Evaluation of Bridge Cleaning Methods on Steel Structures

FINAL REPORT

12/31/2013

By
Kevin Alland
Julie M. Vandenbossche (PI), P.E., Ph.D.
Radisav Vidic, P.E., Ph.D.
Xiao Ma

University of Pittsburgh

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

1. Report No. FHWA-PA-2013-007-PIT WO 2	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Evaluation of Bridge Cleaning Methods on Steel Structures		5. Report Date: 12/31/2013	
		6. Performing Organization Code N/A	
7. Author(s) Kevin Alland, Julie Vandenbossche, Radisav Vidic, Xiao Ma		8. Performing Organization Report No. N/A	
9. Performing Organization Name and Address University of Pittsburgh Department of Civil Engineering 735 Benedum Hall 3700 O'Hara Street Pittsburgh, PA 15261		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. 4400004037, PIT WO 2	
12. Sponsoring Agency Name and Address The Pennsylvania Department of Transportation Bureau of Planning and Research Commonwealth Keystone Building 400 North Street, 6th Floor Harrisburg, PA 17120-0064		13. Type of Report and Period Covered Final Report: 2/15/13 – 12/31/13	
		14. Sponsoring Agency Code	
15. Supplementary Notes			

16. Abstract
Corrosion due to soluble salts is a major factor in the lifespan of the bridges and there protective coating. However, deicing salts are required to maintain the serviceability of the transportation infrastructure during the winter months. Therefore, it is beneficial to develop a bridge washing program, which can remove soluble salts from steel bridge members. This study evaluated the Pennsylvania Department of Transportation procedures for bridge washing. It was found that water is effective at removing soluble salt from steel bridges as long as good practices are. The washing effectiveness did decrease when the distance between the washer nozzle and the target area was too great with respect to the pressure being used. From a programming stand point, it was found that members directly above a roadway contained high concentrations of soluble salts and are not cleaned in the current specification. Contrary to this, the full length of truss and arch members below the bridge deck are currently being cleaned but, for the bridges evaluated, were not found to have high surface salt concentrations. It was also determined that the bridge washing process did not adversely affect the surrounding environment.

17. Key Words Bridge Washing, Maintenance, Corrosion, Salt Removal, Coating Failure, Surface Salt Concentration, Chloride, Steel Coatings.	18. Distribution Statement No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price N/A

Table of Contents

List of Figures

List of Tables

Executive Summary

Corrosion due to soluble salts is a major factor in the lifespan of the bridges and their protective coating. However, deicing salts are required to maintain the serviceability of the transportation infrastructure during winter months. Therefore, it is beneficial to develop a bridge washing program, which can remove soluble salts from steel bridge members. This study evaluated the Pennsylvania Department of Transportation (PennDOT) procedures for bridge washing.

A literature review and a survey of several other state departments of transportation revealed a variety of washing programs and techniques, but no data was available regarding how effective these programs were at removing soluble salts from steel surfaces. A total of five bridge washings were observed. The first three visits were to observe bridges being cleaned in accordance with PennDOT procedures. The surface salt concentration was tested before and after washing, and wash water was collected and tested for the presence of copper, lead and zinc. The final two observations were made on sections of the bridge where the operator was instructed to wash the bridge with the washer nozzle at a specific location relative to the target area. Surface salt concentrations were tested before and after washing at these locations.

It was found that using water without any cleaning agents is effective at removing soluble salt from steel bridges as long as good practices are followed while washing the bridge and the bridge coating is intact. Washing was found to be ineffective if the pressure used was significantly below the pressure prescribed in the PennDOT specification, the surface being washed showed significant evidence of coating failure and corrosion, or if the washer nozzle was too far below the target area for the pressure being used. From a programming stand point, it was found that members directly above a roadway contained high concentrations of soluble salts and are not currently required to be cleaned. On the other hand, the full length of the truss and arch members below the bridge deck are currently being cleaned and do not have large surface salt concentrations. It was also determined that the wash water generated during the bridge washing process did not adversely affect the surrounding environment.

1. Introduction

An investigation was undertaken to establish the effectiveness of cleaning steel bridges. If a bridge is properly cleaned, the soluble salts will be removed, increasing the performance life of the steel bridge and its coating. With any such endeavor, the first step is to identify the state-of-the-practice. A literature review was performed to determine how best to evaluate the effectiveness of bridge washing, the deleterious effects of soluble salts on bridges, test methods currently available for determining the soluble salt concentration on bridges, and standards used to determine acceptable levels of salt concentrations. A review of the bridge washing techniques currently used by the Pennsylvania Department of Transportation (PennDOT) and by other organizations was also performed.

After information regarding the state-of-the-practice as well as the state-of-the-art was compiled and synthesized, site visits were made to evaluate the current PennDOT bridge washing procedures. Bridge washing operations were observed for three bridges, with one bridge being washed by a contractor, and two bridges being washed by PennDOT maintenance crews. As part of these observations, pre-wash and post-wash surface salt concentration measurements were taken to identify areas of the bridge having high concentrations of soluble salts and how effective the washing operations were in removing the salt. The potential detrimental effects of releasing the waste wash water into the surrounding environment was also evaluated.

Lastly, field trials were performed to validate the conclusions drawn from the observations made during the evaluation stage of the study. The main variables explored in the field trials were the horizontal distance from the nozzle of the washer to the area being cleaned, the angle between the wash stream and the steel surface being cleaned, and the difference in elevation between the nozzle of the washer and the area being cleaned. Two simple experiments were set up to determine the effect these variables have on the effectiveness of bridge washing. Based on the results from these three activities, a set of recommendations were developed and are presented in this report.

2. Literature Review

2.1. Introduction

Throughout their service lives, bridges are exposed to a significant amount of dissolvable salts. These contaminants can increase the rate of corrosion of steel structures and ultimately shorten the service life of the bridge. Aggressive anions from dissolved salts can enhance corrosion rates and harm the protective coating on steel structures. As a form of preventative maintenance, the PennDOT washes its bridges to remove these substances. The washing operations are divided between department maintenance staff and contractors. Contractors primarily wash the larger bridges where specialized equipment is needed for access, whereas the maintenance staff primarily washes smaller bridges.

There are currently no quantitative PennDOT standards available regarding testing requirements, or acceptable criteria for allowable salt concentration. Standards developed by other agencies specifically for bridge washing procedures are also not available. The International Standards Organization (ISO) and United States Naval Sea Command (NAVSEA) do have standards regarding the concentration of ions allowed on a steel surface before a coating can been applied. Several tests have been developed to check the surface concentration of ions on a structure for this purpose. These tests could also potentially be used to check the concentration of ions after bridge washing operations.

Another area of concern when performing bridge washing is environmental contamination by the runoff. The Pennsylvania Department of Environmental Protection (PADEP) does have standards with regards to the allowable concentration of various chemicals in the wash water runoff. Standardized tests are available to check the concentrations of these chemicals. Proprietary solutions that claim to aid in the removal of salts (e.g., CHLOR WASH, Salt-x, and Salt-a-Way) can be added to the water during the bridge washing process. These products may also cause the wash water runoff to violate environmental standards.

Below, the mechanisms in which salts can decrease the service life of steel and concrete members are discussed. To aid in evaluating the effectiveness of cleaning

methods, tests which can determine the surface concentration of salt on a member are identified. Current bridge washing practices in Pennsylvanian and elsewhere and possible alternatives to pressure washing bridges with water are also examined. Finally, environmental concerns are also investigated along with tests that can be performed to insure environmental regulations are met.

2.2. Effect of Salts on Service Life of Bridges

Deicing salt (Sodium Chloride Brine) is used extensively in Pennsylvania to prevent the buildup of snow and ice. In the United States, the use of deicing salts has been shown to have an 18:1 benefit/cost ratio (Wolfosky 2011). However, salt exposure can decrease the service life of a bridge through several mechanisms.

2.2.1. Steel Structural Members

Corrosion in structural steel will only occur in an environment with a relative humidity as low as 40 percent if chloride (Cl^-) ions are present. The relative humidity must be near 70 percent if exposed to sulfate ions (SO_4^{2-}) and 100 percent without any exposure to salts (Bayliss and Chandler, 1991). The National Climactic Data Center website of the National Oceanic and Atmospheric Administration shows that the average relative humidity in Pennsylvania is greater than 40 percent for all months (NCDC, 2013). When investigating corrosion on highway bridges exposed to deicing salts or marine environments, it is generally assumed that a majority of the aggressive anions are chloride ions, although sulfates and other ions are often present. If the chloride ions from the deicing salts are not removed from the steel substrate, the steel will be in the "corrosion danger zone" for most of its service life.

A. Pitting Corrosion

Pitting corrosion is a process caused when the anions from salts, especially chlorides, attack the passivating thin oxide layers, which develops around the steel (Strehblow and Marcus, 2012). The passivating film is broken down in three steps, the penetration mechanism, the film breaking mechanism and the adsorption mechanism. The penetration mechanism begins when the aggressive ions (most likely chlorides) are

3

able to pass through the passivating layer. Once they diffuse inside the layer, the drastic change in the electric potential will cause large stresses and eventually a break in the passivating layer, which is only a few nanometers thick. This is called the film breaking mechanism. Finally the aggressive ions are adsorbed onto the surface of the steel causing the steel to release cations into the electrolyte (water on the steel surface). These cations react with water and oxygen in the electrolyte to form corrosion products, and the loss of metal causes a localized pit around the break in the film (Strehblow and Marcus, 2012). The presence of these pits can make steel much more difficult to clean as salts are likely present at the very bottom of the pits (Bayliss and Chandler, 1991). The presence of pitting can be seen as an indication that the corrosion was caused by the presence of aggressive anions, such as chlorides (Strehblow and Marcus, 2012).

B. Osmotic Blistering of Protective Coatings

The expected life of protective coatings is largely a function of the aggressive anions present. There are two types of coatings available, barrier coatings and galvanic coatings. Galvanic coatings contain a metal, such as zinc, which is naturally anodic to structural steel. When the structure is exposed to a corrosive environment, the coating will act as a sacrificial anode, preventing corrosion of the steel. The second type of coating is a barrier type coating, which electrically isolates the steel from the electrolyte while blocking aggressive anions from reaching the steel (Bayliss and Chandler, 1991). Even with care, the coating may not be applied homogenously and air bubbles, cracks, micro-voids, contaminants, trapped solvents, unbonded and weak areas, may occur. These flaws allow aggressive anion species to be transported through the coating (Sorensen et al., 2009).

The diffusion rate of aggressive ions through barrier coatings is much smaller than the diffusion rate of water and oxygen through the same coatings. Therefore, these coatings will act as a semi-permeable membrane. The presence of aggressive anions beneath the semi-permeable membrane can create an osmotic gradient, drawing water beneath the paint, which may result in a large pressure beneath the coating. If this pressure exceeds the adhesion strength of the coating, the coating will delaminate from the steel and form a bubble in a process known as osmotic blistering (de la Fuente and

Marcillo, 2005). Coatings tend to be more sensitive to chloride ions then sulfate ions (Appleman, 2002).

The presence of aggressive ions beneath the surface can be from either the presence of salts on the steel substrate prior to painting or the slow diffusion of the ions through flaws in the coating. To minimize the chance of osmotic blistering due to salts present on the substrate before a coating is applied, NAVSEA has developed standards for the allowable surface concentration of salts prior to painting (8 mg/m^2, $12\text{x}10^{-3}$ grains/ft^2) (Frenzel, 2011). International Standard Organization (ISO) Standard 15235 limits the concentration of chlorides on a surface to 15 mg/m^2 ($22\text{x}10^{-3}$ grains/ft^2) but allows the total anion concentration to be up to 30 mg/m^2 (43 grains/ft^2) (Palle et al., 2003). The Society of Protective Coatings (SSPC) and the National Association of Corrosion Engineers (NACE) have issued joint documents on surface preparation techniques and surface salt testing methods but have stated that the allowable surface concentration should be determined by the coating manufacturer. Some studies have shown that very low concentrations of ions, as low as 3 mg/m^2 ($4\text{x}10^{-3}$ grains/ft^2), can lead to osmotic blistering. However, these tests were usually performed with accelerated testing methods. Tests performed under conditions similar to atmospheric exposure tend to return more reasonable results. Allowable concentrations from long-term tests usually range between 5 and 25 mg/m^2 ($7\text{x}10^{-3}$ and $36\text{x}10^{-3}$ grains/ft^2) depending on the type of coating. These results align with the recommendations of coating manufacturers (Frenzel, 2011).

C. Chloride Sensitivity of Weathering Steel

Weathering steel sold in the United States under the trade name COR-TEN is a low alloy structural steel, intended to function without a coating. Weathering steel is an alloy of steel with a small amount, usually about 2-3 percent, of alloying elements such as copper nickel and chromium. This allows a dense layer of protective rust to form over the structure, preventing further metal loss.   The exposure of weathering steel structures to marine environments or de-icing salts has been found to severely diminish the corrosion resistance of these structures and cause them to corrode like mild steel structures (Bayliss and Chandler, 1991). The 924-meter (3030-ft) long New River Gorge

Bridge near Fayetteville, West Virginia is constructed from weathering steel. Soon after construction of the bridge, the West Virginia Department of Transportation (WVDOT) noticed that the bridge was corroding faster than expected. The department switched from using NaCl de-icing salts on the bridge to using a mixture of calcium magnesium acetate and liquid potassium acetate to remove ice and snow from the bridge (WVDOT 2013).

Rust in the form of iron (II) oxide (FeOOH) can occur in three different forms: α, β and γ. The α form is the stable form, which protects the steel from further corrosion. The β and γ forms tend to be flaky and easily removed and do not protect the structure from further deterioration. The presence of chloride ions has a tendency to cause a larger portion of iron (II) oxide to be in the β form (Singh et al., 2011). This rust is large and flaky and is formed mainly in the summer months. A study in Japan found that washing the bridge with water in the spring at a pressure of 2-4 MPa (290-590 psi), prevents the development of the thick flaky β corrosion, which allows the weathering steel to act as it was intended (Hara et al., 2005). It should be noted that the wash was performed at a much lower pressure level than the 10-35 MPa (1500-5000 psi) traditionally used to wash bridges in the United States. It is unknown whether a higher pressure would damage the protective patina.

2.2.2. Concrete structural members

A. Corrosion of Rebar Embedded in Concrete

Rebar in concrete has the advantage of a very alkaline environment, with a pH around 11. This allows a very stable passivating layer to develop around the rebar, which is advantageous in preventing corrosion. This passivating layer will remain until it is either attacked by aggressive anions, usually chloride, or the pH becomes less alkali through carbonation of the concrete (Broomfield, 2007). Chloride ions are introduced into the concrete pore structure when de-icing salts are applied to bridges, in marine environments or due to chloride ions in the concrete mix water during construction (Bhattacharjee and Pradhan, 2011). When a sufficient amount of salt is applied to melt all of the snow on the bridge, most of the chloride ions are flushed off the bridge with the melt water. However, if an insufficient amount of chloride is applied and the snow and ice are transformed into a "slush" phase, the slush containing the chlorides will remain on

the bridge surface for a longer period of time. The resulting increase in exposure can lead to more opportunities for rebar corrosion (Paulsson-Tralla, 1999).

The chloride content in the top 1.4-cm (1/2-in) of the concrete surface is highly time dependent, as ion transport in this area is dominated by capillary action. The ion concentration increases rapidly in this zone immediately following the application of de-icing salts but decreases rapidly following a rain or a wash. At a depth below 1.4 cm (1/2 in), the chloride transport is diffusion controlled and therefore is substantially slower. The rate of diffusion can be approximated using Fick's second law, which states (Broomfield, 2007):

$$\frac{d[Cl^-]}{dt} = D_C \frac{d^2[Cl^-]}{dx^2}$$

Corrosion can be initiated when the chloride concentration at the surface of the rebar exceeds a threshold level. This threshold concentration is debated in the literature. The Federal Highway Administration (FHWA) has defined this to be 0.3 percent by weight of cement (Wolofsky, 2011). The British Standards Institute (BSI), on the other hand, has established this threshold concentration to be as high as 0.4 percent (Ann and Song, 2007). The critical concentration is a function of the pH of the concrete and cannot be defined by any one value (Hunkeler, 2005). The oxidizing layer is rapidly destroyed once the threshold level is reached. This time can be approximated by applying the parabolic approximation to Fick's second law as defined below (Broomfield 2007):

$$t = \left(\frac{x}{1 - \sqrt{\frac{C_{thresh} - C_{initial}}{C_{surface} - C_{initial}}}} \right) /12D_0$$

where x is the depth being evaluated; t is time; C_{thresh} is the chloride threshold level; $C_{initial}$ is the built in chloride content; $C_{surface}$ is the chloride content at a depth of 1.4 cm (1/2 in); and D_0 is a diffusion constant which is dependent on the concrete properties. From this equation, it can be seen that the closer the surface chloride level is to the threshold chloride level, the longer the time to corrosion initiation.

