from previous projects awarded by ALDOT. Since the purpose of this study was to model regional riprap markets across the state, it was considered that no source could better represent ALDOT's construction market. Initially, historical bid data from construction projects awarded by ALDOT between the years 2006 and 2016 was extracted. This data was available on ALDOT's Bid Tabulations website.

Data attributes provided by the collected bid data included letting date, location (county), number of bidders, item ID, item description, units and quantity of the material, and the final price for each bidder. ALDOT's bid tabulations show the set of unit prices submitted by each bidder according to the pay item list outlined in the Request for Proposals (RFPs). Pay items and bid quantities are provided by ALDOT in its RFPs, while bidders submit their corresponding unit prices in their price proposals. The author found 1,244 projects that included the purchase and installation of riprap during the 11 years of collected bid data. ALDOT's Bid Tabulations website provides historical bid data in the form of Portable Document Format (PDF) files, one file per project. Figure 3.2 shows a screen capture of one of those PDF files for a new alignment and bridge replacement over the pea river by ALDOT in Coffee County in 2018. Data in PDF format is not ideal for data processing and analysis; therefore, great efforts were invested in converting and integrating all individual PDF files into a single spreadsheet file. To facilitate data manipulation and analysis, it was crucial to converting all PDF files into excel.



Alabama Department of Transportation
Tabulation of Bids

DATE: 12/7/2018
Page: 10

Call Order: 001
Contract ID: 20181207001
County: COFFEE
Letting Date: December 07, 2018
Area/District: 0702
Contract Time: 290 Working Days
Contract Description:
Project(s): BRF-0167(508)
NEW ALIGNMENT AND BRIDGE REPLACEMENT ON SR-167 OVER THE PEA RIVER

Line No / Item ID Item Description		(1) MURPHREE BRIDGE CORPORATION		(2) F & W CONSTRUCTION COMPANY, INC.		(3) NEWELL & BUSH, INC. AND W. S. NEWELL & SONS, INC., JV	
Alt Set / Alt Member	Quantity and Units	Unit Price	Ext Amount	Unit Price	Ext Amount	Unit Price	Ext Amount
0750 608A000 Separation Geotextile	82,684.000 SQYD	2.85	235,649.40	1.70	140,562.80	3.67	303,450.28
0760 610C001 Loose Riprap, Class 2	5,815.000 Ton	42.00	244,230.00	43.45	252,661.75	42.81	248,940.15
0770 610D003 Filter Blanket, Geotextile	9,934.000 SQYD	2.50	24,835.00	2.35	23,344.90	3.93	39,040.62
0780 619A101 18" Side Drain Pipe End Treatment, Class 1	4.000 Each	1,500.00	6,000.00	900.00	3,600.00	1,000.00	4,000.00

Figure 3.2: Screen Capture of Project information in PDF(ALDOT 2018)

After integrating the historical bid data from all available projects into a single spreadsheet, the next step was to clean and reorganize this data into a tidy dataset. The well-defined and consistent structure of a tidy dataset facilitates data manipulation, visualization, and processing. In a tidy dataset, each variable is a column, and each observation is a row (Wickham 2014). In this study, a single observation corresponds to a pay item used in a given contract. Thus, the data attributes in the columns include letting date, location (county), number of bidders, item ID, item description, units and quantity of the material, and unit prices submitted by all bidders on that specific pay item.

After an exploratory analysis, it was revealed that ALDOT uses eight different riprap pay items in its contracts, including temporary and permanent riprap structures for some of the types of riprap described in Section 1.2. Those eight pay items are Loose Riprap Class 1-5 and Temporary Riprap Class 1–3. According to ALDOT Standard Specifications (2018), Class 1 riprap is mostly designed for hand placement and use with minimal water currents. Classes 2 and 3 are intended for use in areas with minimal to medium water currents and wave action. Class 4 and 5 riprap is designed for use in medium to high water currents and wave actions for the protection of bridge piers and abutments, and protection of channel slopes.

Table 3.1 summaries the number of contracts that used each of the different riprap pay items between 2006 and 2016, as well as the total amount awarded in tons and dollars. Based on this table, it was evident that Loose Riprap Class 2 is the most frequently used and the one with the greatest impact on ALDOT's construction program.

Table 3.1: ALDOT's Riprap pay items

ITEM	Number of Contracts	Total Quantity Awarded (Tons)	Total Amount Awarded (Dollars)
Loose Riprap, Class 1	49	51,835	$ 1,492,611
Loose Riprap, Class 2	716	1,779,033	$ 58,652,725
Loose Riprap, Class 3	15	25,801	$ 663,667
Loose Riprap, Class 4	2	1,589	$ 47,129
Loose Riprap, Class 5	1	147	$ 3,857
Temporary Riprap, Class 1	37	28,944	$ 1,191,291
Temporary Riprap, Class 2	422	344,288	$ 12,136,868
Temporary Riprap, Class 3	2	250	$ 11,750
TOTAL	**1,244**	**2,231,887**	**$ 74,199,898**

As shown in Figure 3.3, about 79% based on all riprap purchased by ALDOT between 2006 and 2016 was Loose Riprap Class 2. This pay item was the most frequently used for the construction of permanent riprap structures in projects awarded by ALDOT during those 11 years. For that reason, this item was selected for the development of the proposed annual RLCI.

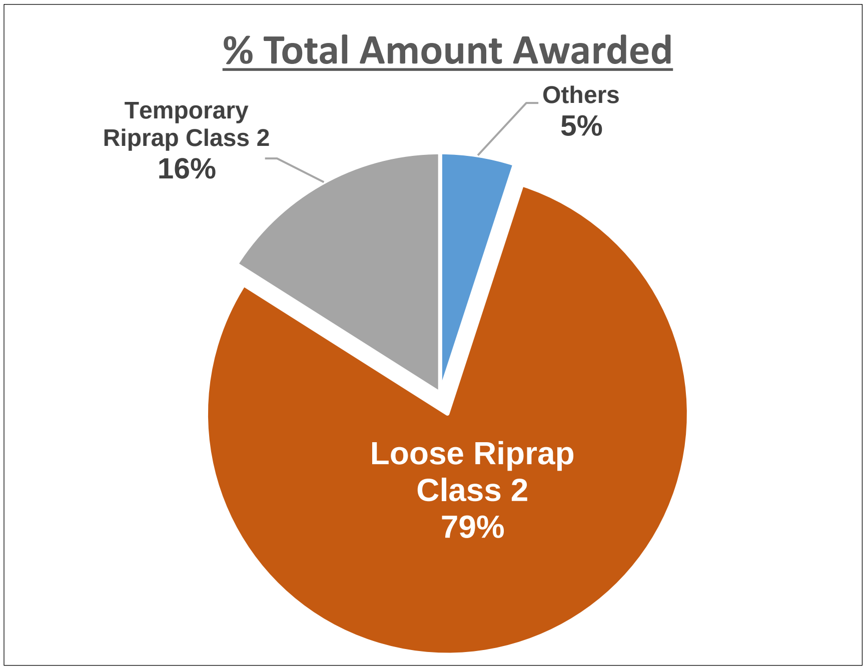


Figure 3.3: Percentage of Total Amount Awarded

After the most relevant pay item was selected, the pricing data from the contracts using Loose Riprap Class 2 was extracted. Stone for this class riprap shall consist of graded stones ranging from 10 to 200 lbs (5 kg to 100 kg) with not over 10% weighting 200 lbs (100 kg) and at least 50% weighting over 80 lbs (40 kg) and not over 10% weighting 1 lbs (5 kg) (ALDOT 2018a). As shown in Table 3.1, a total of 716 contracts required the use of this pay item between 2006 and 2016. The unit prices obtained from those contracts were the initial database for the development of RLCI. Two-step outlier detection methods were used to clean the data further.

3.2.1 Methods for outlier detection and removal

In statistics, an outlier is a data point that varies significantly from other observations. In this study, those outliers could be just atypical unit prices submitted by bidders to unbalance their bids intentionally, could be unintentional mistakes made by bidders, or they could be the result of errors in the data recording process. Errors in large databases can be extremely common, so it is necessary to remove outliers to avoid alterations in the calculated statistics. Outliers were identified and eliminated in this study through the application of the following statistical methods.

Modified Z-score method

The presence of outliers can affect the performance of data-driven models substantially. It is a common practice to implement outlier detection mechanisms at an early stage during the development of those models in an attempt to discard unbalanced bids, as well as other unintentional outliers (Federal Highway Administration 1988).

The traditional Z-score (non-modified) method provides a metric that indicates the numeric distance of a data observation from the sample’s mean. However, the mean value could be heavily influenced by outliers in small datasets, preventing this traditional method from identifying them. To address this issue, the modified Z-score method uses the Median Absolute Deviation (MAD), instead of the mean.

This method was applied to identify outliers among unit prices from the same contract, which could correspond to a small sample. The modified Z-score is calculated using Equation 3. Values that contain an absolute modified Z-score higher than 3.5 ($|Mi| > 3.5$) were eliminated from the dataset, as suggested by Iglewicz and Hoaglin (1993)

$$Mi = \frac{0.6745(\mathrm{Xi}-\check{x})}{\mathrm{MAD}} \qquad \textbf{Eq. 3}$$

Where:

Mi = Modified Z-Score for Observation i

MAD = Median Absolute Deviation = $\{|Xi$ – Median$|\}$

xi = Value of observation i

$\check{x}$ = Median of all observations

Robust Regression and Outlier Removal (ROUT)

Even though some outliers could be just typographical errors, a number of them are expected to be the result of unbalanced bids, which is a common practice in the construction industry (Rueda Benavides 2016). According to Manzo (1997), a price proposal is considered to be unbalanced if each of its bid items “fails to carry its proportionate share of the overhead and profit in addition to the necessary costs for the item. The results are understated prices for some items and enhanced or overstated prices for others.”

The second approach in the outlier detection process consisted of the use of the Robust Regression and Outlier Removal (ROUT) method. This method was proposed and developed by Motuslsky and Brown in 2006. ROUT method combines robust regression and non-linear regression techniques to identify data points that are significantly apart from the regression equation. Regression models assume that the scatter of data around the ideal curve follows a Gaussian or normal distribution. This assumption leads to the familiar goal of regression: to minimize the sum of the squares of the vertical or Y- value distances between the points and the curve (Motulsky and Brown 2006).

Since the modified Z-score method identifies outliers between unit prices for the same item under the same given contract, this method could miss outliers in unusual projects where all bidders are forced to submit atypical unit prices. The ROUT method was applied to data from all contracts, allowing the detection and removal of those unusual projects.

GraphPad Prism 8 is a statistical software that facilitates the use of the ROUT approach. This software identifies the outliers, eliminates them, and fits the remaining data points with a new regression model. Figure 3.4 is an example of the ROUT output obtained from GraphPad Prism 8.

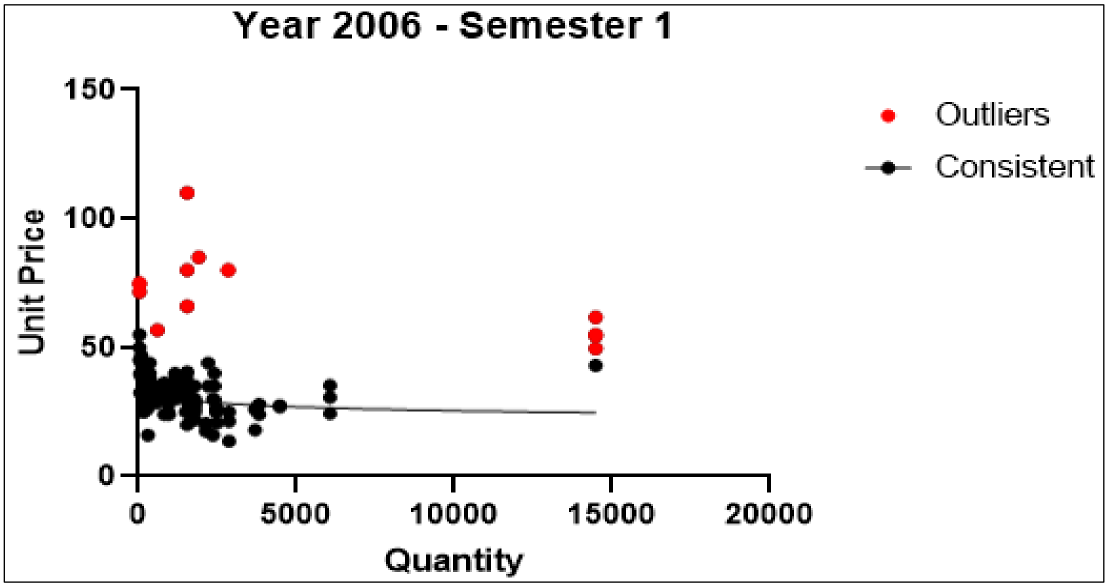


Figure 3.4: GraphPad Prism 8.1.1 outlier's example

3.3 Initial partition of the State: ALDOT’s geographic regions

ALDOT is in control of approximately 11,000 miles of roads across its 67 counties in Alabama. ALDOT’s maintenance and operation activities on those roads are organized into five geographic regions: north (N), east-central (EC), west-central (WC), south-east (SE), and south-west (SW), as shown in Figure 3.5.

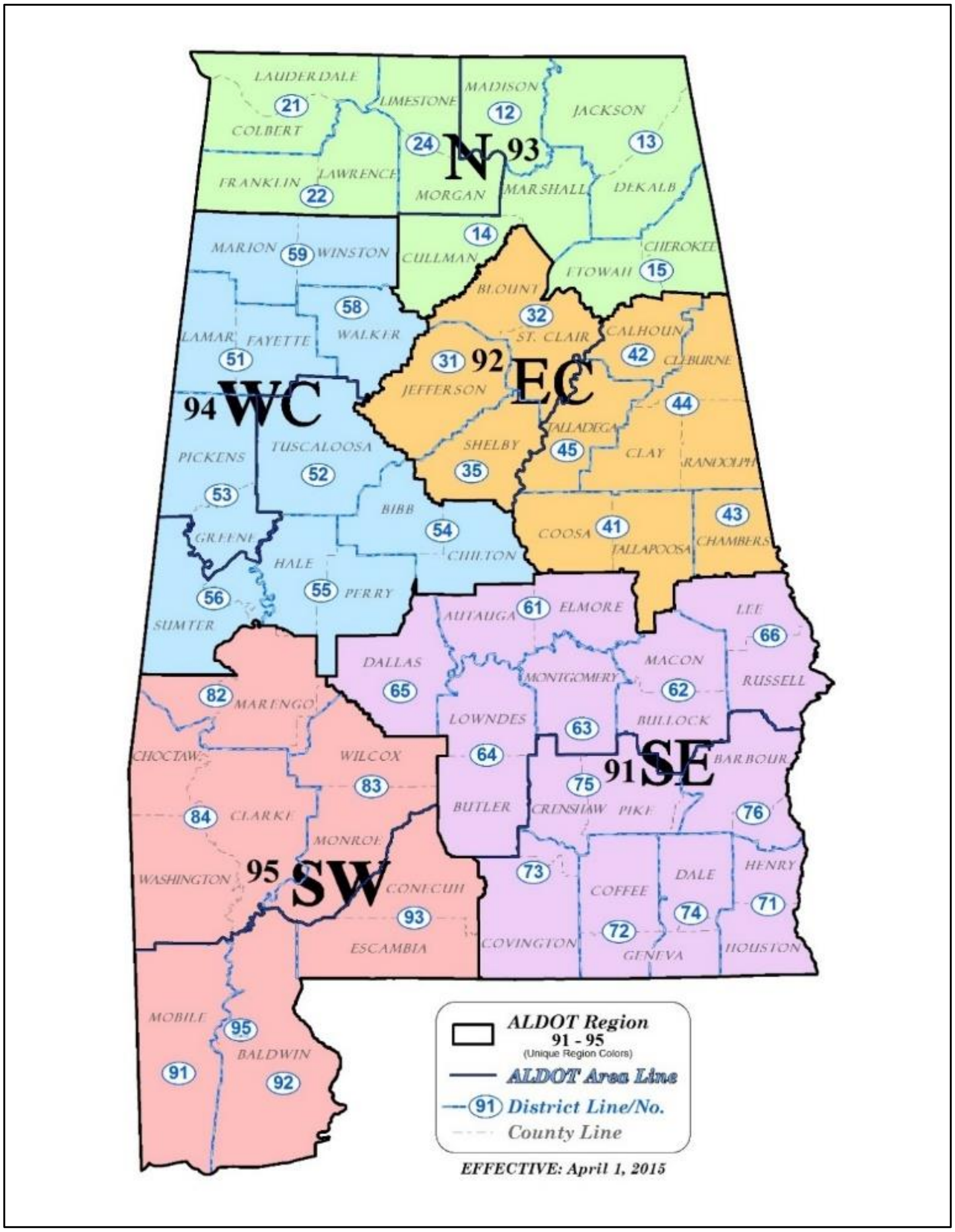


Figure 3.5: ALDOT Regional Classification (ALDOT 2018a)

The purpose of the proposed RLCI is to model riprap market differences among different geographic regions in Alabama. Thus, it was first necessary to divide the state into regions representing different market conditions. The first attempt for this partition was using ALDOT's geographical classification. Average price differences were then compared among these regions using the analysis of variance (ANOVA) and the least significant difference (LSD) statistical tests to determine if there are statistically significant differences among them. It would not make sense to consider two different adjacent regions separate if their pricing levels are not significantly different. In that case, those regions could be combined into a single region. Likewise, the application of these statistical tests served to validate the consistency of the initial partition of the state to determine if an alternative division of the state should be considered.

The use of ALDOT's regions was initially considered because it would be more practical to align the RLCI with ALDOT's operation practices. However, the author considered previously that ALDOT's division might not represent the behavior of the riprap market across the state adequately. The methodology described in Section 3.4 was also developed in the case scenario of the need for an alternative regional classification. This alternative division was the one used in this study.

3.3.1 Statistical tests

Analysis of variance (ANOVA) single factor

The evolutionary biologist Ronald Fisher (1918) introduced the term variance and proposed its formal analysis. ANOVA is a form of statistical hypothesis testing and is commonly used to analyze experimental data. ANOVA single factor, or one-way, is used to test the null hypothesis that the means of numerous populations are all equal. A probability value (p-value) lower than 5% is commonly assumed to be sufficient, in virtually all research fields, to reject the null hypothesis and demonstrates that not all the population means are equal. Those results would indicate, with a 95% confidence level, that there are significant differences among the mean values under consideration. However, ANOVA can not specify where the gaps are. The LSD test can then be necessary to find those differences.

Least Significant Difference (LSD)

After running the ANOVA test, the results may indicate that the mean of one or more groups differs from the other groups. To address this, Fisher (1953) also developed the LSD test, which is used only when the null hypothesis is rejected. LSD allows a direct pairwise comparison between groups. If the numerical difference between the means of two groups is greater than their respective LDS, the groups are deemed to be statistically significantly different, with a confidence level of 95%. The LSD value between two groups (regions in the case of this study) is calculated using Equation 4.

$$LSD_{1,2} = t\sqrt{MSM\ \left(\frac{1}{N1} + \frac{1}{N2}\right)} \qquad \textbf{Eq. 4}$$

Where:

$LSD_{1,2}$ = Least Significant Difference between Groups 1-2

t = Critical value

MSM= Mean square within, obtained from the results of ANOVA test

N= Number of scores used to calculate the means

3.4 Alternative partition of the state of Alabama

The research approach for this study considered a methodology that includes qualitative and quantitative processes to define an alternative partition of the state in the case of finding that ALDOT's regions were not consistent. That would mean that the regions established by ALDOT do not appropriately represent regional riprap market conditions. A more detailed description of the quantitative and qualitative parts of this methodology are presented in the next sub-sections.

3.4.1 Quantitative Analysis

In general terms, quantitative analyses are usually performed to interpret or model a situation or phenomenon using statistical and mathematical methods. Introduced by Richard Herrnstein (1961), quantitative analysis of behaviors aims to reproduce a real-world event in terms of numerical values. The mathematical models describe or predict relations between a dependent variable and one or more independent variables.