The threshold level is reached at different times for various locations on the structure due to non-uniform chloride exposure and the presence of cracks in the concrete

(Nanayakkaro and Kato, 2009). This will cause penetration points to be anodic to the remaining sections of the bar resulting in what is known as macro-cell corrosion. With this mechanism, the concrete pore water will act as an electrolyte. Electrons from the anodic reaction will travel through the concrete pore water and be consumed by the cathodic reaction. Inside the rebar, electrons can move from the cathode to the anode creating a complete corrosion cell. Most of the rebar is part of the cathode, with small areas acting as the anode. The damage to the rebar is localized to the anode sites (Hunkeler 2005). If oxygen is present, the bar will be coated with corrosion products, which are much larger in volume then the metal lost due to corrosion. This expansion causes enormous pressure in the concrete and leads to concrete cracks and spalls. If oxygen is not present, the corrosion products, known as black rust, dissolve into the concrete pore water and do not cause spalling. This can potentially be catastrophic since it can lead to brittle failure of the rebar without warning (Broomfield, 2007).

A study by the Oregon Department of Transportation evaluated the possibility of removing chloride ions from a bridge through washing. The premise was that if the surface layer of concrete could be very close to free of chlorides, the diffusion gradient could be halted or reversed, preventing the chloride concentration at the rebar from reaching the threshold level. However, this study found that it was not plausible to remove chlorides once they reached the 1.4 cm (1/2 in) depth where transport is dominated by diffusion. It was found that the chloride diffusion rate could only be arrested with daily washings. However, daily washing is not practical without installing sprinklers on every bridge, and the material costs for the suitable water would be prohibitory (Soletsz, 2005). Hong and Hooten reached the same conclusion in their study on the "Effects of Fresh Water Exposure on Chloride Contaminated Concrete" (Hong and Hooten, 2000).

Deicing salts can also have detrimental effects on concrete structures unrelated to the corrosion of reinforcement steel. Previous research showed that deicing salts contribute to water-soluble alkali in the concrete, which could react with the aggregate to promote the generation of expansive gel in the alkali-silica reaction (ASR) (Katayama et al., 2004). This will only occur if high silica aggregates are used in the concrete mix. The presence of deicing salts can also increase the possibility for non-structural scaling to

occur at the surface of concrete under freeze thaw conditions if the paste is not durable (Valenza and Scherer, 2006).

2.3. Testing Procedures to Measure Surface Salt Concentration

Several tests are available to determine the concentration of salts on a surface. They are standardized by ISO 8502, "Preparation of steel substrates before application of paints and related products – Tests for the assessment of surface cleanliness," and the SSPC Technical Guide 15 (Corbett, 2010). All of these tests involve extracting the salts from a given area on the surface into a solution and then determining the salt concentration of the solution. The only way to extract all of the salt from a surface is to mechanically remove the surface material and place it in boiling de-ionized water. This is not practical for field applications. Some of the tests quantify the presence of specific ions, whereas other tests measure the conductance, which demonstrates the total ion content. This is acceptable because the effect of anions of different species on coated steel structures is roughly additive (de la Fuente and Morcillo, 2005).

Salt concentrations are not uniform on a surface, due to the crystalline nature of salts. Two adjacent areas can have very different readings. Salts tend to concentrate in the last areas to dry, such that the surface concentration of salts around coating nicks and other rough areas will be much higher than the average value. For this reason, it is easy to have data containing a bias if the samples are not spatially uniform (Frenzel, 2011).

An alternative to this sample collection method is the swabbing method. It consists of rubbing three cotton balls saturated with de-ionized water on a premeasured area and then rinsing the swabbed water into a beaker with a known quantity of deionized water. The concentration of salts can then be determined using chloride ion test strips (Corbett, 2010). The extraction efficiency for the swabbing method is considered to be between 15-35 percent. Traditionally, the measured ion concentration is multiplied by four to estimate the approximate salt concentration (de la Fuente and Morcillo, 2005).

The patch method, on the other hand, allows for slightly higher extraction rates and a more precise representative measurement of the area. This method consists of a latex patch with foam adhesive edges that is placed on a steel member. Water is then injected into the patch with a hypodermic needle. A slight variation of this is the latex

sleeve, where a premeasured volume of water is placed into a latex sleeve, and the adhesive end is placed on the steel substrate. In both versions, the de-ionized water is manually agitated against the substrate and can then be tested in a variety of ways (Corbett, 2011). The extraction level of these tests is typically between 40 - 60 %. Measured values are traditionally multiplied by two to give an approximation of the actual surface chloride content (de la Fuente and Morcillo, 2005).

Once the salts have been extracted with a patch or a sleeve, the ion concentration in solution can be estimated in a variety of ways. These include specific ion detection tubes and strips, drop titration and the Bresle test. The Bresle test measures the conductivity of the solution. The conductivity of a solution is a function of the concentration of dissolved ions and therefore the conductivity in μs can be converted to a surface salt concentration in mg/m^2 (grains/ft^2) (Corbett, 2010).

SaltSmart is a derivation of the Bresle test intended to give easier and more consistent results. It was developed with funding from the United States Navy. A disposable test kit with a premeasured amount of de-ionized water and contact area is adhered to the steel substrate for 10 minutes and then removed. The test is then inserted in a digital meter, which reads the conductivity and automatically converts the value to surface salt concentration. The extremely small surface contact area of the SaltSmart test (slightly larger than 1 cm^2, 0.15 in^2) allows it to be used in very tight areas. It will also result in a larger amount of variability since it is taking the average salt concentration over such a small area (Corbett, 2010).

The Soluble Salinity Meter (SSM) is another device used to determine salt concentration on the surface. It is a computerized measuring device with no associated consumables. The meter was developed by Richard Parks, the former director of corrosion for NAVSEA. The meter magnetically attaches to the substrate to form a sealed chamber with a specific surface area. De-ionized water is then automatically pumped into the chamber and agitated by the meter. Like SaltSmart, the meter reads the conductivity of the extracted solution and automatically converts the conductivity to a surface chloride concentration. This is then stored in a file that is downloadable to a computer. The meter extracts 90-100 percent of the dissolved salts on the surface and therefore a multiplier is not needed to estimate the actual values of surface salt

concentration (de la Fuente and Morcillo, 2005). It is currently accepted by the departments of transportation in Florida, Texas, California and Georgia and is included in the NAVSEA, ISO 8502 Part 9 specification and SSPC Technical Guide 15 (Parks, 2013).

Some of these procedures include a large initial investment, while others require a significant amount of inspector's time and/or consumables. Therefore, the price per test is largely dependent on the number of tests being performed. Assuming 1000 readings and an inspector cost of $50 per hour, the SSM would cost between $6-$9 dollars per test. The Bresle test using a patch would cost $9.40-$18.60 per test. The SaltSmart test would be about $15-$21 per test and the Chlor-Test latex sleeve chloride test would be $23-$27 per test. After the initial investment is amortized, the cost of an SSM test can decrease to $2.50-$3.30 per test (Frenzel, 2011). Requiring crews to meet a cleanliness standard can add an unknown to the amount of work required. Contractors will most likely build an allowance for rework into their rates. Therefore, under the current lump sum contract structure the cost of bridge washing could potentially increase. This was confirmed by one of the contractors interviewed. This may not be a significant problem if time and materials contract is used.

2.4. Current Bridge Washing Practices

Interviews were conducted with the Colorado (Mr. Thomas Tatalaski), Illinois (Mr. Mahmoud Etenadi), New York (Mr. Peter Weykamp), Pennsylvania (Ms. Gina Russell and Mr. Jonathon Gesinski) and Washington (Mr. Gregory Myhr and Mr. Chris Keegan) departments of transportation to gain more information regarding their bridge washing procedures. The Colorado Department of Transportation (CDOT) is in the process of evaluating if they will begin a bridge washing program and therefore could not provide any information regarding their current bridge washing procedures. Information provided by the other agencies is summarized below.

A. Pennsylvania Procedures

The bridge washing requirements for Pennsylvania can be found in the County Maintenance Measurement Tool (CMMT) Section 18, and in PennDOT Publication 55:

Bridge Maintenance Manual 9000-001- Bridge Cleaning and Washing. There are two forms of bridge washing performed. Deck cleaning and flushing of all topside surfaces, including the deck, sidewalks and parapets, is performed on a frequent cycle. Per the CMMT, decks are washed annually in most counties and biannually in Allegheny and Philadelphia counties. Bridge structure cleaning, on the other hand, occurs on approximately a 5-year cycle. It is a 10-year cycle that is required in Allegheny and Philadelphia counties due to the vast number of bridges in these counties (PennDOT, 2012). This cycle can be decreased at the discretion of the district engineer based on the importance and condition of the asset.

Bridge cleaning is performed by both department maintenance staff and contractors with contractors working on large river crossings where specialized equipment is required for access. All steel horizontal surfaces, which are exposed to deicing salts are cleaned. These are defined as all surfaces within five feet of expansion joints and abutments on interior beams and all horizontal surfaces along the full length of fascia beams. Panel points on truss bridges are a likely location for contaminated water accumulation and are cleaned from the bottom chord to eight feet above the deck (PennDOT, 2010). The pressure for cleaning is specified to be between 12 and 14 MPa (1750 and 2000 psi). (PennDOT, 2012).

In 1994, task force consisting of representatives from PennDOT, PADEP and the Pennsylvania Fish and Boat Commission established best practices for bridge washing. Before flushing bridges, PennDOT is required to mechanically remove as much debris as possible to prevent it from entering the waterway. When decks are flushed over high quality streams and wetlands, it is required that the scuppers are blocked to prevent discharge into the river. If the scuppers and downspouts are to be cleaned over high quality streams and wetlands, a plan must be in place to filter the water before it is discharged. Care must also be taken to prevent paint chips from entering the waterway (Hoffman, 1994). PennDOT Publication 55 recommends chipping off loose paint chips before water washing the bridge. Water used for flushing the bridge is required to come from the adjacent waterway. If this would result in a significant drop in the water level, such as for a small stream, the water must come from a source with less contaminants than the receiving water (PennDOT 2010).

There are some issues with the current practices. The first issue is related to the frequency in which the bridge washing is performed. In District 11, bridges are cleaned every five years as required in the CMMT. However, according to PennDOT Publication 55, both bridge cleaning and deck washing should occur annually after winter services have ended. It is unclear why there is the discrepancy between the CMMT and Publication 55. Another area of concern is that the department maintenance staff uses tanker trucks for wash water transportation that are used to transport salt brine for winter services. It is unknown whether the water in these trucks is adding more salts than they are removing. Finally, there is no guidance provided on how long an area should be washed or cleanliness criteria that must be met upon completion of the bridge washing.

B. Procedures Adopted by Other Agencies

Several other states and international agencies have specifications published for bridge washing operations. The United States Department of Transportation (USDOT) does not provide much guidance regarding on bridge washing except to recommend that bridges should be washed every 1-2 years (USDOT, 2011). This recommendation does not differentiate between a full bridge cleaning and flushing of the deck. No states have published quantitative cleanliness standards for bridge washing operations, or responded with standards to our survey. Most agencies accept work based on visual cleanliness. Some specifications mandate or recommend pressure and flow rate for the pressure washer. From an environmental perspective, many states require bridge washing to occur in spring when (high river flow season) large volumes of water are available to dilute contaminants from the washing operations.

The Swedish Roads Authority has a quantitative requirement that bridges should be 95 percent clean before June 30. However, they do not provide specific guidance on what constitutes 95 percent clean. Also, this acceptance level is thought to be largely arbitrary, and there is no research or documented empirical evidence to support it. An international literature review was performed in Sweden, which agreed with these findings in that there are currently no other quantitative standards used for bridge washing. A case study in Uppsala County, Sweden highlighted the vagueness of the current standards worldwide. This study cited that two inspectors observed maintenance

issues on 400 bridges in the county. These inspectors identified defects which were defined by the Swedish General Technical Regulation for Bridge Maintenance. These defects consisted of unclean areas, areas with deicing salts present, the presence of vegetation, closed drainage systems, nonintact fittings and wide cracks. One inspector identified 186 defects, and the other 283 defects (Silfwerbrand, 2011).

The New York Department of Transportation (NYSDOT) performs bridge deck washing on nearly all of its bridges every year. The superstructure is cleaned every other year to the extent allowed by the access to the bridge. However, special equipment is not used in an attempt to access the structure. As a result, a large portion of the steel structure is not cleaned. Washing is currently performed at a pressure of 21 MPa (3000 psi) when bridges are washed by contractors. State maintenance crews clean at the pressure they feel will efficiently clean the bridge (Weykamp, 2013). Wash water can be drawn from local sources or the contractor can use municipal water. The contractor is not allowed to use wash water drawn from a body of water to wash a bridge crossing a body of water in a separate watershed. This prevents invasive species from entering watersheds through the wash water. If some sections of the paint are chipped or cracked, there is a clause in the contract indicating that these areas are not to be cleaned to avoid stripping the paint. Unfortunately, both contractors and state maintenance crews tend to default on this clause too often, resulting in bridges with only a small amount of chipping paint not being washed (Weykamp, 2013).

WSDOT is currently engaged in a study on the cost effectiveness of bridge washing procedures with the University of Washington. WSDOT believes that using lower pressures and higher flows effectively washes bridges and decreases the damage to the environment by diluting the contaminants. Therefore bridges are flushed with a fire hose rather than pressure washed. The current washing program focuses on steel truss bridges, and the entire superstructure of the bridge is typically flushed. WSDOT recently performed a pilot study where a bridge was hand cleaned before it was flushed with water in the first year of the pilot study and then flushed annually without hand cleaning in subsequent years. Sampling of the wash water showed less contaminants in the wash water in the subsequent years then in the first year, which allowed WSDOT to flush bridges without hand cleaning as long as washing is performed every year. They found

that flushing a steel truss bridge is only around 40 percent of the cost of hand cleaning before washing. Therefore, bridges are now flushed every year for less than the cost of flushing them every other year (Keenan, 2013).

The Illinois Department of Transportation leaves the decision on whether to wash individual bridges to the districts. District 2, in northwestern Illinois, washes many of their bridges including several large spans over the Mississippi. Not every bridge in the district is washed. The same set of bridges is washed each year. (Etenadi, 2013).

2.5. Salt Neutralizing Chemicals

There are several commercially available salt-removing agents, which claim to aid in the removal of salts and other ions to reduce the risk of corrosion. In 2002, Wisconsin was using chemical salt neutralizers to wash bridges every spring after winter de-icing salt exposure (Palle et al., 2003). Examples of these are Chlor*rid, Salt-X and Salt-a-Way. The Material Safety Data Sheet (MSDS) for Salt-a-Way clearly states that it needs to be disposed of in a drain, which flows to a sewage treatment plant to avoid violating the Clean Water Act (Salt-A-Way, 2012). This would prevent the use of this product for washing bridges. However, it is possible that Salt-a-Way may be suitable for cleaning the tanker trucks after they were used to carry salt-brine for winter services but before using these same tankers to transport bridge wash water.