The quantitative part of the methodology to define an alternative partition of the state was first intended to gain a better understanding of the variability of riprap prices across the state, and then used to make the actual regional partition by grouping adjacent counties that show similar riprap prices. The data obtained from the 716 contracts using Loose Riprap Class 2 was initially cleaned with the modified Z-score method, as the first outlier removal filter. The remaining data were then organized by year, and the ROUT method was then used to detect and discard unit prices that significantly differ from typical pricing levels within their respective years.

Having the data cleaned with the second outlier detection method, the study proceeded to use the resulting annual non-linear regression curves as models of state average pricing levels. These curves were used as a point of reference to determine the average price difference between each county and the annual state average. This average difference indicates how apart county data points are from the state average curve, as shown in Figure 3.6. The calculation of the average deviation of each county from the state average was performed, as shown in Equation 5.

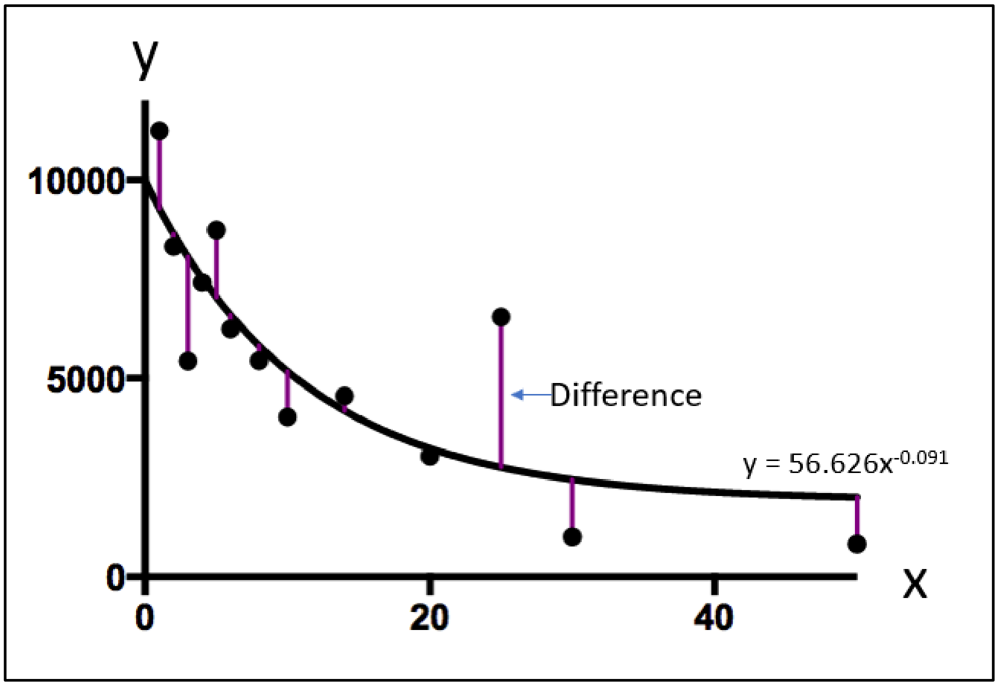


Figure 3.6: Differences with the state average

$$APDSA_j = \frac{1}{n}\sum_{i=1}^{n}\frac{AP_{ij}-SAP_{ij}}{SAP_{ij}} \times 100\% \qquad \textbf{Eq. 5}$$

Where:

$PDSA_j$ = Average price deviation of riprap prices in County j from state average (%)

AP_{ij} = Actual recorded unit price for riprap pay item for Project i in County j

SAP_{ij} = Estimated unit price for riprap pay item for Project i in County j using state average regression curve

n = Number of projects using the selected riprap pay item in County j

Average price deviations calculated with Equation 5 for all counties were then sorted from lowest to the highest value, and the ANOVA and LSD tests explained above were used again, but in this case, in an iterative systematic manner to generate the new geographic classification. This systematic iterative process starts with an ANOVA test applied to the average price deviations of all counties to confirm that there are significant differences among them. After confirming that with the ANOVA test, the LSD test is performed to identify counties with similar average price deviations among those showing the lowest values. Among those counties selected with the LSD test, only those forming a continuous area are kept becoming the form the first geographic area, and the other counties are returned to the original list. The two tests are applied again, but this time to the counties that remained in the original list, forming the second geographic region. The process is repeated multiple times until obtaining an ANOVA test that finds no significant difference among the remaining counties, meaning that those would form the final geographic group.

3.4.2 Qualitative Analysis

While quantitative analysis aids as a powerful approach based on a mathematic evaluation of riprap prices, it is common to supplement this type of quantitative procedures with a qualitative analysis. Qualitative analyses usually seek to respond “why” or “how” questions associated with the quantitative results. Thus, the qualitative part of this methodology was intended to support the output of the quantitative process by determining if that was a sound partition, given the location of the quarries that produce riprap. This information facilitated a better understanding of the factors influencing the variability of riprap prices across the state of Alabama.

Location of Quarries in the state of Alabama

A quarry is a surface mining operation for the extraction of sand, gravel, limestone, and other types of construction aggregates and materials. There are several methods of removing stones from natural beds, such as digging or blasting, depending on the size of rocks and the soil characteristics. Alabama has several quarries located in different counties across the state. A list of all those quarries was made, and one by one were contacted to determine how many of them produce Loose Riprap Class 2. The objective of this investigation was to find the precise location of quarries that provide this type of riprap. This helps to gain a better understanding of the connection between unit prices and the area where the material is produced, which is contained by the distribution of soils in Alabama.

Types of soils in Alabama

Soils are dynamic natural bodies having properties derived from the combined effects of climate and macro-and microorganisms, conditioned by relief, acting on parent material over a period of time. A product-soil differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics (Soil Survey Staff 2008).

As shown in Figure 3.7, the state of Alabama is divided in several major areas based on the different soil areas: Limestone Valleys and Uplands (Pink), Appalachian Plateau (Orange), Pedemonte Plateau (Green), Coastal Plain (Yellow), Backland Prairie (Blue), Major Flood Plains and Terraces (Grey), and Coastal Marshes and Beaches (Purple).

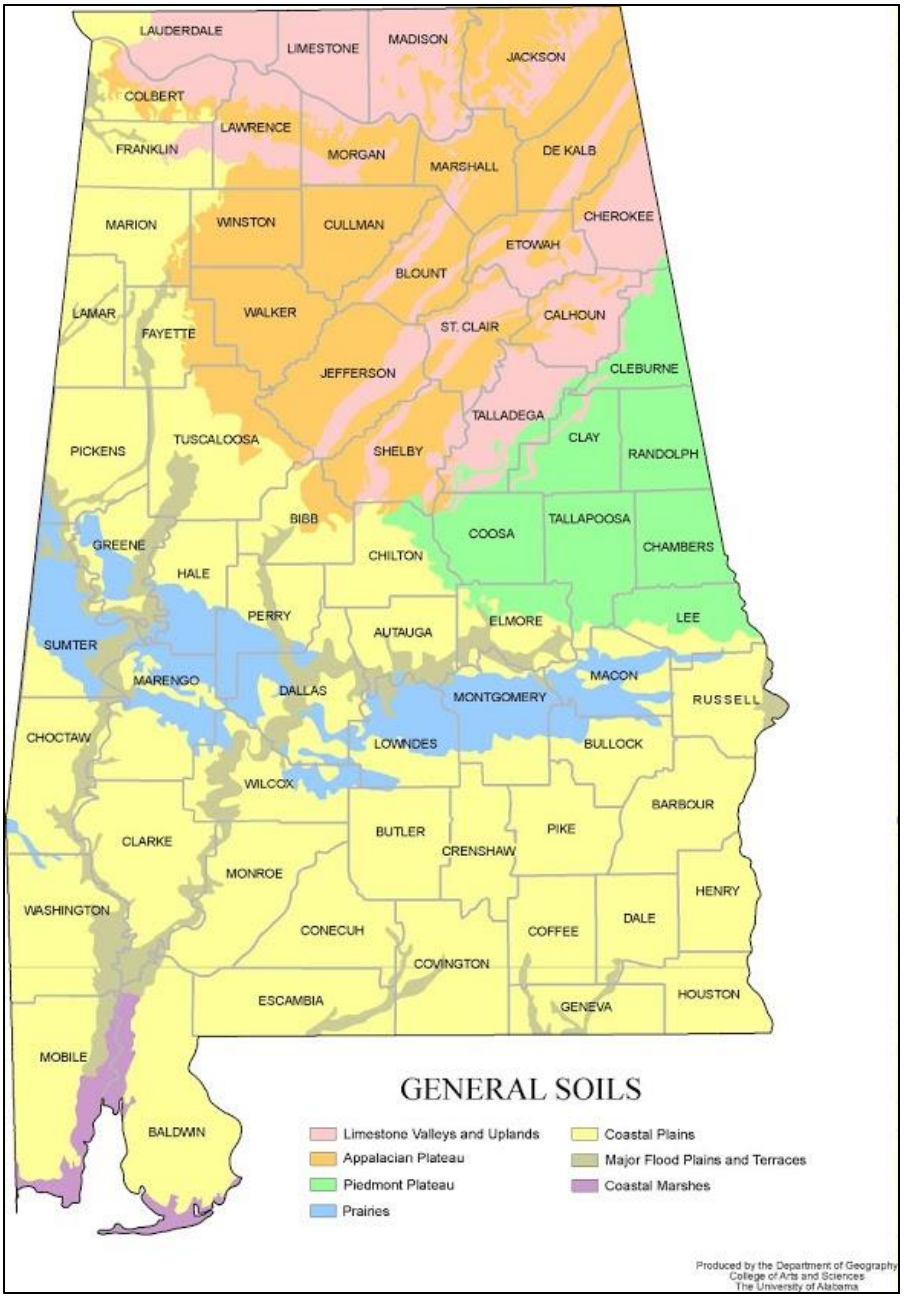


Figure 3.7: General Soil Areas in Alabama.
(Department of Geography, University of Alabama)

- Limestone Valleys and Uplands (Pink): Soils in this area were formed mainly in residuum weathered from limestones. The topography is commonly level to undulating and has an elevation of 600 feet. Cotton and Soybeans are the crops that predominate in this area.