Chlor*rid claims to be a 100 percent biodegradable solution, which consists of organic acids and does not contain any volatile organic compounds (VOCs). The active ingredients in Chlor*rid include amines, anionic surfactants, carboxylic acids and sulfonic acids (Johnson, 1997). The acids bind with the chloride and sulfate ions and allow them to be washed away ("Chlor*rid Announces…" 2009). A test in Kentucky found that Chlor*rid removed all of the measurable chlorides on the surface when added to a 21 MPa (3,500 psi) pressure wash. Unfortunately, no areas with a similar concentration of surface chlorides were washed with plain water to determine the actual effectiveness of this agent (Palle et al., 2003). WSDOT has considered using Chlor*rid as part of their bridge washing efforts. However, the Washington Department of Ecology has not approved its use (Keenan 2013). Wisconsin has been using Chlor*rid for maintenance wash while New Jersey currently uses it for surface preparation before

painting. The New Jersey Department of Transportation performed a test trial on washing trucks with Chlor*rid that was successful according to a Chlor*rid representative. However, New Jersey does not currently use Chlor*rid to clean trucks (Doucette, 2013).

The NYSDOT and PennDOT have discussed the possibility of using a generic detergent such as dish or laundry soap to reduce the level of salts on steel structures. However, it is unlikely that a standard detergent would increase the removal of salt ions. Most soap based detergents are hydrophobic and intended for dissolving grease and oils. Soluble salts are hydrophilic and would be more easily dissolved by acids. However, detergents could be helpful in removing debris and oils from the structure. Although the detergents may release sulfur, nitrogen and phosphorus into the receiving water, it is expected that the concentration of these chemicals in the wash water would be almost negligible.

2.6. Environmental Impacts of Bridge Washing

Runoff water from bridge washing will transfer contaminants from a bridge to the receiving water below. Debris, such as dirt, bird feces, garbage, oil and gasoline contain high concentration of organic matter. When these enter the receiving water, they can reduce the dissolved oxygen, harming aquatic life and producing odor. Paint chips and metal residue may also be released into the receiving water. These may contain toxic heavy metals such as lead, zinc, and copper.

A. Environmental Impact of Debris in Wash Water Runoff

Much of the debris present on bridges contains organic material. High concentrations of organic material can cause a decrease in the dissolved oxygen in a body of water. Dissolved oxygen is essential for all aquatic life and is a commonly adopted water quality parameter. Pennsylvania code requires minimum daily average dissolved oxygen for flowing streams to be 6.0 mg/L (6.0 ppm) (PA Code, 2013).

Debris in the runoff water can also cause turbidity. Turbidity is a measure of water transparency, which is affected by the presence of small particles. According to the Pennsylvania Code, surface water turbidity is required to be no more than 40 NTU from

May 15 to September 15 of any year, and no more than 100 NTU from September 16 to May 14 of any year (PA Code, 2013).

In Pennsylvania, bridges are dry cleaned before flushing. Mechanical methods, such as sweeping or shoveling, are used to remove and properly dispose of as much of the debris as possible before a bridge is washed (Hoffman, 1994). This prevents dirt and debris from having a significant environmental impact on the receiving water.

B. Environmental Impacts of Toxic Metal Contents in Wash Water Runoff

Many protective bridge coatings contain metals, such as lead or zinc (USDOT, 2011). During washing operations, these coatings could possibly release toxic metals into the receiving water. The United States Environmental Protection Agency (EPA) provides a National Recommended Water Quality Criteria, which recommends maximum contaminant concentration in surface waters. The maximum recommended concentrations for an acute exposure in fresh water are: 65µg/L (6.5 ppb) for lead, 120 µg/L (120 ppb) for zinc, and 1.3 mg/L (1.3 ppm) for Copper.

The Kentucky Transportation Center (KTC) conducted an investigation on over 10 bridges with lead based paint being washed with pressurized water (>17 MPa [2500 psi]) in 2003. The results revealed that the total lead in wash water runoff from these bridges contained high concentration of lead even though bridges were dry cleaned prior to flushing. The total lead in the runoff water varied from 2.3 to 110 mg/L (2.3 to 110 ppm), and dissolved lead varied from below the detection limit (< 0.1 mg/L [0.1 ppm]) to 5.5 mg/L (5.5 ppm) (Hopwood et al, 2003). This is well above the EPA recommendations but might still be acceptable when diluted after entry into the waterway below.

The Washington State Department of Transportation (WSDOT) monitored the quality of bridge washing runoff water from April 2004 to April 2009. The study reported copper, lead and zinc as contaminants of concern in the runoff water (WSDOT, 2009). The concentrations of these metals are shown in Table 1 (WSDOT, 2009). The concentration of lead was within the range that was observed in the KTC study. The concentration of lead and zinc both exceeded the EPA recommendations; however the

contaminants would be diluted by the receiving stream and its flow rate needs to be taken into account when evaluating the impact of the bridge wash water runoff.

Table 1.

Table 1. Metal Concentrations found in the wash runoff water reported by WSDOT

Pollutants	Mean dissolved concentration, mg/L or ppm	Mean total concentration, mg/L or ppm
Copper	0.072 (0.003 – 0.24)	0.36 (0.13 – 1.1)
Lead	0.109 (0.011 – 0.76)	3.909 (0.12 – 20)
Zinc	0.7 (0.12 – 3.2)	7.517 (2 – 15)

Note: values in parentheses represent the range of pollutant concentrations.

C. Environmental Impact of Deicing Salt in Wash Water Runoff

The main focus of this study is on bridge washing for the removal of deicing salts for corrosion prevention. It is then expected that wastewater generated by this operation may contain high concentrations of deicing salts, e.g., chloride, sodium, or calcium. The environmental impacts from these ions are not significant and there is currently no specific surface water regulation for sodium or calcium.

2.7. Environmental Impacts Specific to PennDOT Bridge Washing Activities and Related Environmental Regulations

A study conducted by Villanova University documented the current coating materials used in Pennsylvania and found that most bridge coating systems in Pennsylvania employed zinc-rich materials (Radlinska et al. 2012). There is a good chance that some bridges in the state still have a lead-based coating. Therefore, zinc and lead should be considered as primary potential contaminants. Because the cleaning crews mechanically remove dirt and debris before washing, the environmental impact from this material should not be significant.

Water quality goals for surface waters of the United States are established based on the Federal Clean Water Act (FCWA). The National Pollutant Discharge Elimination System of Permits (NPDES permits) was created and administered by the EPA to achieve

these goals in 1972. The EPA authorized each state to manage the NPDES permit program in the state. In Pennsylvania, PADEP is responsible for NPDES permitting and enforcement (PADEP, 2013).

Table 2 shows selected surface water quality criteria used by Pennsylvania for NPDES permits that is based on Biotic Ligand Model. The Biotic Ligand Model (BLM) generates the site-specific water quality based on parameters such as pH, hardness and dissolved organic carbon. A BLM analysis is performed by incorporating site specific water quality parameters into a computer model and analyzing the output (Niogi and Wood, 2004; Paquin et al., 2002). The BLM was adopted by the EPA in its latest national ambient water quality criteria (EPA, 2007).

Table 2. Pennsylvania surface water quality criteria for copper, lead, and zinc (PA Code, Chapter 93)

Contaminant	Continuous concentrations criteria, fish and aquatic life (μg/L or ppb)	Maximum concentration criteria, fish and aquatic life (μg/L or ppb)	Human health criteria (μg/L or ppb)
Copper	$0.960 * e^{0.8545*\ln[H]-1.702}$	$0.960 * e^{0.9422*\ln[H]-1.700}$	N/A
Lead	$(1.46203 - \ln[H] * 0.145712)e^{1.273x\ln[H]-4.705}$	$(1.46203 - \ln[H] * 0.145712)e^{1.273x\ln[H]-1.460}$	N/A
Zinc	$0.986 * e^{0.8473x\ln[H]+0.884}$	$0.960 * e^{0.8473x\ln[H]+0.884}$	N/A

H: stream water hardness in mg/L CaCO₃; according to USGS, surface water hardness in western Pennsylvania is 61 to 120 mg/L as calcium carbonate (CaCO₃).

PADEP also requires the maintenance, testing, repair, rehabilitation or replacement of water obstructions and encroachments to obtain NPDES permits. The general permit BWM-GP-11 regulates the activities of bridge or culvert maintenance, replacement projects or upgrades to existing facilities to meet current standards (PADEP, 2013). However, bridge cleaning/washing activities are governed by the agreement between PennDOT, PA DEP and Fish and Boat Commission established in 1994. This agreement stipulates that a permit is not required provided dry debris removal precedes any wet washing activities to minimize contaminant load in the receiving water. The bridge washing runoff water is typically diluted in the stream water. The only exception is for high value or exceptional quality (HQ/EV) streams where the runoff water is required to be collected and treated prior to discharge.

Since salt removing chemicals such as Chlor*rid are under investigation in this study, standards regarding the release of amines, and sulfonic acids into the receiving water should be considered. Table 3 shows the current surface water quality standards for amine groups from the Pennsylvania Code, Chapter 93. Table 4 shows surface water quality criteria standards for sulfate, nitrite plus nitrate, and chloride from the same code and chapter.

Table 3. Pennsylvania surface water quality criteria for amine group
(PA Code, Chapter 93)

Contaminants	Continuous concentrations criteria, fish and aquatic life (µg/L or ppb)	Maximum concentration criteria, fish and aquatic life (µg/L or ppb)	Human health criteria (µg/L or ppb)
N-Nitrosodimethylamine	3400	17000	0.00069
N-Nitrosodi-N-propylamine	N/A	N/A	0.005
N-Nitrosodiphenylamine	59	300	3.3

Table 4. Specific surface water quality criteria

Contaminant	Criteria
Sulfate	Maximum 250 mg/L (ppm)
Nitrite plus nitrate	Maximum 10 mg/L (ppm) as N
Chloride	Maximum 250 mg/L (ppm)
Total Phosphorus*	N/A

Pennsylvania Code chapter 93 states that "Regulations contemplate that the Department will evaluate the degree to which phosphorus contributes to the impairment designated uses on a case-by-case basis and may impose more stringent limitations where necessary" (PA Code, 2013).

2.8. Testing Procedures to Measure Pollutants in Wash Water Runoff

WSDOT established a monitoring procedure in 2010 to determine whether bridge wash water runoff meets water quality. One bridge a year must be tested according to

WSDOT's NPDES permit. Generally, WSDOT collects three samples from the washed bridge and one sample from the receiving water. Collected samples are analyzed for hardness, total and dissolved copper, lead and zinc using EPA standard methods.

According to WSDOT's bridge maintenance practices, runoff water from flushing represents almost all of the runoff water that enters the receiving water as part of bridge washing operations. WSDOT collects three samples from three different locations along the bridge. These locations should be near structural connection points where debris builds up or near vertical supports. To collect runoff samples, sample containers with a wide opening, such as buckets, are lowered over the bridge and tied off before washing begins and left there until washing ends. WSDOT requires the buckets to be hung from the lowest horizontal support directly under the bridge. It is also recommended to hang off two buckets per sampling location. When two buckets are used per location, they should be hung next to each other and at the same elevation from the bridge. After washing is completed, contents from the two buckets at each of the three sampling locations are mixed and then poured into labeled sampling bottles for delivery to the laboratory. WSDOT also requires collecting one sample from the receiving water to find background water quality (WSDOT, 2010).

EPA standard methods are used to analyze collected water samples in the laboratory. The samples are tested for total hardness, total and dissolved copper, total and dissolved lead and total and dissolved zinc. The EPA standard methods for each parameter are shown in Table 5.

Table 5. Sample analytical methods used by WSDOT

Parameter	Method type	Method number	Holding Time	Detection Limit
Total Hardness	Color/auto or Titration/EDTA	EPA 130.1/EPA 130.2	6 months	2 mg/L, ppm
Total and Dissolved Copper	ICP/Mass Spectrometry	EPA 200.8	6 months	0.4 µg/L, ppb
Total and Dissolved Lead				0.1 µg/L, ppb
Total and Dissolved Zinc				0.5 µg/L, ppb

2.9. Conclusions

Literature contains limited information pertaining to the methods used in bridge washing. Most transportation officials interviewed believed that washing bridges was an effective maintenance strategy for increasing the life span of bridges, but did not have any quantitative evidence to support this claim. The University of Washington is currently engaged in a study for WSDOT to determine how cost effective is washing bridges from a life cycle analysis stand point. However, no research has been performed on how effective the current procedures used throughout the country are at removing chlorides. It is possible that the conclusions of the University of Washington study could be altered if the most efficient methods of removing a sufficient amount of chlorides are available.

Most of the research on the removal and testing for chlorides and other salts is based on preparing a steel substrate for painting. The effort required to remove chlorides from a bare steel structure prior to painting may not correlate with the effort required to remove chlorides during maintenance washing. Several methods for cleaning structures are used in the United States, including flushing with a fire hose and pressure washing.

There are no available standards for the allowable concentration of soluble salts on a surface after maintenance washing. However, there are standards available for chloride removal for painting as stated earlier. If the surface salt concentration is lower than the standards prescribed for painting surface preparation (below 15 mg/cm^2, 22x10^{-3} grains/ft^2) after cleaning with a specified method, it can be concluded that the method is acceptable for the removal of chlorides from steel structures. If the surface salt concentration after cleaning is high (above 50 μg/cm^2, 717x10^{-3} grains/ft^2), then the method may not be appropriate for the removal of chlorides. If the post cleaning surface salt concentration is consistently between these two values then further analysis is needed to determine if this method can be accepted. Establishing an allowable surface salt concentration after cleaning to prevent corrosion is not included under the scope of this study. Further research in this area is essential before a reliable estimate of the cost benefit of bridge washing can be obtained. The rate at which salts accumulate on a

structure in between wash cycles is also unknown but essential information in establishing the cost benefit.

The primary pollutants from the bridge washing operations will most likely be lead, copper and zinc. Hand cleaning a bridge before it is flushed and preventing paint chips from entering the receiving water through filters are effective ways of reducing the amount of these metals released. If a salt removing chemical, such as Chlor*rid, is used the wash water should also be checked for amines and sulfonic groups.

3. Evaluation of Current PennDOT Procedures

3.1. Overview and Objective

The effectiveness of bridge washing operations is currently determined visually by the on-site Pennsylvania Department of Transportation (PennDOT) inspector. However, the true effectiveness of removing the soluble salts cannot be established through visual methods. Determining the exact pre-wash salt concentrations on the structural members and the effectiveness of removing these salts with washing is much more difficult. As part of this study, measurements of the surface salt concentrations were taken at several locations on three different bridges using the Soluble Salt Meter II by ARP Instruments (SSM). These tests were used to determine which areas of the bridge have the largest pre-wash surface salt content, and how effective the current PennDOT bridge washing procedures are at removing these salts. The SSM is an electronic testing device, which magnetically attaches to the metal substrate to form a test chamber. The tester then injects 3 mL (0.10 oz) of deionized water into the chamber and agitates the water in the chamber to dissolve all of the salts in the test area. The total conductivity of the water is then measured by the device. The meter automatically converts this conductivity to a surface salt concentration in mg/m^2 (grains/ft^2), adjusting for temperature. For a complete description of the Soluble Salt Meter II, please see the Task 1 report.

At all three bridges evaluated, washing runoff water was also collected in 19 L (5 gallon) plastic buckets for testing. This water was analyzed to determine whether the runoff water contained a large amount of salt, which would indicate effective washing, and to determine whether large amounts of harmful chemicals are released into the

receiving waters. The water was collected from sets of two five gallon buckets hung from three strategic locations on each bridge, following a procedure established by the Washington Department of Transportation (WSDOT). These samples were then evaluated in the lab to determine the chloride content, turbidity, and zinc, lead and copper concentrations.

There was some concern that the effectiveness of the bridge washing is compromised by salts in the wash water. The PennDOT bridge washing crew uses a tanker truck for bridge washing which is also used to distribute salt brine in the winter months. Water samples were taken directly from the truck at each washing location, and tested for salt concentration in the laboratory. The samples were also tested for turbidity, and zinc, lead and copper concentrations to be used as a baseline for the runoff water testing.

3.2. Testing Locations

3.2.1. Vanport Bridge

The Vanport bridge is a steel truss bridge near Vanport, PA in Beaver County. It carries Interstate 376 (I376) over the Ohio River. The bridge deck is approximately at mid-depth of the truss. The bridge is a statically determinant system with no expansion joints in the structure. There are periodic deck expansion joints throughout the span. The washing was performed by Michael Facchiano Contracting Company. At the time of observation, the crew was washing the center span of the western truss adjacent to the southbound travel lanes. The bridge was washed by two pressure washers. The first pressure washer was used on the bridge side of the truss from the bridge deck, from bridge deck elevation to approximately 3 m (10 ft) above the bridge deck. The second washer was placed in a "snooper" bridge inspection crane. This crew member washed all members beneath the bridge deck. The bridge deck and scuppers were swept and flushed prior to bridge washing.

The tanker truck used for this site was filled with water drawn from the Ohio River near the bridge location. According to the contractor, the tanker truck was used solely for bridge washing. The contractor did not know the exact pressure and flow rates

used for washing. In a later project observed for this study the pressure was observed to be 1500 psi (10.3 MPa) and the contractor indicated that this setting had not changed. In a given shift, only a very small portion of the water in the truck is used. This is consistent with the estimated flow rate of 7.5 liters (2 gallons) per minute determined from the contractor interviews discussed in the literature review. Five locations were selected for testing on the bridge. The first location was the underside of a diagonal truss member above the bridge deck. The second location was the roadside face of a vertical truss member with intact coating. The third location was the underside of a horizontal member approximately 6.5 m (21.5 feet) above the roadway. The fourth location was a bottom chord gusset plate on the inside of the truss. The fifth and final location was the roadside face of a vertical truss member, in which the coating had failed and it was exhibiting a significant amount of corrosion. These locations are highlighted in Figure 1.
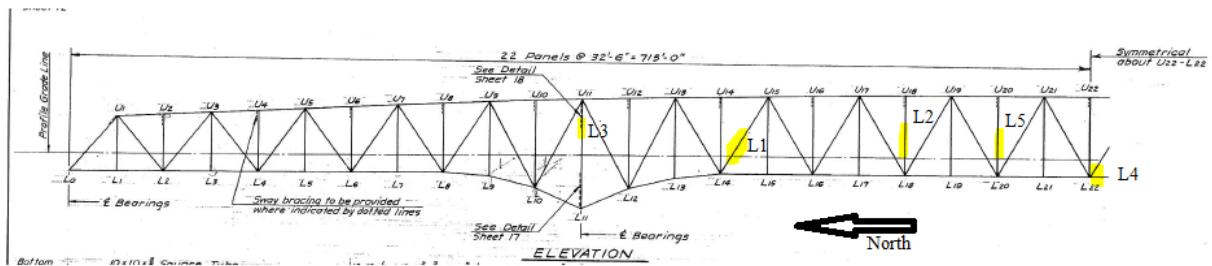
Figure 1: Vanport Bridge Testing Locations

In order to sample the runoff water at this location buckets were hung from auxiliary structures on the bridge, a light pole and a mile marker sign, and lowered approximately 3 m (9.4 feet) below the deck with rope. A third sample was collected by setting a bucket on the deck to collect the runoff water generated from washing the inside face of the truss.

3.2.2. Hassam Road over Montour Run

The Hassam Road Bridge over Montour Run is a two span, simply supported, steel I-Beam bridge spanning across Montour Run and its adjacent spillway in Robinson Township, PA. Expansion joints are located at the abutments on each side of the bridge and at the central span. There are several locations where the expansion joint showed

evidence of leaking. The washing and observation occurred on the spillway span to allow easier access. Washing was performed by a maintenance crew from PennDOT District 11. The bridge was not originally scheduled for washing this year, however the crew was brought on to wash selected areas of the bridge, where testing was performed as part of this study. No lift truck was available, and washing was performed by one pressure washer entirely from the ground. The crew used potable water from a municipal source for the washing.

Similar to the Vanport Bridge, there were five locations selected for testing. The first location examined was a connection between a diaphragm beam and a bearing plate stiffener beneath a leak in the expansion joint. The second location was the adjacent connection between a diaphragm beam and bearing plate stiffener, in which the expansion joint was intact and not leaking. The third testing location was the topside of the bottom flange near mid-span of the diaphragm beam between locations one and two. There were signs that the expansion joint was leaking above this test location. The fourth location was the web of the fascia beams near the central pier expansion joint. The final location was the topside of the bottom flange of the fascia beams near the same expansion joint. The locations are marked on the plans in Figure 2.
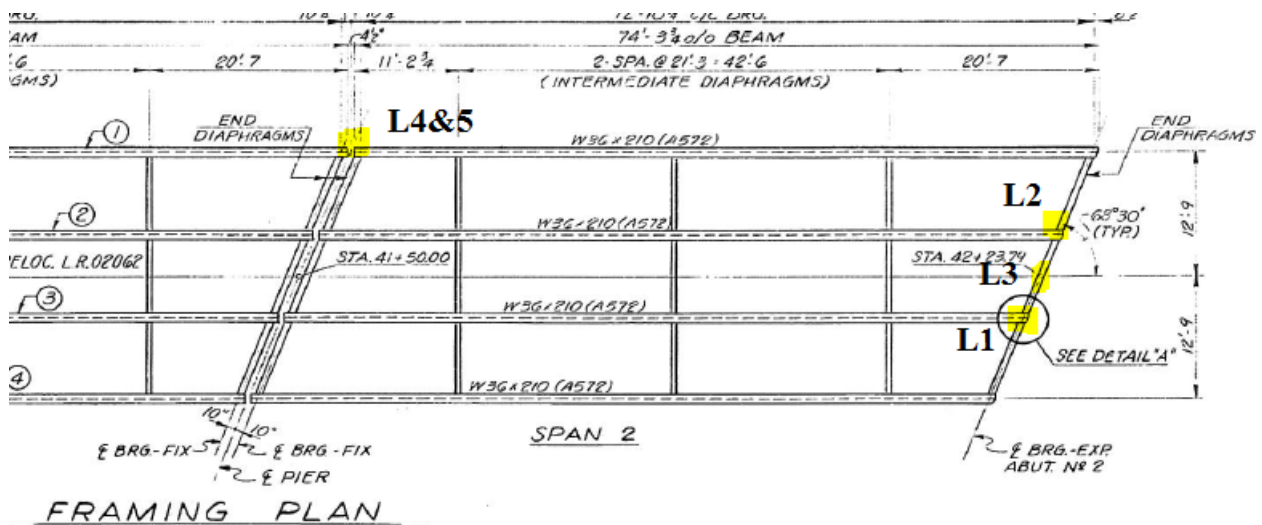

Figure 2: Hassam Road over Montour Run Testing Locations

To collect wash water runoff, sets of two buckets were hung from three locations below surface salt concentration testing Locations 1, 2, and 4. The buckets were hung

from ropes which were tied to the beam bearing seats and lowered to approximately one meter (3 feet) below the bottom flange of the beam.

3.2.3. I79 over Thomas Run Road

The final bridge tested was a three span continuous plate girder bridge carrying Interstate 79 (I79) over Thomas Run Road and Chartiers Creek in Bridgeville, Pennsylvania. The testing was performed on the bridge carrying the northbound lanes of I79, however a similar bridge carrying the southbound lanes is adjacent to the structure. One span of the bridge spans Thom's Run Road, while the second span crosses Chartier's Creek and the third span is an approach span. The bridge was washed by a maintenance crew from PennDOT District 11. A bucket truck was used to allow the pressure washer to access the bridge above the road. However, any area on the slope between the abutment and the roadway was washed from the ground, since the bucket truck could not access these locations. Washing was performed using potable municipal water.

A total of six locations were tested before and after washing. Location 1 was on the bearing stiffener on the eastern fascia beam at the abutment. Location 2 was on the topside of the bottom flange of the western fascia beam above the westbound traffic lane on Thoms Run Road. Location 3 was on the web of the western fascia beam directly above location 2. Location 4 was on the underside of the bottom flange of an interior beam above the westbound traffic lane on Thoms Run Road. Location 5 was on the web of the beam above location 4. Location 6 was the topside of the bottom flange web above Location 4. These locations can be seen in Figure 3. The buckets were hung to collect water from wash water runoff at three different locations, marked B1, B2, and B3 on Figure 3.
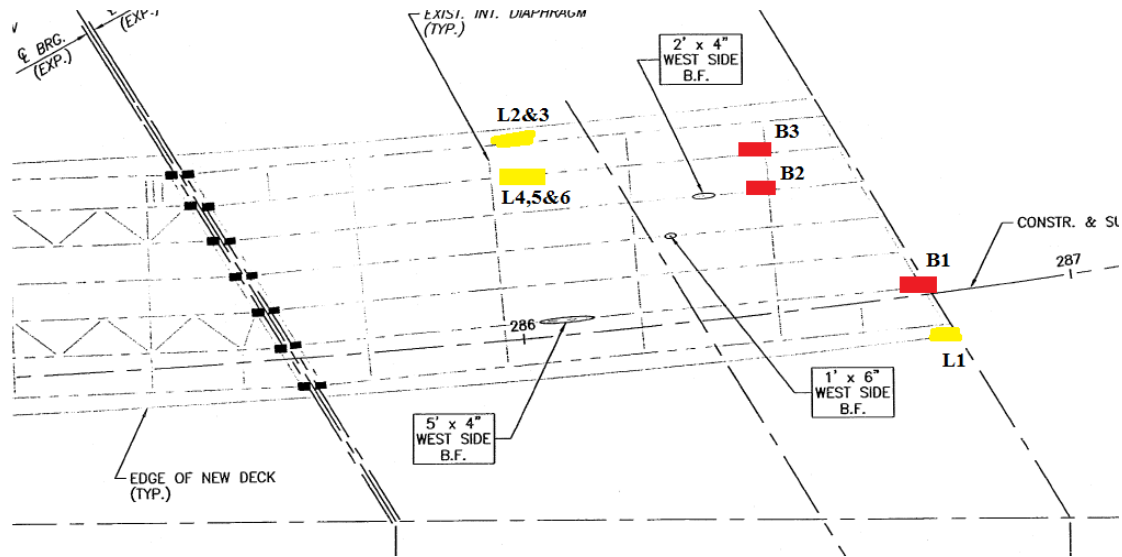
Figure 3: I79 over Thoms Run Road Testing Locations

3.3. Surface Salt Concentration Testing

3.3.1. Vanport Bridge

Location 1 - The first location tested, the underside of a diagonal truss member, was chosen because it was hypothesized that this area receives tire spray containing salt during deicing season, but is sheltered from rain. This area was also used to evaluate the salt concentration before and after washing. To do this, twelve measurements were taken before and after washing at this location. The measurements were taken in a staggered row pattern. After washing, the pattern was reversed and the tests were performed in the gaps between the pre-wash test locations. This pattern was established to provide testing conditions before and after washing that are as similar as possible. These patterns can be seen in Figure 4. The test locations marked in black with red labels were tested before washing, and those marked in gold with black labels were tested after washing. Staggering the test locations was essential because the meter removes all the salt from the substrate in the tested area. Tests were always performed from the bottom of the pattern first, such that water released from the chamber did not affect later tests. The results from the tests at this location are shown in Table 6. These results were checked for normality by creating a normal probability plot of the residuals using the statistical software package Minitab. Surface salt concentrations before and after washing are shown in Figures 5 and 6, respectively.

28
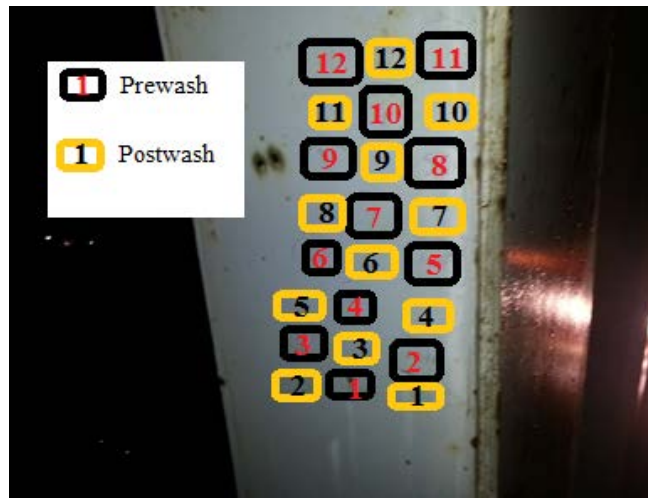
Figure 4. Bridge, Location 1: Underside of Diagonal Truss Member.

Table 6: Vanport Bridge, Location 1 Test Results

Vanport Bridge Location 1 Test Results		
Reading	Salt Concentration, mg/m^2 (x10^{-3} grains/ft^2)	
	Pre-wash	Post-wash
1	12 (17)	7 (10)
2	15 (22)	7 (10)
3	15 (22)	6 (9)
4	13 (19)	3 (4)
5	8 (11)	6 (9)
6	15 (22)	6 (9)
7	11 (16)	7 (10)
8	7 (10)	3 (4)
9	15 (22)	1 (1)
10	18 (26)	7 (10)
11	7 (10)	6 (9)
12	16 (23)	1 (1)
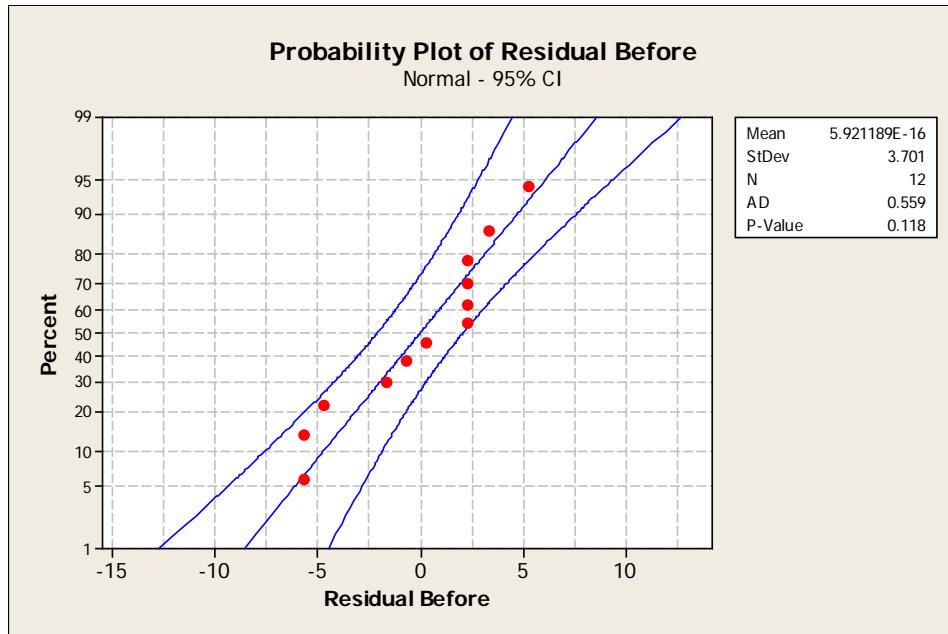
Figure 5: Probability Plot of Residuals Pre-wash
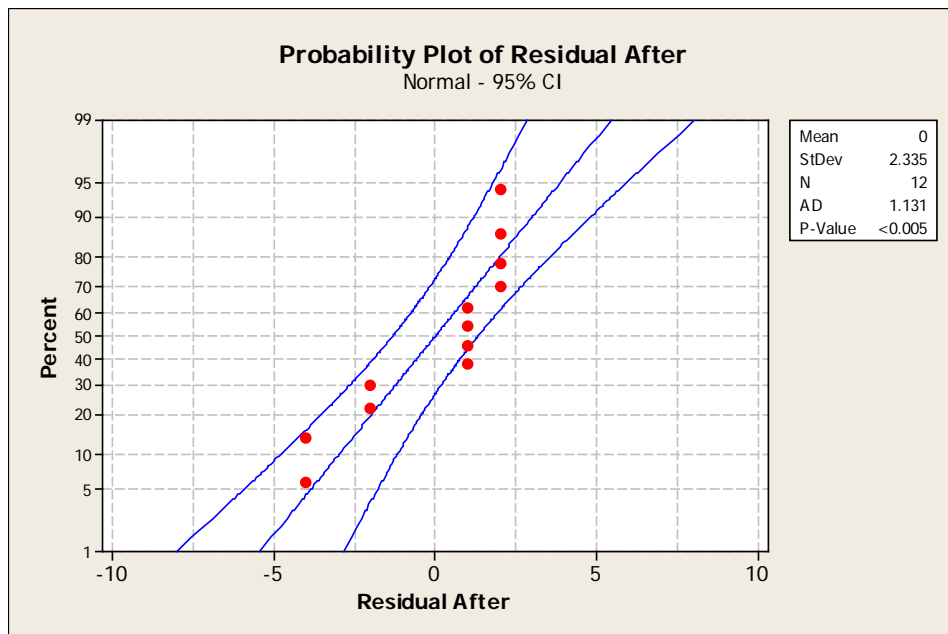
Figure 6: Probability Plot of Residuals Post-wash

It can be seen from Figures 5 and 6 that the surface salt concentrations before and after washing closely follow normal probability distribution. There is one data point that is slightly out of the normality envelope at a 95 percent confidence interval; however, it appears that the approximation of normality is valid for areas with an intact coating for

both pre-wash and post wash conditions. There also does not appear to be any trends based on test order, which would correlate to a change in concentration with height along the member for a typical sample area. Therefore, using statistics based on the assumption of normality is justified for areas where the coating is intact.