- Appalachian Plateau (Orange): Soils in this area derived from sandstone or shale. The topography contains slopes less than 10 percent and elevations around 1,300 feet. Corn, soybeans, potatoes, and tomatoes are the major crops.
- Pedemonte Plateau (Green): Soils in this area are derived from granite, hornblende, and mica schists. The topography is rolling to steep and has elevations from 700 to 1,000 feet. However, the Talladega Hills has elevations between 900 to 2,407, being the last one the highest point in Alabama. Areas are now in pasture or forest.
- Coastal Plain (Yellow): Soils in this area were derived from marine and fluvial sediments eroded from the Appalachian and Piedmont plateaus. They have loamy subsoils and sandy loam or loamy sand surface layers. The topography is level to very steep, with elevations ranging from 200 to 1,200 feet. Corn, peanuts, soybeans, and horticultural are the major crops.
- Backland Prairie (Blue): Soils in this area were delivered from alkaline, Selma chalk, or marine acid clays. It has a dark-colored surface layer and a yellowish colored subsoil. The topography is level to undulating, and the elevation is about 200 feet. Soybeans are the major crop, and the soils in this area are used for timber and pasture.
- Major Flood Plains and Terraces (Grey): Soils in this area are delivered from alluvium deposited by the streams. These soils are found along streams and rivers.
- Coastal Marshes and Beaches (Purple): These soils are not extensive in the state, and most of them are deep and poorly drained. The elevation is from sea level to a few feet above sea level.

As explained in Section 1.2, riprap is usually made from either limestone or granite. Thus, and base on the soil areas described above, it is easy to infer the quarries producing riprap in Alabama are most likely located Limestone Valleys and Uplands and the Pedemonte Plateau areas. This was actually confirmed by this study, as discussed in Section 4.2.2.

3.5 Development of Riprap Location Cost Index

After defining a suitable geographic classification of regions, the final step of the research methodology was the actual development of the RLCI. The RLCI is intended to represent riprap price differences across the defined geographic regions at each index period (one-year periods – January to December). RLCI index values were calculated at each index period following the steps outlined below:

1. Develop an annual statewide non-linear regression model using only the bid data contained within each index period under consideration.
2. Calculate the percent difference between each actually recorded unit price, and the state average unit price calculated for the same quantity of riprap with the regression model for the index period under consideration.
3. Calculate the average percent difference per region and under each index period.
4. For each region, set the statewide RLCI value as 1.00 and calculate regional index values by applying their respective average differences to the statewide index value. (1.00 x (1 + average difference from state average).

CHAPTER 4: DATA ANALYSIS AND RESULTS

4.1 Introduction

This chapter analyzes and discusses the results of the findings obtained from the application of the methodology presented in Chapter 3. Following that methodology, this chapter starts with the assessment of the suitability of ALDOT's regions as representatives of regional riprap markets. Given that inconsistencies were found with that initial partition of the state, the chapter proceeds to define an alternative regional classification using the ANOVA and LSD tests described in Section 3.4. The final geographic classification of the riprap market was then applied to the development of the annual RLCI for each region between 2006 and 2016. Finally, the chapter discusses the main findings and observations made throughout the thesis.

4.2 Analysis of ALDOT's Geographic classification

As explained before, in Chapter 3, the geographic classification of ALDOT operations was considered as the initial partition of the state for the development of the RLCI (see Section 3.3). After applying the ROUT method and removing possible outliers, a non-linear regression model was created for each geographic region combining all regional bid data contained in the available 11-year period. At the same time, the study created a state average regression curve combining the data from all regions. Figure 4.1 illustrates each non-linear regression models at the regional and state level created with the 11 years of historical bid data for Loose Riprap Class 2. The x-axis in this figure indicates the bid quantity in tons of riprap, and the y-axis indicates the average price in dollars for the specific quantity.

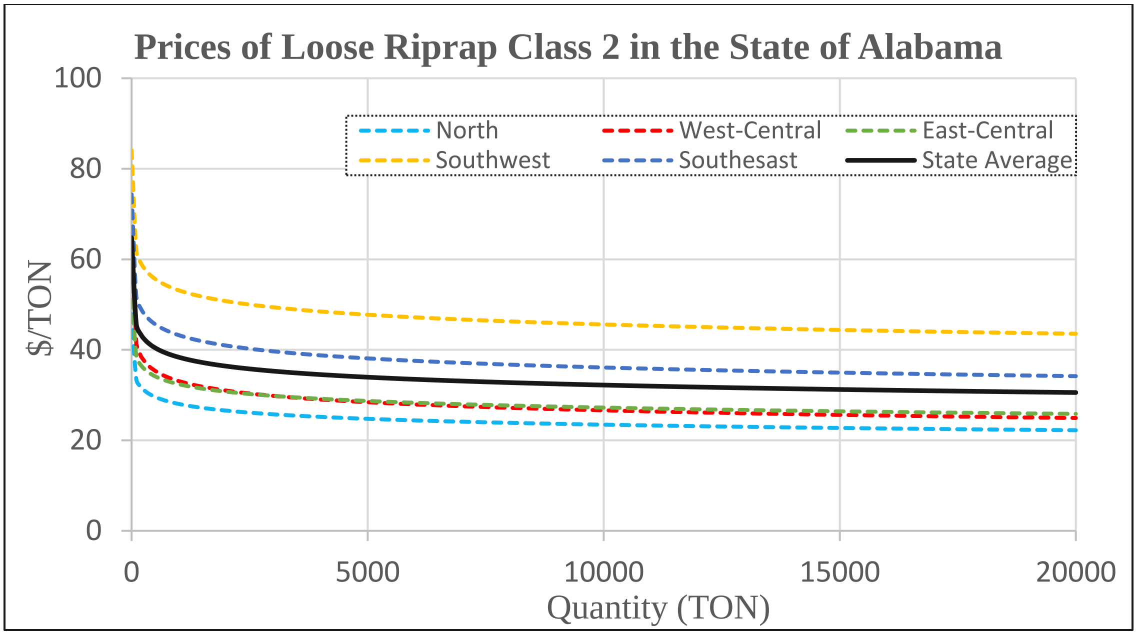


Figure 4.1: Non-linear regression models per region

The outcomes in Figure 4.1 reveal that prices in the southern regions tend to be higher than in northern regions, with the southwest region showing the highest overall prices. Likewise, it can be observed that the regression curves of east-central and west-central have a similar trend. This may indicate that there is no significant difference between the two regions, making it possible to combine them into a single region. This statement was confirmed by the statistical analysis described later int this section.

The similar shapes of the six curves in Figure 4.1 reveals a high degree of consistency of the quantity-unit price relationship across the state of Alabama. It allowed the author to assume that different ”elevations” of the state average curve would reasonably represent regional riprap markets. Thus, the average percentage gap between each regional curve and the state average can be assumed to be an effective metric of the relative riprap pricing levels across the state. The assessment of the suitability of this first geographic partition started with annual ANOVA tests among all regions and applied in six-month intervals to see if there have been precise changes in the relative regional pricing levels over the 11-year analysis period.

Tables 4.1 and 4.2 show the results for one of those ANOVA tests. This test was applied to the second semester of the year 2006; July to December. Based on these results, it is possible to conclude, with a 99.99% confidence level (p-value = 8.9 x 10-10), that there are significant deferences in riprap pricing levels among these regions. That defines that the means of the five regions are not all equal; at least one of them is different.

Table 4.1: Summary ANOVA test year 2006: July to December

SUMMARY				
Groups	**Count**	**Sum**	**Average**	**Variance**
N	35	-6.58201	-0.18806	0.0319
WC	3	0.483184	0.161061	0.049956
EC	9	-0.75657	-0.08406	0.0200835
SW	26	6.589922	0.253459	0.077917
SE	5	-0.11916	-0.02383	0.006734

Table 4.2: Results of ANOVA test year 2006: July to December

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F crit**
Between Groups	3.050432	4	0.762608	16.73768	8.90E-10	2.497129
Within Groups	3.326051	73	0.045562			
Total	6.376483	77				

The LSD test was then used for that (or those) significant difference within those mean values. Table 4.3 shows the results after running the LSD test for the same six-month period in 2006. This table corresponds to a pairwise comparison of adjacent regions (e.g., the north region was not compared against the southern regions). For this period, the results show that indeed there is no statistical significance between the west-central and east-central. It was also observed that there is no statistical significance between other regions, suggesting that some of these regions could be combined into one. These observations could indicate that the division of ALDOT regions is not the most suitable for the development of the RLCI. However, Table 4.3 also shows two inconsistencies. First, it shows no significant difference between the north and east-central, as well as between the west-central and east-central regions. That suggests that there should be no significant difference between the north and west-central regions either, but that is not the case. A similar inconsistency can also be observed among the west-central and both southern regions.

Table 4.3: Results of LSD test year 2006: July to December

Regions	LSD	ABS DIF	Statically Significant
N-EC	0.159	0.104	no
N-WC	0.256	0.350	yes
WC-EC	0.284	0.245	no
SE-EC	0.237	0.060	no
SE-WC	0.311	0.185	no
SW-EC	0.165	0.338	yes
SW-WC	0.260	0.092	no
SW-SE	0.208	0.277	yes

ANOVA results from all six-month periods showed the existence of significant differences among regional riprap prices, but there was more variability in the results from the LSD tests. Those results from all six-months periods are summarized in Table 4.4. Due to possible divergences in the division of the state, it was decided to carry out ANOVA and LSD tests per semester between the years 2006 to 2016. It can be observed that in 77% of those periods, the two central regions showed no significant difference in riprap prices (with a 95% confidence level). Likewise, a 64% value was calculated in the same way between the north and east-central regions. As occurred with the single six-month period discussed in Table 4.3, it could suggest a similar percentage between the north and west-central regions, but it was approximately 41%, reflecting an inconsistency that extends over the 11-year analysis period.

Moreover, the individual analysis of each of the 22 six-month periods revealed, at least, 17 inconsistencies similar to those identified for the second semester of 2006. All the inconsistencies found in the results fo the statistical analysis allow conclusions that the initial partition of the state assumed for this study does not appropriately reflect the regional division of the riprap market in Alabama. For this reason, a new analysis was performed to obtain a more consistent geographic classification, as discussed in the next section.

Table 4.4: Regions no statistically significant between years 2006 to 2016 in Alabama

Year	**Semester**	**Statistically Significant**							
		N-EC	**N-WC**	**WC-EC**	**SE-EC**	**SE-WC**	**SW-EC**	**SW-WC**	**SW-SE**
2006	1			No	No	No			
	2	No		No	No	No		No	
2007	1	No	No	No					
	2		No						No
2008	1			No		No			
	2	No	No	No					No
2009	1	No		No					
	2	No		No		No		No	No
2010	1			No	No				
	2	No						No	
2011	1	No	No	No					No
	2	No	No	No					No
2012	1	No	No	No					
	2	No				No		No	
2013	1	No		No					
	2	No		No		No			
2014	1	No	No	No	No				No
	2	No		No					
2015	1		No	No			No	No	No
	2			No	No	No			
2016	1				No				
	2		No		No				
Total		**64%**	**41%**	**77%**	**32%**	**32%**	**5%**	**23%**	**32%**

4.3 Analysis of an alternative partition of the State of Alabama

This section presents the results of the quantitative and qualitative analysis of the methodology described in Section 3.4 for the definition of an alternative and more suitable geographic classification of regional riprap markets in Alabama.

4.2.1 Results of Quantitative Analysis

As explained in the previous chapter, the quantitative analysis started with the assessment of riprap prices at the county level, by calculating the price deviation between each county and the state average riprap pricing level. The results of this analysis are illustrated in Figure 4.2. This heat map shows a general decrease in riprap prices while moving from the northern to the southern regions. The darker the tone in this heat map, the higher the average local price of riprap. Average price deviations from the state average shown in this figure range from riprap prices 35% lower than the state average (Lawrence County) to prices 56% greater than the state average (Mobile and Baldwin). Table 4.5 shows the ranking of counties according to the values shown in Figure 4.2 from the lowest to the highest average price deviation.

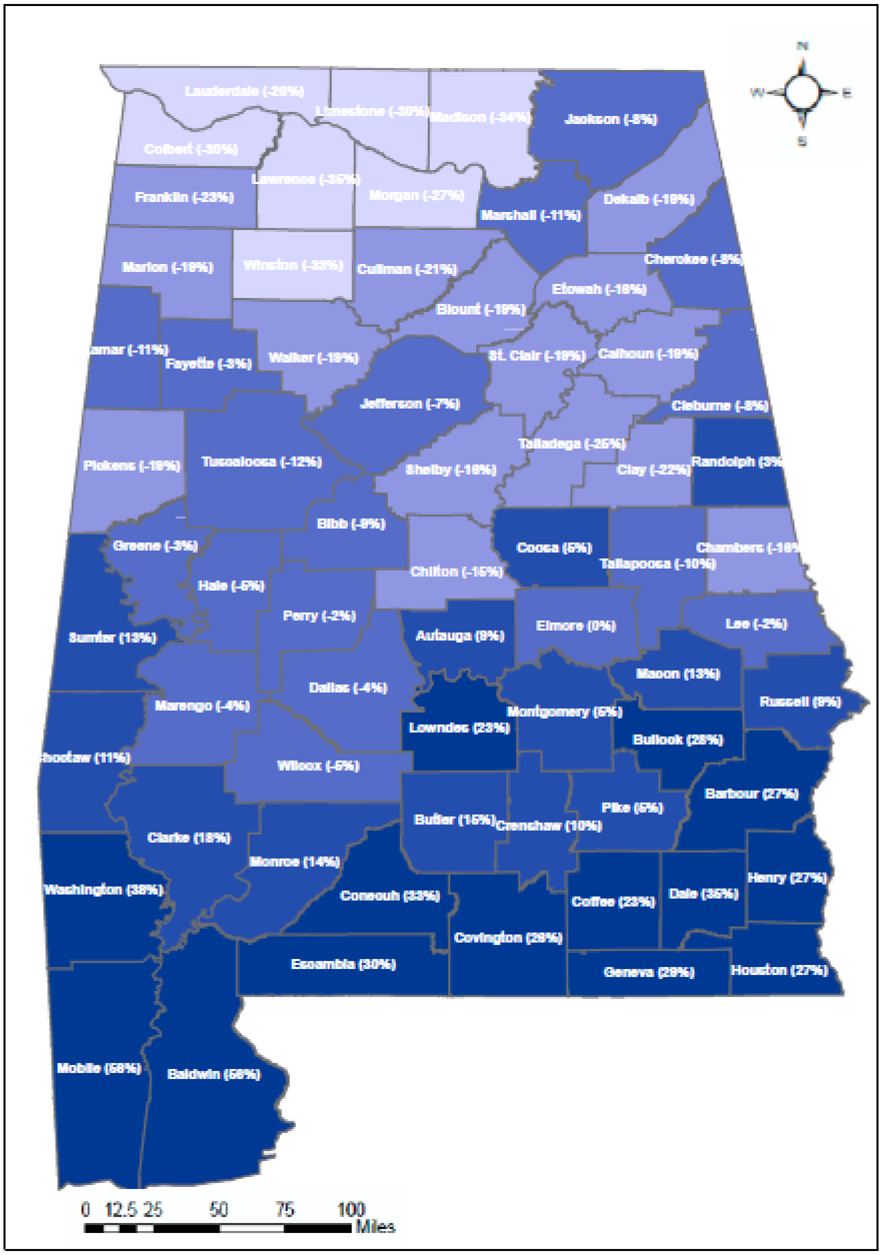


Figure 4.2 Variability in prices of Loose Riprap Class 2 from 2006 to 2016 in Alabama

Table 4.5: Ranked of counties in Alabama from lowest to the highest price of riprap

RANKED	COUNTY	AV. DIFF	RANKED	COUNTY	AV. DIFF
1	Lawrence	-35%	35	Dallas	-4%
2	Madison	-34%	36	Fayette	-3%
3	Winston	-33%	37	Greene	-3%
4	Limestone	-30%	38	Lee	-2%
5	Colbert	-30%	39	Perry	-2%
6	Morgan	-27%	40	Elmore	0%
7	Lauderdale	-26%	41	Randolph	3%
8	Talladega	-25%	42	Montgomery	5%
9	Franklin	-23%	43	Pike	5%
10	Clay	-22%	44	Coosa	5%
11	Cullman	-21%	45	Autauga	9%
12	Pickens	-19%	46	Russell	9%
13	Blount	-19%	47	Crenshaw	10%
14	Calhoun	-19%	48	Choctaw	11%
15	Marion	-19%	49	Sumter	13%
16	Walker	-19%	50	Macon	13%
17	Dekalb	-19%	51	Monroe	14%
18	St. Clair	-19%	52	Butler	15%
19	Shelby	-16%	53	Clarke	18%
20	Etowah	-16%	54	Lowndes	23%
21	Chambers	-16%	55	Coffee	23%
22	Chilton	-15%	56	Covington	26%
23	Tuscaloosa	-12%	57	Houston	27%
24	Marshall	-11%	58	Barbour	27%
25	Lamar	-11%	59	Henry	27%
26	Tallapoosa	-10%	60	Bullock	28%
27	Bibb	-9%	61	Geneva	29%
28	Cherokee	-8%	62	Escambia	30%
29	Cleburne	-8%	63	Conecuh	33%
30	Jackson	-8%	64	Dale	35%
31	Jefferson	-7%	65	Washington	38%
32	Hale	-5%	66	Mobile	56%
33	Wilcox	-5%	67	Baldwin	56%
34	Marengo	-4%			

The next step was the systematic iterative application of the ANOVA and LSD tests described in Section 3.4, to adjacent group counties with similar riprap pricing levels, starting by those at the top of the ranking in Table 4.5. Table 4.6 shows the first group of counties that could be grouped into the same region due to their similar riprap prices according to the LSD test. It should be remembered that the LSD test is applied on a pairwise basis. Thus, this table shows all the counties that could join Lawrence County in the first region, since their absolute difference with Lawrence County is lower than their respective LSD values.

Table 4.6: First group of counties with no statistical significance in Alabama

Counties	LSD	ABS DIF
Lawrence-Madison	0.220933021	0.007771163
Lawrence-Winston	0.333601546	0.09192699
Lawrence-Limestone	0.239439361	0.086857388
Lawrence-Colbert	0.248651911	0.056161844
Lawrence-Morgan	0.22240103	0.130777474
Lawrence-Lauderdale	0.224030364	0.160622892
Lawrence-Talladega	0.239439361	0.214710172
Lawrence-Franklin	0.232848021	0.189875981
Lawrence-Clay	0.304535153	0.256726606
Lawrence-Cullman	0.248651911	0.205207828
Lawrence-Pickens	0.285679296	0.278928346
Lawrence-Marion	0.235891915	0.231652867
Lawrence-St. Clair	0.262476292	0.239707903
Lawrence-Walker	0.254792389	0.190517475
Lawrence-Chamber	0.304535153	0.121357404
Lawrence-Chilton	0.239439361	0.207320713
Lawrence-Marshal	0.262476292	0.198594661
Lawrence-Lamar	0.248651911	0.23708589
Lawrence-Tallapoosa	0.333601546	0.226647249
Lawrence-Bibb	0.333601546	0.275941299
Lawrence-Cherokee	0.333601546	0.140550048
Lawrence-Cleburne	0.333601546	0.140550048
Lawrence-Jackson	0.248651911	0.236202012

A closer look at these results revealed that there were counties that could not be classified into the same continuous region due to their geographic location. The highlighted rows in Table 4.6 correspond to those counties that can form a continuous region around Lawrence. This study has called this Region 1. Once the first region was established, the same process was followed to continue forming the next regions. The first county in the rank that was not selected to join Region 1 was then used to continue the comparison among the remaining counties. For the second iteration, Talladega was the county selected to keep on the analysis for the formation of Region 2. Finally, the systematic iterative application of the ANOVA and LSD tests led to the formation of four different regions, as shown in Table 4.7. These regions are also illustrated in Figure 4.3. Average riprap prices increasingly grow as riprap construction activities move from Region 1 to Region 4.