The mean surface salt concentration in location 1 before washing was 13 mg/m^2 (19×10^{-3} grains/ft^2) with a standard deviation of 3.7 mg/m^2 (5.3×10^{-3} grains/ft^2), After washing, the mean surface salt concentration in location 1 was 5 mg/m^2 (7×10^{-3} grains/ft^2) with a standard deviation of 2.3 mg/m^2 (3.3×10^{-3} grains/ft^2). The post washing surface salt concentration level is significantly lower than the surface salt concentration before washing at a 95 percent confidence level, using a two sample t-test. Results from this location support that hypothesis that the salt concentration on intact coatings is normally distributed and that washing with river water successfully removes salt from a member with an intact coating. An estimated 61 percent of the salt was removed from the structure by washing.

Location 2 - The second location tested was the roadside face of a vertical truss member. This location is exposed to more salt than location one as it faces the salt spray from tire splash directly. However it is also more exposed to rain, which could reduce the salt concentration on the member between wash cycles. Three measurements were taken in this location before and after washing. The test locations were selected such that the meter could be placed on a flat section of steel so that before and after tests could be made adjacent to each other without testing on visible rust. The testing locations before washing are shown in Figure 7. The darker color shown on the left side of the member is not due to corrosion but a simple discoloration of the coating.

Figure 7: Vanport Bridge, Location 2: Inside of a Vertical Member

Three tests were performed before and after washing at this location. Based on the assumption of normality observed at Location 1, normality was also assumed for the statistical analysis of Location 2. The mean surface salt concentration before washing was 17 mg/m^2 (24×10^{-3} grains/ft^2) with a standard deviation of 0.6 mg/m^2 (0.8×10^{-3} grains/ft^2). The mean surface salt concentration after washing was 10 mg/m^2 (14×10^{-3} grains/ft^2) with a standard deviation of 1.5 mg/m^2 (2.2×10^{-3} grains/ft^2). Similar to Location 1, these results support the hypothesis that the mean salt concentration after washing is significantly lower than the mean salt concentration before washing. The salt concentration at this location after washing was larger than at Location 1 and only 40 percent of the surface salt concentration was removed at this location. However, the percentage of salt removal was not statistically different between Locations 1 and 2 using a two sample t-test.

Location 3 - The third location tested was the underside of the lowest horizontal member above the bridge deck. This member was aligned with the northern interior bridge pier. According to the construction drawings, the height between the roadway and

the bottom flange of this beam is approximately 6.5 m (21 feet) above the bridge deck. Neither the current Bridge Maintenance Manual (Publication 55) nor the project specifications require horizontal members above the roadway to be cleaned, and therefore this beam was not washed by the contractor. The underside of the beam exhibits visible signs of corrosion (Figure 8) and therefore the pre-wash salt concentration of this beam was measured for comparison with the other locations. Although the visible corrosion was above the westbound passing lane three tests were taken at the centerline of the eastbound truck lane due to traffic control concerns. The mean surface salt concentration at Location 3 was 31 mg/m^2 (44×10^{-3} grains/ft^2), with a standard deviation of 5.9 mg/m^2 (8.5×10^{-3} grains/ft^2).

Figure 8: Vanport Bridge Location 3, Horizontal Member above Roadway.

(Photo taken from Google Streetview 10/2/2013)

In order to compare the salt level from Location 3 with other locations, Tukeys Paired t Test was used to compare the initial salt concentrations at each of the five locations. The pre-wash salt concentration on the underside of the horizontal member (Location 3) was significantly larger than at Locations 1, 2, and 4 at a 95 percent confidence level but was not significantly different than the pre-wash salt concentration at Location 5 (the vertical truss member with a failed coating and visible rust). Table 7

shows the results of the paired t-test, and lists the areas that were not significantly different at a 95 percent confidence level.

Table 7: Tukey Paired t-Test Results on Pre-wash Surface Salt Concentrations

Vanport Bridge Pre-Wash Surface Salt Concentrations		
Location	Mean SSC $(mg/m^2[grains/ft^2])$	Statistically Similar Location
3	31[44]	5
5	27[39]	2,3
2	21[30]	5,4
4	14[20]	2,1
1	13[19]	4

Location 4 - The fourth location sampled was a gusset plate on the inside face of the bottom chord of the truss. The gusset plate tested appears to have been recently renovated. The coating is mainly intact and the rivets, which are prevalent in most of the structure, have been replaced by bolts as can be seen in Figure 9.

Figure 9: Vanport Bridge, Location 4, Gusset Plate on Inside of Lower Chord

This particular gusset plate was tested because it was the only gusset plate accessible from the catwalk. Several other gusset plates were in much worse shape, and had visible signs of corrosion. The contractor provided a bucket of rusted steel, which they had scraped from the deteriorated gusset plates but was not sure about the exact location of the gusset plate where the rusted steel was removed.

As shown in Table 2, the gusset plate evaluated with the Soluble Salt Meter did not have a large pre-wash surface salt concentration. The mean salt concentration at this location was only slightly higher than the underside diagonal member (Location 1). The mean pre-wash surface salt concentration at Location 4 was 12 mg/m^2 ($17x10^{-3}$ grains/ft^2), with a standard deviation of 3.5 mg/m^2 ($5.0x10^{-3}$ grains/ft^2). The mean post-wash surface salt concentration was 9 mg/m^2 ($13x10^{-3}$ grains/ft^2) with a standard deviation of 2.1 mg/m^2 ($3.0x10^{-3}$ grains/ft^2). This is the only location tested where the post-wash surface salt concentration was not significantly lower than the initial surface salt concentration. Due to the limitations of the "snooper truck," the crew was forced to wash the lower gusset plates at a shallow angle. It appears that this angle limit adversely affected the effectiveness of bridge washing.

The contractor also provided the author with a five gallon bucket partially filled with rusted steel taken from bottom chord gusset plates which were not accessible from the inspector's catwalk. This metal was evaluated for chloride content using a modified version of the Mayne Test, which was originally developed in 1959 in one of the earliest studies that identified soluble salt content as the cause of coating failure after painting rusted steel. In this test, 200 mL (6.8 ounces) of deionized water was boiled for 10 minutes and then cooled. A rusted specimen, which has been wire brushed to remove the "masking" layer of rust, was inserted into boiling water for 10 minutes and then cooled. The salt content of the water was then evaluated using titration (Mayne 1959). In this study, an Oakton Conductivity meter was used with a chloride selective electrode to evaluate the chloride content. Three triangular specimens with surface areas ranging from 7.4 to 9.0 cm^2 (1.1 to 1.4 in^2) were tested. The results are shown in Table 8. It should be noted that the reported concentrations are solely for chlorides, whereas the soluble salt meter reports the total salt content. As discussed in Task 1, a majority of soluble salts in the case of bridges are usually chlorides.

Table 8: Vanport Bridge, Mayne Test Results

Mayne Test Results			
Specimen	Area (m^2)	Total Cl (PPM)	Surface Chloride (mg/m^2),(*10^{-3}gr/ft^2)
1	0.00078	0.37	477 (683)
2	0.00074	0.25	333 (477)
3	0.00090	0.60	667 (956)

The surface salt concentration reported in Table 8 exhibited a large variance, which was expected because the rusted steel pieces were mixed in a bucket and it was impossible to know if the areas selected for sampling were from adjacent locations. The surface chloride concentrations are much higher in the rusted pieces than the surface salt concentrations measured on the gusset plate with the intact coating.

Location 5 - The final location tested is a similar to Location 2, in that it was the inside face of a vertical truss member. The main difference between the two locations is that the protective coating in Location 5 was deteriorated and visible rust covered the entire testing area (Figure 10). This area was tested for two reasons: (a) to determine if the pre-wash salt content of the rusted areas is higher than similar areas which did not exhibit rust (i.e., salt concentration may have contributed to the premature failure of the coating in this area) and (b) to determine if a standard pressure washer is capable of lowering the surface salt concentration on a rough, corroded surface.

Figure 10: Vanport Bridge, Location 5: Vertical Surface with Significant Corrosion.

The visual characteristics of the member support the hypothesis that salts contributed to the failure of the coating. In Figure 10, many individual round areas of rust are visible. This is consistent with the failure mechanism which occurs when salts ingress beneath the coating and cause osmotic blistering. However, the pre-wash surface salt concentration readings did not support this hypothesis. As discussed for Location 4, the pre-wash surface salt concentration at Location 5 was not significantly higher than the surface salt concentration at Location 2. The mean pre-wash surface salt concentration was 27 mg/m^2 (39x10^{-3} grains/ft^2) and the standard deviation was 3.1 mg/m^2 (4.4x10^{-3} grains/ft^2).

The results of the tests at this location summarized in Table 9 clearly indicate that the surface salt concentration after washing is not normally distributed. On a rusted surface, salt tends to concentrate into deep pits, which are difficult to clean. As a result, the surface salt concentration is not normally distributed, as the reading would be very dependent on how many pits were captured in the test area. It appears that a small layer of rust formed on the member above the salt acts as a barrier that prevents the salt from being detected by the meter. This phenomenon was also observed in the Mayne study

(Mayne 1959). The pressure washing effectively removed this barrier, exposing the salts underneath, but did little to remove these salts. Comparison between Figure 11, that shows the member after washing, and Figure 10, which was taken before washing, suggests that some rust was removed. It is interesting to note that the higher levels of post wash surface salt concentration are similar to the results obtained from the Mayne Test on the rusted metal retrieved from the lower chord gusset plates.

Table 9: Vanport Bridge, Location 5: Test results

Vanport Bridge Location 5 Test Results		
Reading	Salt Concentration, mg/m^2 (x$^{10-3}$ grain/ft^2)	
	Before Washing	After Washing
1	30 (43)	37 (53)
2	24 (34)	278 (399)
3	28 (40)	44 (63)
4		328 (470)

Figure 11: Vanport Bridge, Location 5: Rusted Area Post-wash

3.3.2. Hassam Road over Montour Run

Location 1 - The first location tested was the connection between a bearing stiffener and an end diaphragm beam. The expansion joint above this location shows signs of leaking. Corrosion is visible at the location where the deck meets the top flange

of the diaphragm beam where several orange stains, apparently from dripping rusty water, are visible at the connection. In addition, the bearing plate is visibly very corroded. Unfortunately, the corrosion has made the surface of the bearing plate so rough that the SSM could not bond to the surface. Therefore, testing was performed on the bearing stiffener and the diaphragm beam where it is connected to the stiffener. The first two tests before and after washing were taken on the stiffener itself, and the third test taken on the end of the diaphragm beam as shown in Figure 12.

Figure 12 Hassam Road, Location 1, Bearing Stiffener Exhibiting Rust

The surface salt concentration at this bearing was significantly higher than at any location on the Vanport bridge, except the rusted area after washing. The mean surface salt concentration before washing was 250 mg/m^2 (358x10^{-3} grains/ft^2) with a standard deviation of 84.2 mg/m^2 (120.7x10^{-3} grains/ft^2). After washing, the mean surface salt concentration was 36 mg/m^2 (52x10^{-3} grains/ft^2), with a standard deviation of 13.0 mg/m^2 (18.7x10^{-3} grains/ft^2). The estimated salt removal was 85 percent. A two sample t-test with surface salt measurements before and after washing revealed that they are significantly different at the 95 percent confidence level, with an estimated difference of 213 mg/m^2 (305x10^{-3} grains/ft^2) and a p-value of 0.049.

Location 2- The second location tested was similar to the first, except that the expansion joint above the connection showed no signs of leaking. The tests were taken in the same manner with two tests taken before and after washing on the bearing stiffener, and one test taken before and after washing on the web of the diaphragm beam at the connection. The bearing plate at this location did still show some signs of coating failure, but was not nearly as corroded as the bearing plate in Location 1. Figure 13 shows the same beam bearing location, though the testing was actually performed on the other side of the beam.

Figure 13: Hassam Road, Location 2: Bearing Stiffener Not Exhibiting Rust

Three tests were performed before washing. However, one of the tests resulted in unreasonably high salt concentration of around 2000 mg/m^2 (2866x10^{-3} grains/ft^2). This value is over 600 mg/m^2 (860x10^{-3} grains/ft^2) higher than any other result in this study. When considering the low salt concentrations measured at adjacent locations, it is reasonable to assume that this result was an error and was not considered in the analysis. Based on just the two tests, the mean surface salt concentration before washing was 23 mg/m^2 (33x10^{-3} grains/ft^2) (standard deviation can not be reported for only two valid tests). After washing, the mean surface salt concentration was 10 mg/m^2 (14x10^{-3} grains/ft^2) with a standard deviation of 2.1 mg/m^2 (3.0x10^{-3} grains/ft^2). The salt removal

efficiency was estimated to be 55 percent. The pre-wash salt concentration at Location 2 is significantly lower than the surface salt concentration at Location 1. The mean pre-wash salt concentration at Location 2 is even lower than the mean post-wash salt concentration at Location 1. This shows that a leaking expansion joint is a major conduit for introducing soluble salts onto the structure.

Location 3 - The third location sampled was the topside of the bottom flange at mid-span of a diaphragm beam. As can be seen in Figure 2 the beam tested was between Locations 1 and 2. The mid-span of the beam was beneath the section of the expansion joint, which was leaking. A visible stain from dripping rusty water can be seen in Figure 14. According to Ms. Gina Russell, a PennDOT bridge engineer for District 11, the diaphragm beams are usually the first locations to exhibit rust. The topside of the bottom flange of the beam was soiled with a layer of debris, which was too thick to allow the use of salt meter. A bench broom was used to sweep off the visible dirt while trying to maintain the majority of the soluble salts on the surface. It should be noted that some of the soluble salts may have been removed with the sweeping. This was a necessary step in order to perform readings at this critical location. The cleaned area shown on Figure 14 was the test area.

Figure 14: Hassam Road, Location 3: Bottom Flange of Diaphragm Beam

The mean surface salt content at Location 3 was 1133 mg/m^2 (1624x10^{-3} grains/ft^2), with a standard deviation of 398 mg/m^2 (570x10^{-3} grains/ft^2) and was the highest measured surface salt content in this study. The large salt content could be a combination of the effect of the debris, which holds water and the soluble salts. Also, the bottom flange is a place where drips of water carrying salts from the face of the beam pool cyclically deposits salts after drying. After washing, the mean soluble salt content was 59 mg/m^2 (85x10^{-3} grains/ft^2), with a standard deviation of 22.8 mg/m^2 (32.7x10^{-3} grains/ft^2). A two sample t-test shows a statistically significant surface salt concentration decrease with a p-value of 0.043. The estimated salt removal efficiency was around 95 percent. However, the surface salt concentration was still relatively high after washing, with an estimated mean higher than anywhere on the Vanport Bridge before washing. It is possible that more salt would have been removed if lift equipment were available and the pressure washer could have sprayed directly on the bottom flange of the diaphragm. From the angle which the pressure washer sprayed, most of the water which hit the bottom flange would have been reflected from the diaphragm web, thereby greatly reducing its pressure.