Table 4.7: Final regions of the state of Alabama

Region 1	**Region 2**	**Region 3**	**Region 4**
Lawrence	Talladega	Wilcox	Washington
Madison	Clay	Lee	Mobile
Winston	Pickens	Montgomery	Baldwin
Limestone	Blount	Pike	
Colbert	Calhoun	Autauga	
Morgan	Dekalb	Russell	
Lauderdale	St. Clair	Crenshaw	
Franklin	Shelby	Choctaw	
Cullman	Etowah	Sumter	
Marion	Chambers	Macon	
Walker	Chilton	Monroe	
Marshall	Tuscaloosa	Butler	
Lamar	Tallapoosa	Clarke	
Jackson	Bibb	Lowndes	
	Cherokee	Coffee	
	Cleburne	Covington	
	Jefferson	Houston	
	Hale	Barbour	
	Marengo	Henry	
	Dallas	Bullock	
	Fayette	Geneva	
	Greene	Escambia	
	Perry	Conecuh	
	Elmore	Dale	
	Randolph		
	Coosa		
14 Counties	**26 Counties**	**24 Counties**	**3 Counties**

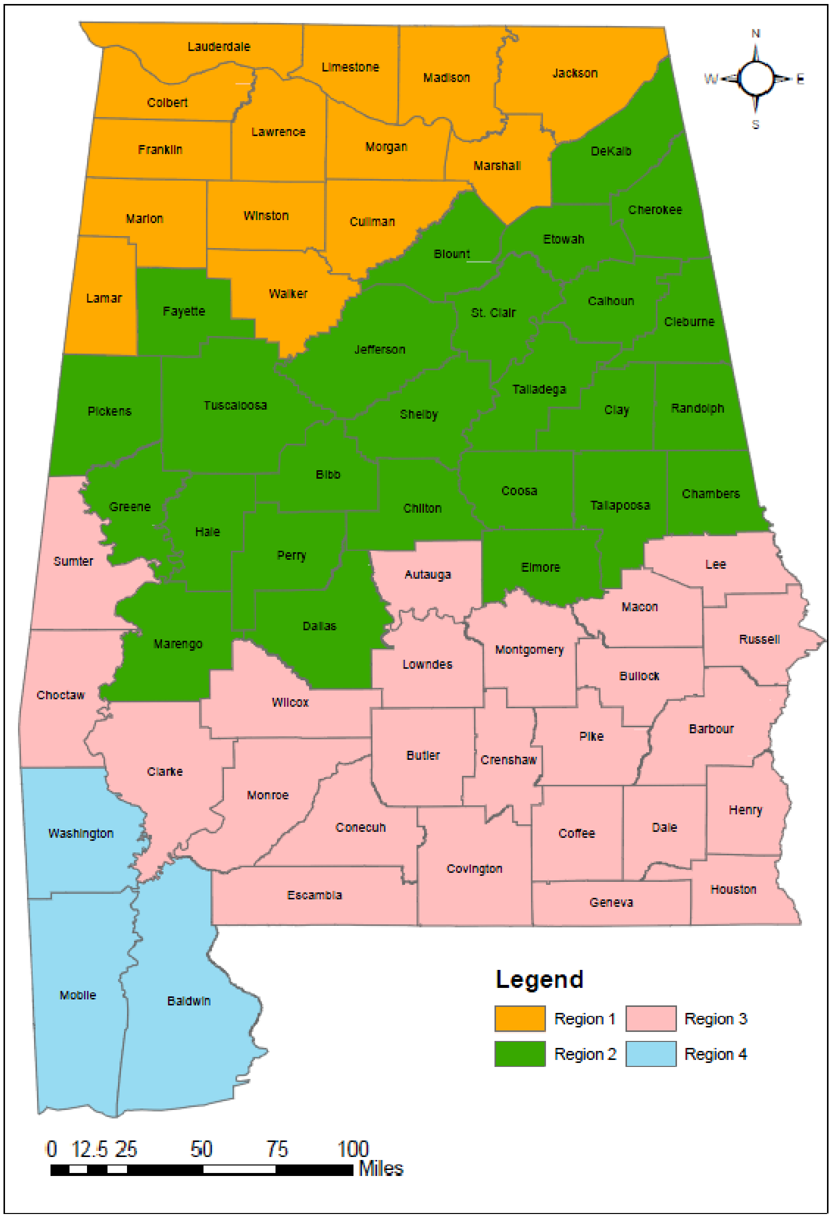


Figure 4.3: Final partition of the state of Alabama

4.2.2 Results of Qualitative Analysis

As previously stated in Chapter 3, the qualitative analysis associated with this section was intended to support and validate the results of the quantitative analysis by providing a better understanding of the main factors driving the behavior of riprap prices across the state of Alabama. These qualitative research efforts are mainly focused the location of the quarries that supply the riprap, which is possibly the more relevant factor influencing the cost of riprap structures. This would provide a better idea of the hauling distances required to deliver riprap to each county. The output from this qualitative analysis that would reasonably explain the change of riprap prices found by the quantitative assessment would be one showing shorter hauling distances for Region 1 and longer distances for Region 4. Thus, the next step was to locate all the quarries that produce and provide Loose Riprap Class 2.

A list of quarries in the state of Alabama was made, and each of them was contacted directly to identify those producing Loose Riprap Class 2. This investigation helped determine the exact coordinates of the quarries that provide this type of riprap. Table 4.8 shows the total number and location of quarries that produce Loose Riprap Class 2 in the state of Alabama.

Table 4.8: List of quarries that produce Loose Riprap Class 2 in Alabama

No.	**Company Name**	**Quarry Location**	**Coordinates**	
1	Vulcan Materials	Lochapoka, AL	32.601754	-85.636718
2	Vulcan Materials	Calera, AL	33.129504	-86.770289
3	Vulcan Materials	Tuscumbia, AL	34.705000	-87.735749
4	Vulcan Materials	Tarrant, AL	33.588595	-86.763193
5	Vulcan Materials	Vance, AL	33.139941	-87.279671
6	Vulcan Materials	Huntsville, AL	34.782386	-86.628829
7	Martin Marietta	Vance, AL	33.182194	-87.219934
8	Martin Marietta	Calera, AL	33.168739	-86.754505
9	Wade Sand and Gravel	Birmingham, AL	33.523787	-86.853554
10	APAC-Midsouth Paving	Alex City, AL	32.877025	-86.034781
11	APAC-Midsouth Paving	Wedowee, AL	33.351484	-85.470901
12	North Montgomery Materials	Titus, AL	32.734620	-86.269731
13	Wadley Crushed Stone	Wadley, AL	33.144831	-85.570469
14	Madison Materials	Guntersville, AL	34.442913	-86.256236
15	Madison Materials	Blountsville, AL	34.192614	-86.483503
16	Blunt Springs Materials	Asheville, AL	33.888952	-86.329328
17	Blunt Springs Materials	Falkville, AL	34.339267	-86.995394
18	Blunt Springs Materials	Hayden, AL	33.946601	-86.784811
19	Blunt Springs Materials	Collinsville, AL	34.188654	-85.916320
20	Reed Contracting	Hollywood, AL	34.753590	-85.990905
21	MK Materials	Russellville, AL	34.513816	-87.519271
22	Dunn Construction	Saginaw, AL	33.217862	-86.789630
23	Hoover Inc	Cherokee, AL	34.719059	-88.109206
24	Rogers Group	Tuscumbia, AL	34.664733	-87.625322
25	Rogers Group	Lacey's Spring, AL	34.555814	-86.571498
26	Rogers Group	Tanner, AL	34.690146	-86.958992

To visualize the previous information, each of the quarries was located on the map with the four regions shown in Figure 4.3. Now, the relationship between material production locations and prices can be more easily understood, as shown in Figure 4.4. Aligning with the results from the quantitative part, Regions 1 and 2 contain the most substantial number of quarries, with only one quarry just lying on the north-east corner of Region 3, and no quarries on Region 4.

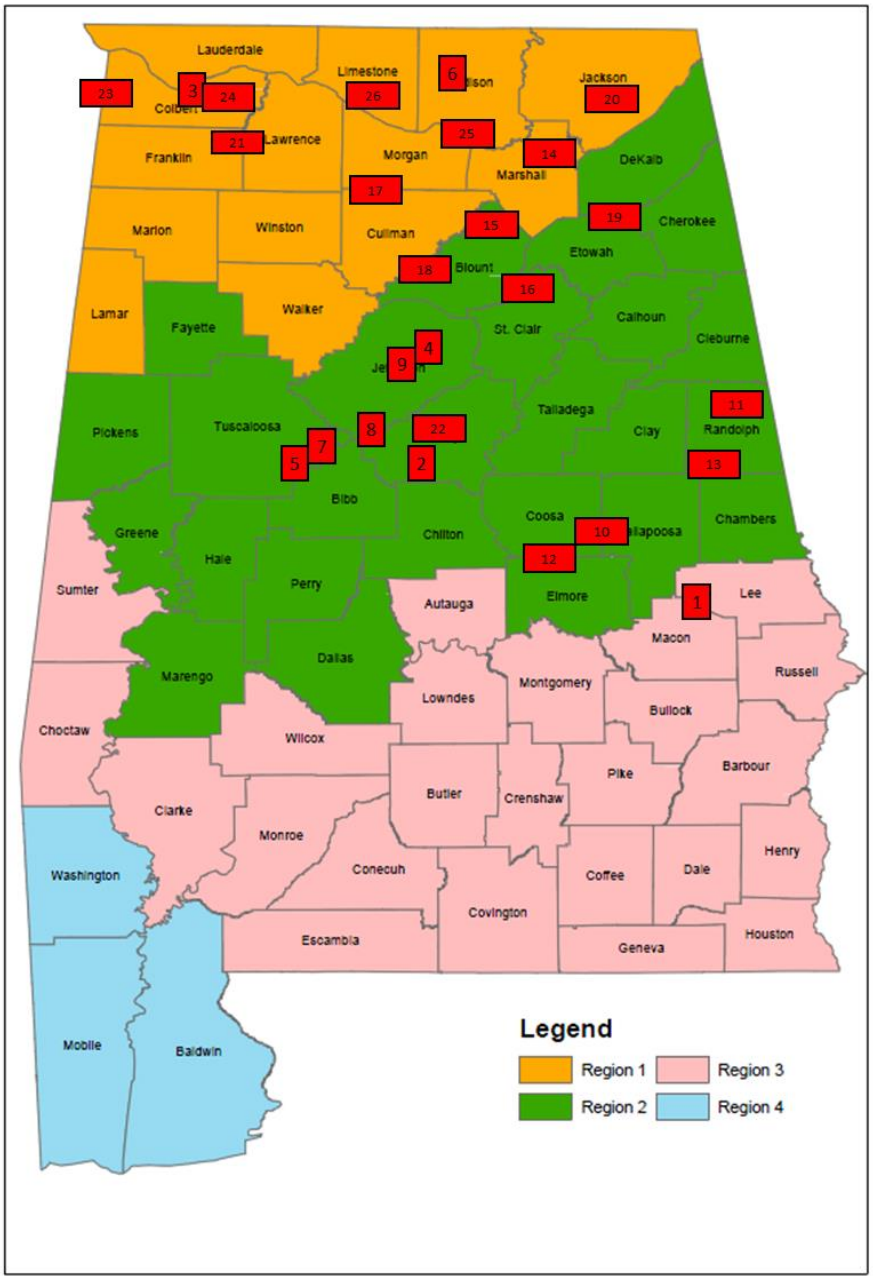


Figure 4.4: Location of quarries that produce Riprap Class 2 in Alabama

It was still not immediately clear why Region 1 presents lower riprap prices than those in Region 2 since the latter contains a larger number of quarries (10 in Region 1 against 15 in Region 2). A possible reason for the lower riprap prices in Region 1 was revealed after making the location of the quarries on the map in Figure 4.5, which shows the different soil areas across the state. Based on the characteristics of each soil area provided in Section 3.4, it is possible to conclude that those quarries in Region 1 are located on a more extensive limestone soil (Limestone Valleys and Uplands), which is the most common composition of riprap used in ALDOT's projects. This could suggest a larger production of limestone riprap from those quarries. Unfortunately, this study did not contain the amount of riprap produced by each quarry to validate this statement. Those quarries in the south-east part of Region 2, and the one in Lee County (Region 3), are on the Pedemonte Plateau soil, indicating that they most likely produce granite riprap, which is less commonly used by ALDOT.

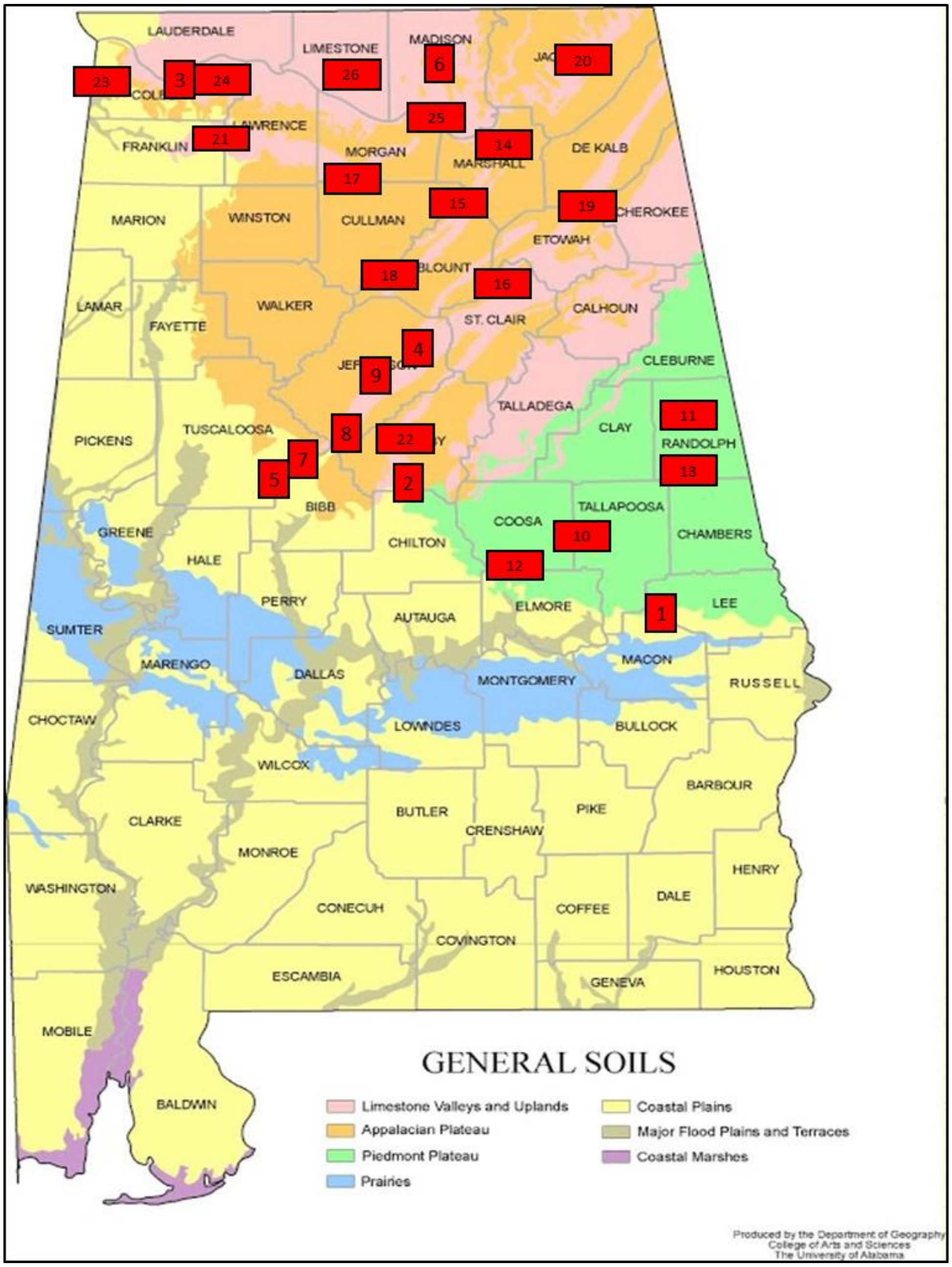


Figure 4.5: Quarries location and soil type in Alabama

Based on the quantitative and qualitative analyses conducted in this study, it was possible to confirm that the geographic classification shown in Figure 4.3 reasonably represent the different regional riprap market for ALDOT. These regions still show riprap prices increasing from north to south, but the final partition of the state is considerably different than from the one used by

ALDOT for the administration of its operations. This new partition consistently showed statistically significant differences between regions, with a 95% confidence level, making it suitable for the development of the RLCI.

4.4 Results: Riprap Location Cost Index

The RLCI developed in this section intends to model riprap price differences across the four geographic regions defined in the previous region. Due to the lack of data at the regional level during some six-month periods, the RLCI was developed on an annual basis. Each year in the 11 years considered in this study corresponds to a separate index period. As explained in Section 3.5, all index values were calculated using state average riprap prices as a reference. Table 4.9 shows the final annual RLCI developed for the four geographic regions between 2006 to 2016. RLCI was established following the four steps described in Section 3.5. RLCI index values for each year are also illustrated in Figure 4.6.

Table 4.9: RLCI years 2006 to 2016 in Alabama

Year	State	Region 1	Region 2	Region 3	Region 4
2006	1.00	0.78	1.00	1.13	1.30
2007	1.00	0.65	0.83	1.25	1.48
2008	1.00	0.70	0.87	1.20	1.47
2009	1.00	0.90	0.88	1.13	1.44
2010	1.00	0.62	0.82	1.16	1.47
2011	1.00	0.74	0.79	1.31	1.66
2012	1.00	0.74	0.87	1.12	1.34
2013	1.00	0.78	0.88	1.19	1.48
2014	1.00	0.70	0.90	1.18	1.56
2015	1.00	0.78	0.97	1.17	1.53
2016	1.00	0.73	0.89	1.14	1.60

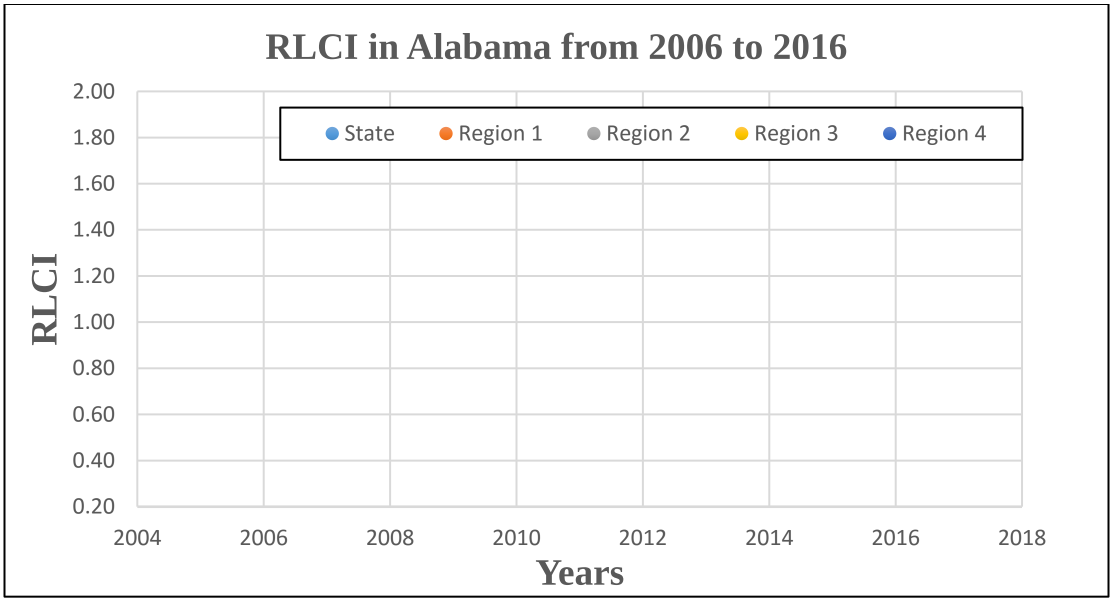


Figure 4.6: RLCI in different regions of Alabama from 2006 to 2016

Region 1, located in the north part of Alabama, which contains fourteen counties, presents the area with the lowest indexes in the state, meaning that projects in this area have the lowest riprap prices. The lowest index value for this area is 0.62 for the year 2010, and the highest is 0.90 in 2009. The 11-year average for this region is 0.74, indicating that riprap prices in this location during the last 11 years tend to be 26% lower than the state average. Region 2 is located in the central part of the state, with a total of 26 counties. This region also shows values below the state average, except for the 2006 index value, which matches the state average. Index values in this area range from 0.79 in the year 2011 to 1.00 in the year 2006. The 11-year average for this region shows that riprap prices in this region are about 12% lower than the state average.