42

Locations 4 and 5 - The fourth and fifth locations selected for testing were the web and topside of the bottom flange of the fascia beams on each side of the central pier. Location 4 is on the web and Location 5 is the topside of the bottom flange. There is an expansion joint between the two piers. The deck expansion joint above this location is showing signs of leaking. There are orange streaks on the web the topside of the bottom flange on each side of the expansion joint. Ten tests were performed at Location 4. The tests were taken in a "zipper" pattern. Before washing, test 1 was performed at the bottom of the web on the spillway side of the expansion joint and test 2 was performed slightly above on the stream side; other test locations followed this "zipper" pattern. After washing, the testing pattern was mirrored, with the first test being taken on the bottom of the stream side of the expansion joint, and the second test being taken slightly higher on the spillway side of the joint. The testing patterns before and after washing can be seen in Figure 15. The testing locations marked in black with red labels were tested before washing, and the locations marked in gold with black labels were tested after washing. There was a small amount of dirt on the spillway side of the joint beneath test 7, which could not be removed with a light sweeping with a bench broom. Two tests were performed before and after washing at Location 5. Before washing, one test was done adjacent to the joint on the spillway side, and another one was done approximately 15 cm (6 in) from the joints on the stream side. After washing, the pattern was reversed with one test done approximately 15 cm (6 in) from the joint on the spillway side, and the other test done adjacent to the joint on the stream side.
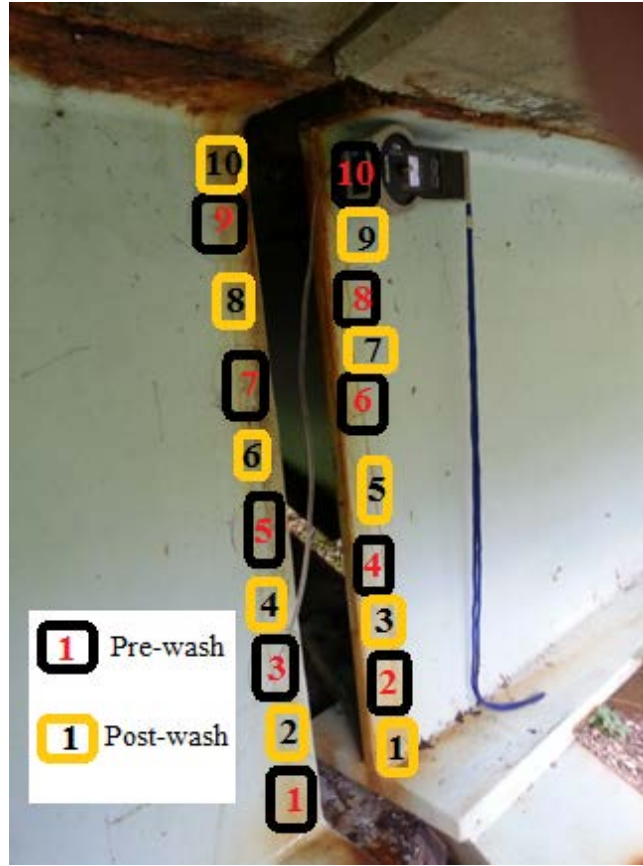
Figure 15: Hassam Road, Locations 4 and 5: Fascia Beam Web and Bottom Flange at Expansion Joint

Unlike Location 1 of the Vanport bridge, the pre-wash salt concentration at Location 4 of the Hassam Road bridge was not normally distributed. In fact, there appears to be a linear trend with the surface salt concentration increasing towards the top of the beam. On the spillway side of the beam, this trend is very defined. Test 7 did not follow this trend, most likely due to the dirt that was present on the beam. When Location 7 was omitted, the pre-wash salt concentrations followed a linear trend with an R^2 of 0.96, as can be seen in Figure 16. On the stream side of the joint, the trend was not as defined; however, it appears that the surface salt concentration at the top of the beam is larger than the salt concentration at the lower end of the beam, as can be seen in Figure 17.
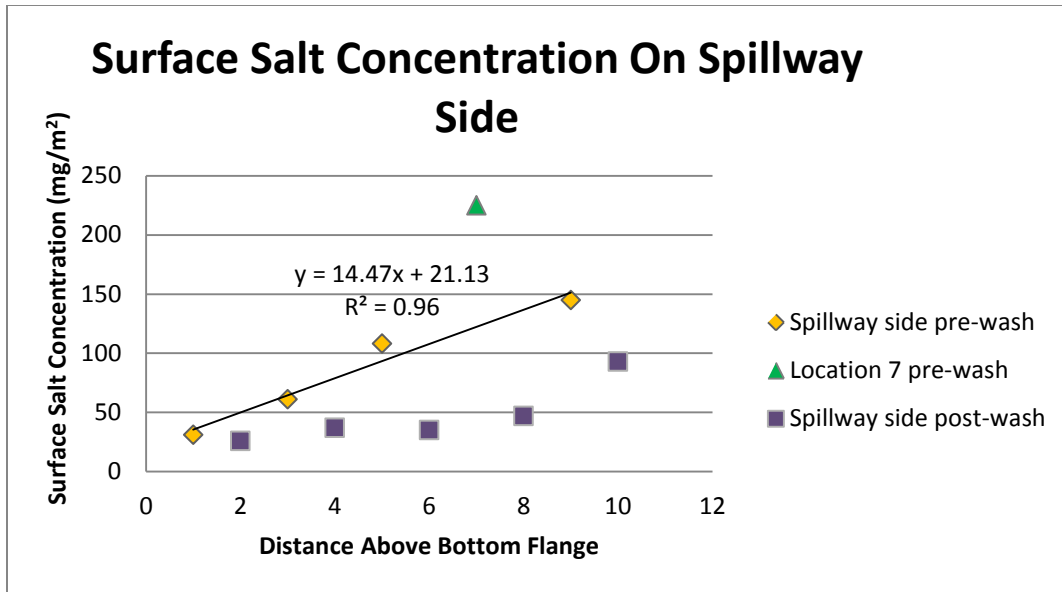
Figure 16: Hassam Road, Location 4: Testing Results, Spillway Side
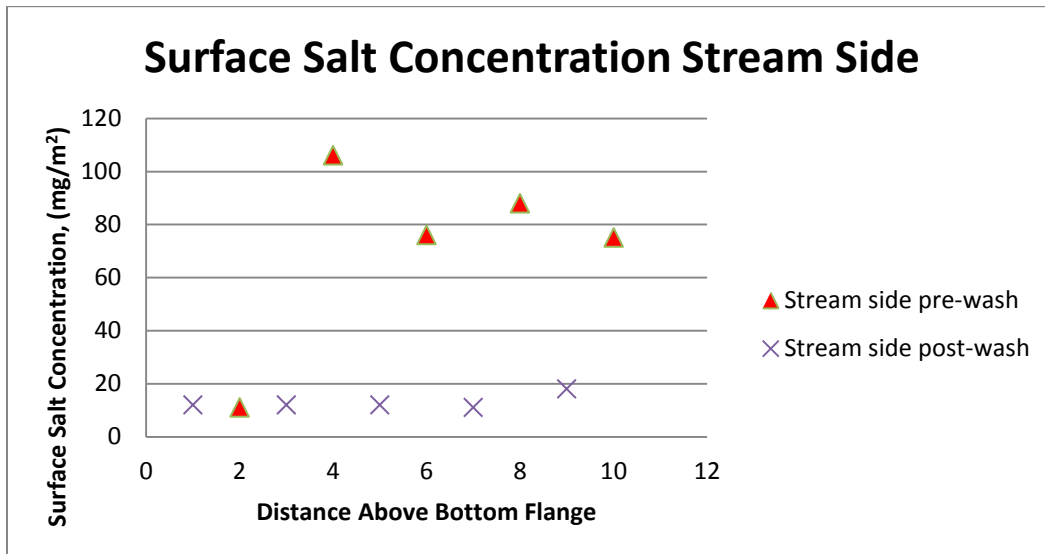
Figure 17: Hassam Road, Location 4: Testing Results, Stream Side

From Figures 16 and 17, it can be seen that washing appears to be effective at lowering the surface salt concentration for most of the beam on both sides of the joint. It is worth noting that the top reading on both sides of the joint after washing was higher than the other post-wash readings. On the spillway side of the bridge, the average post-wash surface salt concentration for tests 2, 4, 6 and 8 was 36 mg/m^2 (52×10^{-3} grains/ft^2)

with a standard deviation of 6.6 mg/m^2 (9.5x10^{-3} grains/ft^2). Test 10 had a surface salt concentration of 93 mg/m^2 (133x10^{-3} grains/ft^2), which is over 6.5 standard deviations above the mean. This result strongly suggests that washing is not nearly as effective near the top of the beam. On the stream side of the bridge, both the pre-wash and post-wash surface salt concentrations were lower than on the stream side; however, there was still a significant difference between the first four tests and the top test after washing. The surface salt concentrations at readings one, three, five and seven was 12 mg/m^2 (17x10^{-3} grains/ft^2) with a standard deviation of 0.5 mg/m^2 (0.7x10^{-3} grains/ft^2). Test 9 had a surface salt concentration of 18 mg/m^2 (26x10^{-3} grains/ft^2), which is 12.5 standard deviations above the mean. It should be noted that test 9 (the upper most test taken on the stream side) was approximately 10 cm (4 in) lower than reading 10 (the upper most test taken on the spillway side) due to the staggered nature of the testing pattern. If test 9 could have been taken at the same elevation as test 10, the increase between test 9 and the four readings below it may have been even more dramatic. This increase in post-washing salt concentration could be because the bridge was washed from the ground. A good portion of the energy in the wash stream was lost at the higher elevations and therefore the wash stream was less effective in removing salt from the surface of the beam.

It is difficult to evaluate the test results from location 5 because it was not possible to take several readings adjacent to the joint and the salt levels were generally lower on the stream side of the joint than on the spillway side. Therefore, a direct comparison was not possible. Before washing, the soluble salt concentration adjacent to the joint on the spillway side was 126 mg/m^2 (181x10^{-3} grains/ft^2) and only 44 mg/m^2 (63*10^{-3} grains/ft^2) 15 cm (6 in) from the joint on the stream side. After washing, the soluble salt concentration was 77 mg/m^2 (110x10^{-3} grains/ft^2) adjacent to the joint on the stream side, and 40 mg/m^2 (57x10^{-3} grains/ft^2) 5 cm (6 in) from the joint on the spillway side. This shows that the decrease in the surface salt concentration was not as large as that observed on the web of the beam. Similar to Location 3, it was not possible for the pressure washer to spray directly on to the bottom flange of the beam from the ground, resulting in less than ideal salt removal.

3.3.3. Interstate 79 over Thoms Run Road

Location 1 - The first location tested on the I79 bridge over Thoms Run Road was on the bearing stiffener of the eastern fascia beam at the northern abutment. The expansion joint near these stiffeners does not appear to be leaking as there were no signs of corrosion on the beam. However, there was a significant amount of debris on the topside of the bottom flange, as can be seen in Figure 21. Ten tests were performed before and after washing. The first test was done near the bottom of the stiffener and the tests were distributed evenly throughout the height of the beam from bottom to top. After washing, tests were performed in the gaps of the pre-washing test pattern. This ensured that the tests before and after washing are taken in similar areas.

Figure 18 I79 Over Thoms Run, Location 1: Fascia Beam Bearing Stiffener

Unlike the Hassam Road bridge, where most of the salt was introduced via a leaking expansion joint, there does not appear to be a mechanism for salty water to reach the beam directly from the bridge deck. The pre-wash salt concentration did not show the increasing trend with elevation that was seen on the Hassam Road Bridge. If anything, it appears that the salt concentration was the highest near the center of the beam and lower toward the top and the bottom, as can be seen in Figure 19.
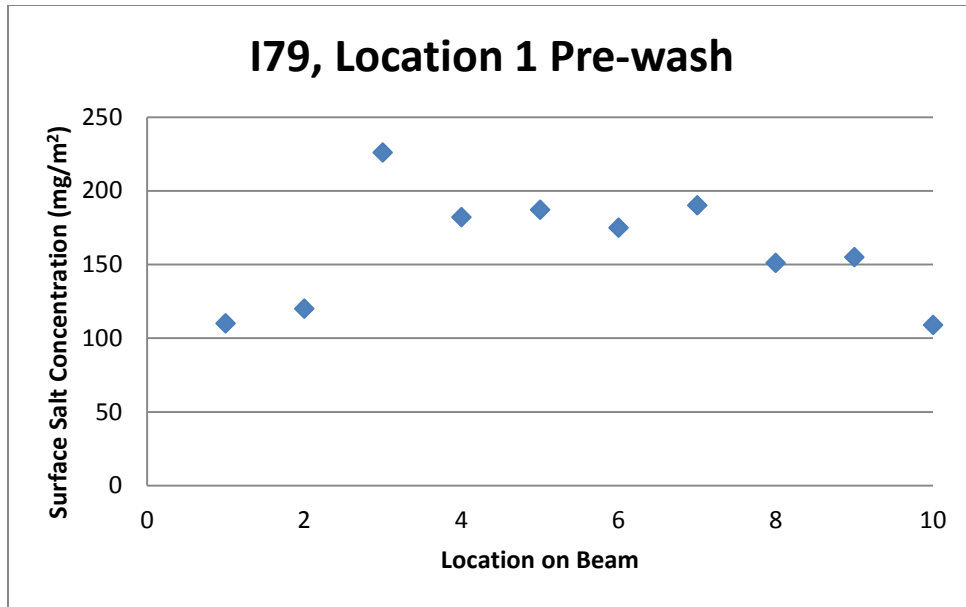
Figure 19: I79 Over Thoms Run Road: Location 1 Pre-wash Soluble Salt Concentration

After washing, the soluble salt concentration readings appear to follow a linear trend with the exception of test 10 (Figure 20). This trend appears to show increasing final surface salt concentrations with increasing elevation. Reading 10, the reading with the highest elevation, does not follow this trend as closely.   The pre-wash salt concentration at Location 10 was lower than the surrounding areas so this is not completely unexpected. It can be seen in Figure 20 that the salt concentration follows a linear trend with an R^2 of 0.79 when Location 10 is omitted. It was also visually evident that the upper region of the beam was not as clean as the lower region of the beam. This supports the observation made on the Hassam road bridge that the washing efficiency decreases the higher the washer has to spray, due to a loss of energy. The pressure washer also did not move away from the beam horizontally while washing the full height of the beam, resulting in the top area of the beam being washed at a shallower angle than the lower portion of the beam. This could also contribute to the diminishing efficiency of the washing with height. Despite the diminishing efficiency of the washing with increasing elevation, the washing was generally effective at decreasing the soluble salt content on the bridge from the average salt content of 161 mg/m^2 (230x10^{-3} grains/ft^2) to 20 mg/m^2 (28x10^{-3} grains/ft^2); the average salt removal efficiency was estimated at 88 perent

despite the apparent trend that washing the top portion of the beam was not as efficient as washing the lower portion of the beam.
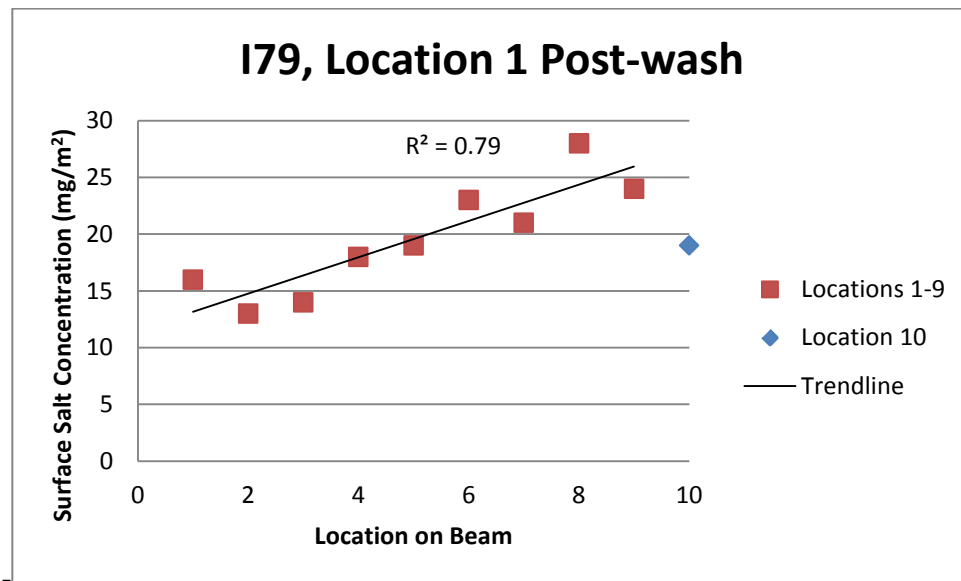
Figure 20: I79 Over Thoms Run Road, Location 1: Post-wash Soluble Salt Concentration

It should also be noted that while it was possible to clean the bearing stiffener from the ground, the bottom flange of the beam still had a lot of visible debris present after washing, as can be seen in Figure 21. Although surface salt concentration testing was not performed on the bottom flange, it appears that washing the topside of the bottom flange was not effective from the ground.