Region 3, with 24 counties and located in the south-east part of the state, show values higher than the state average. The lowest index value is 1.12 in the year 2012, and the highest is 1.31 in 2011. The 11-year average of this region is 1.18. This means that riprap unit prices in this region tend to be 18% higher than the state average. Finally, Region 4, which comprehends three counties located in the south-west corner of the state, shows the highest overall indexes in Alabama. The

11-year average indicates that riprap prices in this region are about 48% higher than the state average (average index value = 1.48). The lowest index for Region 4 was obtained in 2006, with a value of 1.30, while the highest value of 1.66 corresponds to the 2011 RLCI.

To illustrate the application of the RLCI, if the regression curve for riprap unit prices in 2016 indicates an average state unit price of $40 per ton for 500 tons of riprap, the RLCI could be used to translate this price into the local market of each region. The equivalent average price for this amount of riprap in Region 1 during 2016 would be around $29 per ton ($40/ton x 0.73 ≈ $29/ton). A similar regional adjustment could be performed for the other three regions, resulting in the unit prices shown in Table 4.10.

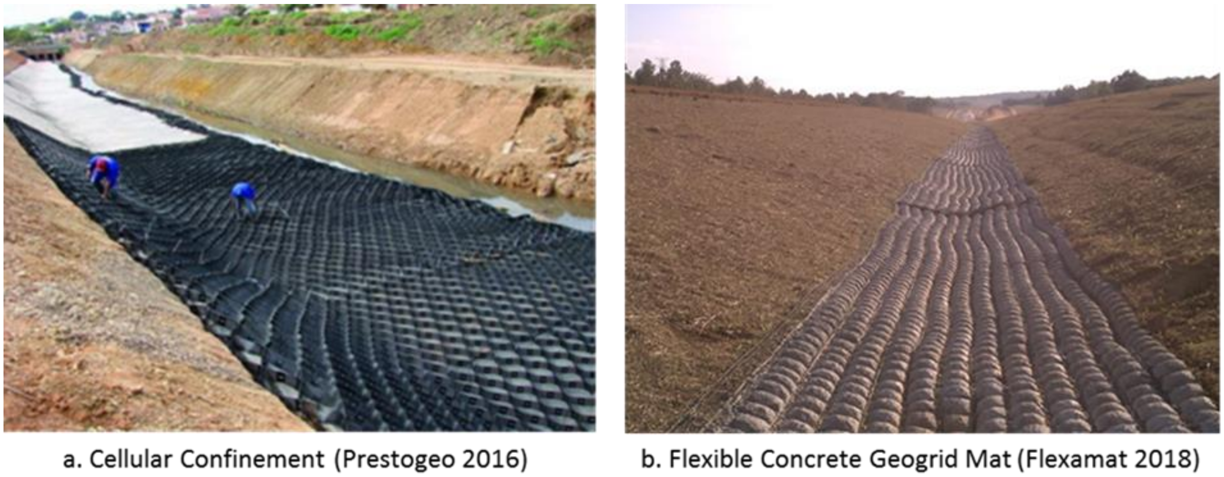
Table 4.10: Example price in 2016 using RLCI in Alabama

Location	Index Year 2016	$/Ton
State	1.00	$40
Region 1	0.73	$29
Region 2	0.89	$36
Region 3	1.14	$46
Region 4	1.60	$64

4.5 Discussion of Results

The RLCI proposed in this thesis was developed with a total of 716 contracts between 2006 to 2016. This dataset includes all projects using Loose Riprap Class 2 during that period, which is the most relevant riprap pay item used in ALDOT's projects. The resulting RLCI shown in Table 4.9 and Figure 4.6 shows that during the 11-year analysis period, riprap regional markets maintained the same tendency across the four regions, with only one occasion in which Region 1 switched places with Region 2 as the lowest-priced region in 2009.

The resulting RLCI also showed a significant variability of riprap prices in Alabama. Unit prices tend to increase as projects move from north to south rapidly. The results from the example summarized in Table 4.10 show that, in 2016, riprap prices in Region 4 were about 120% greater than those paid by ALDOT in Region 1. This study considers that such a substantial difference in riprap prices would justify the consideration of alternative technologies to riprap applications, such as cellular confinement systems or flexible concrete geogrid mats. An example of the implementation of these two technologies is shown in Figure 4.7.


a. Cellular Confinement (Prestogeo 2016)

b. Flexible Concrete Geogrid Mat (Flexamat 2018)

Figure 4.7: Alternative Technologies to Riprap

Although 716 contracts provided the data for this study, due to their distribution across the state, some regions did not have the same amount of data as others, especially Region 4. Initially, this study considered the development of a semi-annual RLCI. However, Region 4 did not offer sufficient data from some six-month periods, leading the author to develop an annual RLCI.

It should be noted that the results of this research are only applicable to ALDOT's riprap market since they were obtained only form the assessment of historical bid data provided by this agency. Other DOT's or public agencies could develop similar RLCIs by replicating the research efforts presented in this thesis, but that would require the use of their internal or local riprap historical prices. Likewise, the methodology presented in this study can be followed by future researchers to generate LCIs for other commodities or construction activities if enough and good-quality data is available for the effective application of data-driven procedures used in this study.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

This study was primarily aimed to model and assess the behavior of the riprap market across the state of Alabama to provide ALDOT with the means to compare the cost-effectiveness offered by riprap against other erosion control alternatives. The research included the application of advanced data collection and cleaning techniques on 11-years of ALDOT's historical bid data, from January 2006 to December 2016. Data from a total of 1,244 projects were collected from ALDOT's bid tabulation website as the initial basis for this study. An exploratory analysis revealed that Loose Riprap Class 2 was the most relevant and frequently used riprap pay item in ALDOT's projects; thus, the rest of the work was only focused on this item, reducing the initial dataset to 716 contracts. Only those contracts using Loose Riprap Class 2 were chosen to conduct this study.

After determining that ALDOT's five operating regions were not feasible to represent regional riprap market conditions, the author proceeded to use a quantitative methodology to define a more suitable geographic classification of the riprap market in Alabama. That methodology consisted of two statistical tests systematically applied to the available bid data to define continuous regions containing counties with similar riprap pricing levels. This methodology produced four geographic regions. In an attempt to ensure the robustness and appropriateness of the geographic classification yielded by the quantitative process, the study also included a qualitative review of the geographic conditions that could explain and support the quantitative results. More specifically, this qualitative analysis was focused on the location of the quarries that produce and provides the type of riprap under consideration. This supported that the longer the distance between a given region and the quarries, the higher the unit price of riprap for that region due to the hauling distance. This was consistent with the results of the quantitative analysis.

The qualitative analysis also included a review of the distribution of the different soil areas in Alabama and their specific compositions. For example, it was concluded that the fact that Region 1, in the north-east part of the state, contains a large limestone formation that could be reflected in the lower riprap prices in that region in comparison with those observed in Region 2, which contains five more quarries than the former. Even though information about the amount of Loose Riprap Class 2 produced by each quarry was not available for this study, it would be reasonable to conclude that higher production levels could be achieved in regions with larger limestone soil areas. This soil is the most common type of riprap used by ALDOT (limestone riprap). In summary, the results qualitative analysis validated the geographic classification proposed by the quantitative analysis by examining the reasons that could have led to that regional partition of the state.

After validating the proposed geographic classification, the study proceeded to model differences in riprap pricing levels between regions in the form of a RLCI. The final RLCI, presented in Section 4.4 of this thesis, not only showed a clear trend in the reduction of riprap prices as projects move from north to south but also revealed, in simple terms, the considerable variability of riprap prices in Alabama. The RLCI showed that, on average, riprap unit prices in the southern counties of the state are over 120% higher than those paid in the northern region (comparison between Regions 1 and 4). This substantial difference in riprap prices between different geographic regions, and the explanation of the results offered by the qualitative analysis, attests to the relevance of the hauling costs in the construction of riprap structures. Likewise, the results from this study suggest that the use of riprap in ALDOT's projects in the southern counties might not be a cost-effective solution. For that reason, the need for further researchers to investigate other suitable erosion control technologies could offer better value for taxpayers' money.

The results of the study were validated by the experience and opinions of ALDOT staff involved in planning and construction activities. Even though they already had knowledge about the behavior of riprap prices across the state, they indicated the lack of reliable mechanisms to analyze this situation objectively. This highlights the value of the proposed RLCI, and it is expected that this work contributes to the evaluation of ALDOTS's future projects. These indexes will allow ALDOT to better evaluate the feasibility of alternative erosion and sediment control technologies, as well as to prepare better construction cost estimates. As mentioned before, the results of this study are only applicable to the construction of riprap structures in Alabama.

The overall methodology can be replicated by other DOTs and to evaluate the use of different materials in construction activities.

5.1 Recommendations for Future Research

This study estimated the riprap price differences in the state of Alabama, presented in the form of Location Cost Index. LCI evaluated the variability of prices in different locations of the state for each index period. The results obtained in this research are only applicable to the state of Alabama, but other DOT's can implement this methodology for their analysis. Additionally, it is recommended for future studies to incorporate the process described in this research to evaluate the prices of other construction materials required for DOTs.

The quantitative analysis conducted by the researcher should be continuously updated for the development of the RLCI, considering that the conditions of the market could change with time. Even though the qualitative analysis in this research was not an input of the model, the opening of new quarries in the future can influence the unit price of riprap of those projects developed at a near distance. Likewise, the grouping of the counties may present variations depending on the similarity of unit prices and the number of projects involved in the study.

To obtain a broader overview of the qualitative analysis, it is recommended to carry out the same study considering neighboring states. The type of soil and the location of quarries in the adjacent states could support even more the changes in the prices of the riprap in different geographical locations of the state of Alabama.

To continue analyzing the results obtained in this study, alternative technologies may be evaluated in regions where the relationship cost-effectiveness is not competitive. Techniques like cellular confinement and flexible concrete geogrid mat could be suitable substitutes of riprap in those locations where riprap costs are expected to be substantially higher. Nevertheless, to evaluate alternative infrastructure investment options, a Life-cycle cost analysis (LCCA) must be performed. LCCA uses a common period of time to assess cost differences between these alternatives so that the results can be fairly compared (U.S. Department of Transportation 2002).

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