Figure 21: I79 Over Thoms Run, Topside of Bottom Flange Near Location 1.

Location 2 - The second location tested was the topside of the bottom flange of the western fascia beam. The testing was performed above the Thoms Run Road westbound traffic lane. This flange was noticeably cleaner than the interior beams adjacent to it. Three tests were performed near the tip of the flange before and after testing, with the post-washing testing performed in the gaps of the pre-wash test pattern, as can be seen in Figure 22. This area was washed from a bucket truck, which allowed the pressure washer to spray down onto the topside of the flange.

Figure 22: I79 Over Thoms Run Road, Location 2: Topside of Bottom Flange of a Fascia Beam.

Before washing, the mean surface salt concentration at this location was 28 mg/m^2 (40×10^{-3} grains/ft^2) with a standard deviation of 7.2 mg/m^2 (10.3×10^{-3} grains/ft^2). The pre-wash surface salt concentrations at this location were much lower than the other areas tested on this bridge. After washing, the mean surface salt concentration was 11 mg/m^2 (16×10^{-3} grains/ft^2) with a standard deviation of 3.9 mg/m^2. The estimated salt removal efficiency was 60 percent. Due to the large variation and small sample size in the pre-wash tests, the salt concentration before and after washing is not significantly different at a 95 percent confidence interval. Using a two sample t-test, the means are statistically different with a p-Value of 0.15 at 85 percent confidence level.

Location 3 - The third location tested was at approximately the mid-height of the fascia beam web, directly above Location 2. Like Location 2, this area was also washed from a bucket truck that allowed water to be sprayed directly onto the beam. An area of grime was visible from the top flange of the beam to slightly below the testing area. Grime was wiped away from the testing area with a rag before testing to ensure that the testing evaluated only the salts that were present on the surface and not the salts that were

trapped in the layer of grime. Similar to Location 2, three tests were performed before and after washing with the post-wash tests performed in the gaps of the pre-wash testing pattern, as can be seen in Figure 23.

Figure 23: I79 Over Thoms Run Road, Location 3 Web of Fascia Beam

Before washing, the mean surface salt concentration was 248 mg/m^2 (356x10^{-3} grains/ft^2) with a standard deviation of 16.3 mg/m^2 (23.4x10^{-3} grains/ft^2). This is even higher than the surface salt concentrations observed on the bearing stiffener on the opposite fascia beam. The high pre-wash surface salt concentrations at this location are most likely due to salt spray being introduced from the traffic above. After washing, the mean surface salt content was 16 mg/m^2 (23x10^{-3} grains/ft^2) with a standard deviation of 0.7 mg/m^2 (1.0x10^{-3} grains/ft^2). The final salt concentrations are similar to the lower end of the post-wash soluble salt concentrations from Location 1, as would be expected since concerns of energy loss and a shallow washing angle were addressed by washing from the bucket truck. The estimated salt removal efficiency was 93 percent. Similar to Location 1, pressure washing was very effective at removing the soluble salts

Location 4 - The fourth location tested was the underside of an interior beam. The bottom flanges of the interior beams were visibly dirty. The closer the beam was to the roadway, the dirtier the beam was visibly. It is also interesting to note that the second span of the bridge, which crosses Chartiers Creek instead of a road with vehicular traffic, was not visibly soiled. Upon closer inspection, the grime on the underside of the beam was an adhered discoloration and not a layer of grime, which could be removed with a dry rag. Three tests were performed on the bottom flange of the beam above the westbound traffic lane of Thoms Run Road before and after washing. It should be noted that this location, which was also tested for Locations 4, 5, and 6, is not defined as an area to wash in the PennDOT specification, but was washed for this study. Similar to other locations, the post-wash tests were performed in the gaps of the pre-wash test pattern. The test locations are shown in Figure 24, which also shows that the coating below these beams is exhibiting signs of failure due to osmotic blistering that might be attributed to possible high surface salt content.

Figure 24: I79 over Thoms Run Road, Location 3 Underside of Interior Beam

Before washing, the mean surface salt concentration was 247 mg/m^2 (354x10^{-3} grains/ft^2) with a standard deviation of 26.3 mg/m^2 (37.7x10^{-3} grains/ft^2). The compressor

supplying the sprayer, was malfunctioning and the pressure being supplied gradually declined. By the time the wash team reached this area, the pressured had greatly reduced. After the initial washing, the mean salt content was 149 mg/m^2 (213.6x10^{-3} grains/ft^2), with a standard deviation of 31.7 mg/m^2 (45.4x10^{-3} grains/ft^2). The salt removal efficiency is estimated at 40 percent. The high mean salt concentration and standard deviation shows that significantly reducing the pressure of the washer greatly reduces the effectiveness and consistency of the wash. After a field repair of the washing equipment, which appeared to restore the pressure to the original level, this section of the bridge was washed again. After the second washing with the repaired equipment the mean soluble salt concentration was reduced to 41 mg/m^2 (59x10^{-3} grains/ft^2) with a standard deviation of 10.1 mg/m^2 (14.5x10^{-3} grains/ft^2). The efficiency of the rewash was 73 percent. The higher pressure was much more effective at reducing the surface salt concentration of the member.

Location 5 - The fifth location tested was the web of the beam, approximately six inches directly above Location 4. As can be seen on Figure 25, the discoloration, which was present at Location 4, is not as evident on the beam web. Like Location 4, three tests were performed before and after washing with the damaged pressure washer and three tests were performed after rewashing with the repaired equipment. This testing area can be seen in Figure 25, as the marked area above the soluble salt meter. Before washing, the mean surface salt concentration was 70 mg/m^2 (100x10^{-3} grains/ft^2) with a standard deviation of 18.5 mg/m^2 (18.5x10^{-3} grains/ft^2). The surface salt concentration at this location was much lower than the soluble salt concentration for the webs of the fascia beams. After washing with the damaged pressure washer, the mean surface salt concentration was lowered to 49 mg/m^2 (70x10^{-3} grains/ft^2) with a standard deviation of 10.4 mg/m^2 (14.9*10^{-3} grains/ft^2). The washing efficiency with the damaged pressure washer was estimated at 29 percent. After washing with the repaired meter, the surface salt concentration was lowered to 18 mg/m^2 (26x10^{-3} grains/ft^2) with a standard deviation of 6.8 mg/m^2 (9.7x10^{-3} grains/ft^2). The washing efficiency with the repaired meter was estimated at 65 percent. The coating in Location 5 had a smoother surface, and a lower

pre-wash surface salt concentration than Location 4. However, it was still not adequately cleaned when the pressure washer was not fully functional.

Location 6 - The final location tested was the topside of the bottom flange directly below Location 5. This location was covered in a thick layer of debris. This layer was wiped off with a dry rag before testing. The contrast between the wiped testing area and the unmodified adjacent area can be seen in Figure 25. This layer of debris did not extend to the second span above Chartiers Creek, indicating that it was most likely caused by the traffic flow below. Similar to Location 2, 3 tests were performed near the beam flange before and after testing, with the post washing tests performed in the gaps of the prewashing pattern.

Figure 25: I79 Over Thoms Run Road, Location 5 and 6 Web and Topside of Bottom Flange, on an Interior Beam

Before washing, the mean surface salt concentration was 298 mg/m^2 (427x10^{-3} grains/ft^2) with a standard deviation of 120.1 mg/m^2 (172.2x10^{-3} grains/ft^2). After washing, the mean surface salt concentration was 246 mg/m^2 (353x10^{-3} grains/ft^2) with a standard deviation of 123.6 mg/m^2 (177.2x10^{-3} grains/ft^2), and an estimated salt removal

efficiency of 17 percent. After the rewash with the repaired pressure washer, the mean surface salt content was 200 mg/m^2 (287×10^{-3} grains/ft^2) with a standard deviation of 48.7 mg/m^2 (48.7×10^{-3} grains/ft^2). The salt removal efficiency after the repair of 18.5 percent was not significantly higher than the washing efficiency with the broken pressure washer. None of these values are statistically different from each other. While washing this section of the bridge, the bucket truck was positioned such that the pressure washer was just above the bottom flange of the beam, resulting in a very small washing angle, and possibly causing the insignificant salt removal.

3.4. Runoff Water Testing and Analysis

At each of the three bridges, runoff water was collected and evaluated for water quality and salt content. The prevalent water quality concerns were turbidity and concentrations of zinc, lead and copper. An effective wash water runoff monitoring protocol developed by the Washington Department of Transportation (WSDOT) that was developed to document compliance with WSDOT's NPDES waste discharge permit (WSDOT 2010) was adopted for use in this study. To generate a representative monitoring regime, three locations around areas that were being washed were sampled with two replicated samples from each location. It should be noted that only selected areas of interest were washed for the study on the Hassam Road and I79 bridges and that the runoff water was representative of these areas and not the entire bridge.

Wash water runoff was sampled from three locations under the washed area of the bridge. At each sampling location, two 19 Liter (5 gallon) buckets were tied and lowered over the bridge structure before washing, and were left there during the washing to collect runoff water, as shown in Figures 13 and 18. After washing was completed, the two buckets from each of the three locations were mixed together and then poured into labeled sampling bottles for transport to the laboratory.

Two samples of the wash water directly from the tanker truck were taken before and after washing. These samples were used as a baseline for the water quality analysis, and to determine whether the salinity of the wash water might be affecting the salt removal efficiency of the washing procedures.

3.4.1. Turbidity

The Pennsylvania code requires that the turbidity of surface water be no more than 40 NTUs from May 15 to September 15 of any year. The turbidity of wash water and runoff water was tested using a Hach 2100A Turbidimeter. The contractor used water from the Ohio River as wash water, while the PennDOT crews used water from municipal sources. As expected, the initial turbidity of the river water was higher than the turbidity of the municipally sourced water. The purpose of washing a bridge is to remove the dirt, dust, salts and other particles from a bridge. Therefore, it is expected that the wash water will have a high turbidity. As can be seen from Table 10, the maximum turbidity of the wash water was 167 NTUs. Assuming that a pressure washer is continuously operated with a flow rate of 7 L/minute (2 gallons/minute) during an 8 hour shift, the amount of wash water used would be approximately 3400 L/day (900 gal/day), which is relatively small compared to even small stream flows around 7 million liters a day (1.85 Million gallons/day). Therefore, the turbidity of the wash water is negligible as it would be diluted by the stream flow.

Table 10: Runof Water Turbidity

Bridge	Sample	Turbidity
VanPort	tanker water before wash	54
	tanker water after wash	55
	runoff water 1	82
	runoff water 2 2	60.5
	runoff water 3	89
Hassam Road over Montour Run	tanker water before wash	0.32
	tanker water after wash	0.31
	runoff water 1	102
	runoff water 2 2	115
	runoff water 3	95
Interstate 79 over Thoms Run	tanker water before wash 1	0.64
	tanker water before wash 2	0.64
	tanker water before wash 3	0.64
	tanker water after wash 1	0.65
	tanker water after wash 2	0.64
	tanker water after wash 3	0.64
	runoff water 1	160
	runoff water 2 2	165
	runoff water 3	167

3.4.2. Zinc, Lead and Copper Content

Total and dissolved zinc, lead, and copper were measure by atomic absorption (PerkinElmer atomic absorption spectrometer, 1100b) following EPA Method 7000B for flame atomic absorption (EPA 2007). Prior to analysis, 9 mL (0.30 ounces) of each water sample was digested with 1 mL (0.03 ounces) of concentrated nitric acid for 2 hours and filtered through a 0.45 μm (1.7×10^{-6} in) nylon membrane to determine the total concentration of metals in each sample. Another 9 mL (0.3 ounces) aliquot of each water sample was filtered through 0.45μm (1.7×10^{-6} in) filter membrane without acid digestion and acidified with 1 mL (0.03 ounces) of 5 percent nitric acid to determine the concentration of dissolved metals.

After it is discharged into the receiving water, runoff water will be diluted by the stream flow, so the diluted metal concentration in the receiving water is estimated as follows:

$$\text{Diluted concentration} = \frac{(\text{metal concentration in runoff water}) \times (\text{runoff water discharge rate})}{(\text{receving stream flow rate} + \text{runoff water discharge rate})}$$

No zinc, lead or copper was detectable in the tanker truck water used at any of the three bridges at the beginning or the end of the wash (Table 11). The average zinc concentration in the wash water runoff was 1.67 mg/L (1.67 ppm) at the Vanport bridge, 22 mg/L (22 ppm) at the Hassam Road bridge, and 20 mg/L (20 ppm) at the I79 bridge. It is interesting to note that the zinc concentration at the Vanport bridge was much lower than at the other locations. It is also interesting to note that the zinc concentration in the runoff water did not vary greatly between Locations 1 and 2 at Hassam Road, although the coating was in much better shape at Location 2 than at Location 1. The metal concentrations detected in each wash water runoff can be seen in Table 11.

Table 11. Concentration of selected metals released during bridge washing

Bridge	Sample	Total Zn	Total Pb	Total Cu
VanPort	wash water before wash	ND	ND	ND
	wash water after wash	ND	ND	ND
	runoff 1	1	ND	ND
	runoff 2	2	ND	ND
	runoff 3	2	ND	ND
Hassam Road over Montour Run	wash water before wash	ND	ND	ND
	wash water after wash	ND	ND	ND
	runoff 1	24	ND	ND
	runoff 2	20	ND	ND
	runoff 3	22	ND	ND
Interstate 79 over Thoms Run Road	wash water before wash 1	ND	ND	ND
	wash water before wash 2	ND	ND	ND
	wash water before wash 3	ND	ND	ND
	wash water after wash 1	ND	ND	ND
	wash water after wash 2	ND	ND	ND
	wash water after wash 3	ND	ND	ND
	runoff 1	15	ND	ND
	runoff 2	22	ND	ND
	runoff 3	23	ND	ND

ND: Not detectable (below the detection limit)

The presence of some level of zinc ion is expected since most coatings in Pennsylvania are inorganic zinc rich systems. The coating at the Hassam Road bridge was labeled as a Type 3 inorganic zinc rich system, as can be seen in Figure 26. The concentration of zinc in the wash water would be diluted in the receiving water. Tables 12 and 13 show an estimate of the total zinc load in the wash water runoff and an estimate of the highest zinc concentration in the receiving contributed by the wash water

runoff, respectively. As can be seen from these tables, the final diluted zinc concentration would be insignificant even considering the worst case scenario. According to Pennsylvania surface water quality criteria for zinc, the ambient zinc concentration in surface water should not exceed $0.960 * e^{0.8473 \text{xln}[\text{Hardness}]+0.884}$ (µg/L or ppb) at any time (Pennsylvania 1994). Using the USGS estimate of water hardness in western Pennsylvania of around 61 - 120 mg/L (ppm) of calcium carbonate ($CaCO_3$) (USGS 2013), the total zinc concentration in any river in western PA should not exceed $0.960 * e^{0.8473 \text{xln}[61]+0.884} = 75.67$ µg/L (ppb). As seen in Table 13, the highest possible contribution of total zinc in different rivers in western PA caused by bridge washing is estimated to range from 1.15×10^{-6} mg/L (0.0011 ppb) in Ohio River to 0.0094 mg/L (9.4 ppb) in Chartiers Creek. Considering that bridge wash water runoff water is not being continuously discharged to the receiving stream but is a one-time event, it can be concluded that the impact of zinc in bridge wash water runoff should not be of any concern.

Figure 26: Hassam Road: Coating Label

Table 12: Estimated maximum total zinc load in wash water runoff

Bridge	Wash water flow rate,L/min (gal/min)	Runoff water discharged, L/d (gal/day)	Maximum zinc concentration, mg/L (ppm)	Maximum zinc load during bridge washing, mg/d, (gr/d)
VanPort	7 (2)	3600 (951)	2 (2)	7300 (113)
Hassam Road over Montour	7 (2)	3600 (951)	24 (24)	87200 (1346)
Interstate 79 over Thoms Run	7 (2)	3600 (951)	23 (23)	83600 (1290)

Table 13: Estimated highest total zinc concentration in receiving water

Stream	Historical minimum flow rate recorded by USGS, L/d (gal/d)	Diluted zinc concentration, mg/L or ppm
Ohio River	6,340,000,000 (1,675,000,000)	1.15×10^{-6}
Montour Run	9,300,000 (2,457,000)	0.0094
Chartiers Creek	6,600,000 (1,744,000)	0.0013

3.4.3. Chloride Content

Chloride concentration was measured by the ion selective electrode using an Oakton conductivity meter connected with chloride selective electrode. The chloride content was measured in the wash water sampled directly from the tanker truck and in the wash water runoff from each bridge. The wash water was tested because there was some concern that high salt levels in the wash water were limiting the effectiveness of the washing operations. This measurement also served as a baseline for the wash water runoff testing. The wash water runoff was checked for chloride content to confirm that chlorides are being removed during bridge washing.

As shown in Table 14, the wash water that was taken from the Ohio River contained an average chloride concentration of 1.96 mg/L (1.96 ppm). The municipal wash water used by the PennDOT crew had an average chloride concentration of 2.33 mg/L (2.33 ppm) at the Hassam Road bridge and 1.76 mg/L (1.76 ppm) at the I79 bridge. These are fairly low concentrations suggest that chlorides in the wash water are most likely not affecting salt removal during pressure washing of these bridges. It is important

to note that the trucks used in this study were used for bridge washing many times before testing occurred. Therefore, the PennDOT trucks had been flushed several times since they had been used for carrying salt brine during winter maintenance and it is not possible to determine if the salt concentrations in the wash water were higher earlier in the washing season. As can be seen in Table 14 and Figure 27, the wash water runoff runoff from the Vanport Bridge contained significantly less chlorides then the wash water runoff from the other two bridges. This is consistent with the results of surface salt concentration testing, which indicated that the salt concentration on the Vanport Bridge was much lower than the surface salt concentration on the other two bridges.

Table 14: Average chloride concentration in wash water and wash water runoff

| Bridge	Sample	Cl (mg/L or ppm)
VanPort	wash water before wash	1.96
	wash water after wash	1.97
	runoff 1	2.20
	runoff 2	2.08
	runoff 3	2.01
Hassam Road over Montour Run	wash water before wash	2.27
	wash water after wash	2.39
	runoff 1	17.10
	runoff 2	17.40
	runoff 3	12.10
Interstate 79 over Thoms Run	wash water before wash 1	1.76
	wash water before wash 2	1.75
	wash water before wash 3	1.76
	wash water after wash 1	1.76
	wash water after wash 2	1.76
	wash water after wash 3	1.76
	runoff 1	13.80
	runoff 2	13.50
	runoff 3	14.70
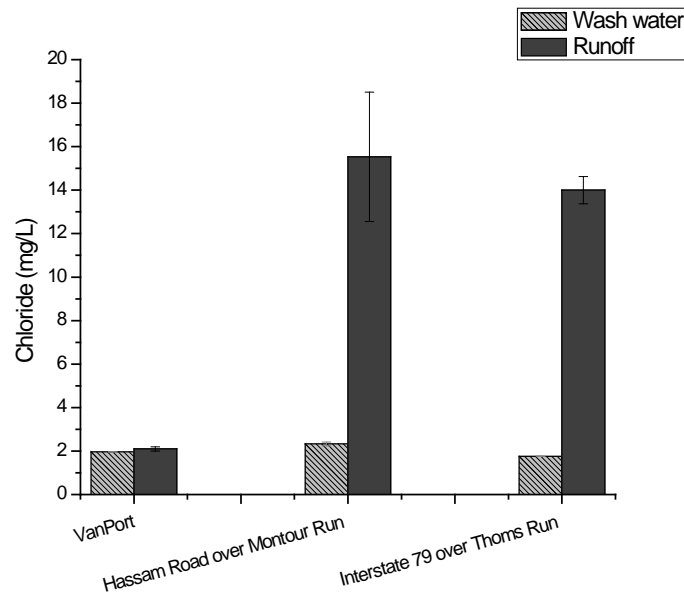
Figure 27 Concentrations in Wash Water and Wash Water Runoff

3.5. Recommendations

Based on the surface salt concentration testing and the wash water runoff analysis, there are several recommendations for improvements to the bridge washing program that could be implemented in order to more effectively extend the service life of the coatings. These recommendations were later evaluated in the field trials portion of the project. These recommendations fall into two categories, programming and procedural.

3.5.1 Programming

The pre-wash surface salt concentration testing showed which areas of bridges contain the highest surface salt concentration. The effect of the bridge washing budget can be maximized by washing the areas with very high salt concentrations, and not spending time and money washing areas which are relatively clean. It should be noted that these recommendations are based solely on the salt concentrations before and after the trial bridges were washed in September and October. It is unknown how quickly the surface salt concentration rebounds after washing.

Current PennDOT Specifications and the recommendations in the County Maintenance Management Tool and Bridge Maintenance Manual (PennDOT Publication 55) do not recommend that the full bottom flange of beams above a roadway be washed as part of the bridge washing operations. After evaluating the pre-wash surface salt concentrations in this study, it appears that beams with a bottom flange within 7 m (23 feet) of the road will contain a significant amount of salt on the bottom flange and that both the top and bottom of this flange should be washed as part of the bridge washing procedure. For Location 3 on the Vanport Bridge, a horizontal member approximately 6.5 m (21.5 feet) above the bridge deck had the highest initial mean surface salt concentration on the bridge. On the I79 bridge, Locations 4 and 6 had the highest and third highest surface salt concentration and showed visible grime and discoloration. These locations were on the topside and bottom side of the bottom flange of a plate girder approximately 6m (20 feet) above the roadway. Therefore, it is recommended that the bridge maintenance manual be adjusted to include the bottom flange of any beam within 7 m (23 feet) of a roadway below in the scope of the washing procedure.

Also, according to the bridge maintenance manual, currently all truss members between the bottom chord and a point eight feet above the deck are cleaned. On large steel trusses, this results in a significant amount of washing. On the Vanport Bride, the pre-wash salt concentration at a bottom chord panel point and on the diagonal and vertical truss members was low when compared to other bridges. This was supported by the relatively low salt concentration in the runoff water.

It is evident from the Hassam Road Bridge that any area below a leaking expansion joint will be subject to large soluble salt concentrations. It is not possible to keep all expansion joints in working order. However, the damaging effects of the leaking expansion joint can be minimized if these areas are targeted for extra washing. Ideally, all documented leaking expansion joints would be flushed in the spring to remove any salt deposited in the joint during the winter. The area directly below the joint should also be washed as often as possible, ideally annually in the spring, until the expansion joint can be repaired. The entire bridge does not need to be washed, only the area directly beneath the leaking expansion joint.

Finally, it is evident that it is very difficult to remove soluble salts from areas where the coating has completely failed and the surface is corroded. The salts in these conditions are in deep pits and will not be removed by standard pressure washing. Therefore, washing any bridge in which the vast majority of the coating has failed should be reconsidered. These bridges should be scheduled for blast cleaning and recoating as soon as possible.

3.5.2. Procedural

The procedural recommendations are based on reviewing the after wash surface salt concentrations to determine the effectiveness of the washing procedure at removing salts at different washing conditions. These recommendations could help ensure that the surface salt concentration is lowered as much as possible during washing.

It was previously unknown if the pressure of the washing stream affected salt removal. After the washer was damaged while washing the I79 bridge, it became evident that a fully functioning pressure washer is essential for the effective removal of salts. If a pressure washer is damaged during operation, washing should not be continued with a

weakened stream. Operations should be suspended until the equipment can be repaired or replaced.

It appears that washing steel members at a small angle is not effective in removing salts. Location 6 of the I79 bridge did not have a large salt removal percentage even after the pressure washer was repaired. This appears to be due to the shallow angle at which the topside of the bottom flange was washed. All washing should occur at a minimum angle to the surface being cleaned to ensure effective washing.   This minimum desirable angle should be established in the field trials.

Finally, for multiple reasons, it appears to be advantageous to have a bucket truck or other access equipment to wash bridges whenever possible. First of all, it is nearly impossible to wash the topside of the bottom flanges without access equipment. The topside of the bottom flange of the diaphragm beam (Location 3) had the highest initial surface salt concentration on the Hassam Road bridge, and the topside of the bottom flange of the first interior plate girder (Location 6) had the highest surface salt concentration on the I79 bridge. Without using access equipment, these high salt concentration areas cannot be washed very effectively.   Also it appears that washing efficiency decreases with an increase in the elevation between the nozzle and target area if the pressure washer nozzle is lower than the target area. This decrease in effectiveness can be avoided by using proper access equipment.

4. Field Trials

4.1. Introduction

From the observations of PennDOT bridge washing procedures, the effectiveness of bridge washing at removing soluble salts is dependent on both the procedure used as well as the amount of corrosion present. The procedural variables include the pressure provided by the compressor, the distance from the tip of the pressure washer to the target area being washed, the angle of washing stream with respect to the member being washed, and the distance in elevation between the nozzle of the pressure washer to the area being washed. The last two components will often be coupled. Assuming the point of origin of the wash water is constant then the further the target area from this point the more shallow the angle between the target area and the spray.

In order to evaluate the effect of these variables on the removal of soluble salts, a simple evaluation was planned and executed. Surface salt concentrations were measured using the Soluble Salt Meter II as described in the observation of PennDOT procedures. The first component of the evaluation focused on the effect of the angle of the projection and distance between the wash water with respect to the target area on the removal of soluble salts in the horizontal direction. The second component of the evaluation focused on effect of the change in angle increase in vertical distance between the tip of the nozzle and the target area. Two site visits were made to the 40th St. Bridge in Pittsburgh, Pennsylvania to evaluate the effects of these two components. These visits were made on November 6 and November 8, 2013. The 40th St. Bridge is a five span steel arch bridge in over the Allegheny River. The bridge was washed by the contractor Michael Facchiano Jr. The water used was for washing was potable water with a pressure held at 10.3 MPa (1500 psi). The outer two spans are simply supported over the spillway on the south side of the river, and the spillway and northbound lanes of PA 28 on the north side of the river. The first site visit was performed while the contractor washed the simply supported section over the spillway. The center three spans are steel arches over the Allegheny River. The second site visit occurred while the contractor was washing the middle arch of the bridge.

4.2. Field Tests

4.2.1. The Effect of Horizontal Distance and Washing Angle on Bridge Washing
Effectiveness

The purpose of test A was to determine the effect of the washing angle and increasing distance on the removal of soluble salts. Pre- and post-washing observations were taken at mid-depth on the web of the fascia beam for two of the three sections, directly below the guardrail. From previous site visits, this location was speculated to have a large soluble salt concentration. However, the prewash salt concentrations at this location were relatively low, below 20 mg/m^2 (29×10^{-3} grains/ft^2) . To attempt to find an area with a higher prewash salt concentration, the observations at the second test area were taken on the bottom flange of the beam. There was some small osmotic bubbling on this surface, although the coating had not failed and no signs of corrosion were present. However, the pre-wash readings on this surface varied widely at adjacent locations. Since observations could not be taken at the exact same location before and after washing, it is very difficult to tell whether the difference in pre-wash and post-wash surface salt concentration was due to the difference in prewash salt concentrations or due to the washing variables. Therefore, the test locations were moved back to the mid-depth of the beam web for the third locations.

The fascia beam of the bridge was divided into approximately 6 meter segments with a guardrail post and stiffener occurring between segments. Three groups of three tests were taken before and after washing. Similar to the observation made during the previous site visits, the prewash test pattern was spaced at approximately 15 cm (6 inches) on center, with the post-wash test placed in between prewash tests. The groups were centered 1 meter (3.3 feet) 2 m (6.5 feet) and 3 m (9.8 feet) from the stiffener, which was used as a reference point. The nozzle of the washer was positioned such that it was aligned with the stiffener and 1.3 m (4.3 feet) away from the beam. The set up can be seen in Figure 28 below. This was repeated for three adjacent beam locations. As previously discussed, the second location the testing was performed on the bottom flange. At the third location, the contractor began washing the beam from 1.4 m (4.6 feet) behind the stiffener. The adjusted angles and distances were calculated for this location, however, the contractor was instructed not to move and wash the entire section of beam

from that location to avoid a section of beam being washed from multiple distances and angles.
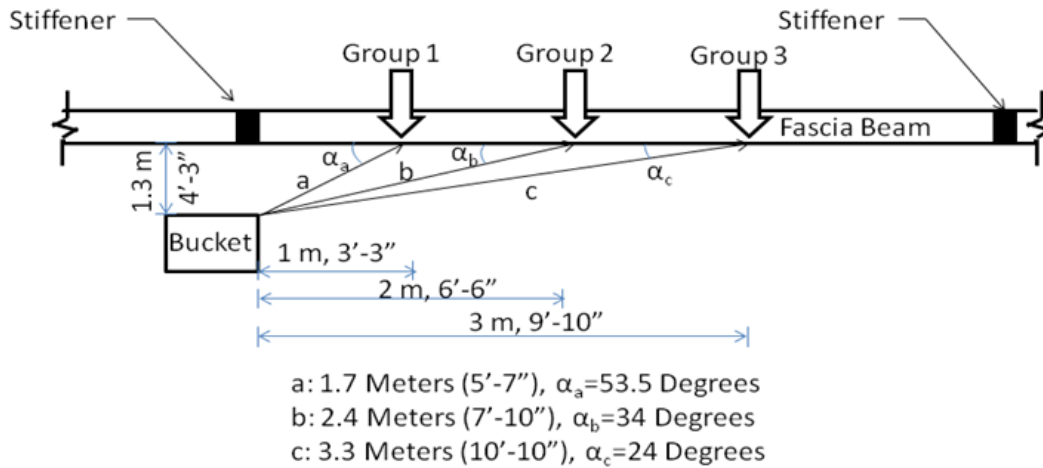

Figure 28: 40th St. Bridge, Test A: Sampling Locations

In this portion of the evaluation, the washer nozzle did not move while washing an entire beam, therefore the distance between the pressure washer and the washing angle was not decoupled. As previously discussed, the data from the second location was not valuable due to the large variation in prewash surface salt concentrations (15 to 201 mg/m^2) within one group, therefore the data analyzed was the data from Locations 1 and 3, and can be seen in Table 15. Accounting for the washing position in location 3 being different than intended, the relationship between washing distance and proportion of salt removal is shown in Figure 29.

Table 15: 40th St. Bridge, Test A: Salt Removal Versus Washing Angle

Test A Salt Removal					
Distance Along Beam, m (ft)	Wash Angle, degrees	Wash Distance, m (ft)	Pre-wash SSC, mg/m^2 (x10^{-3}grains/ft^2)	Post-wash SSC, mg/m^2 (x10^{-3}grains/ft^2)	Salt Removal (%)
1 (3.3)	53	1.7 (5.6)	16 (23)	10 (14)	41
2 (6.5)	33	2.4 (7.9)	10 (14)	6 (9)	41
2.6 (8.5)	27	2.9 (9.5)	9 (13)	5 (7)	48
3 (9.8)	24	3.3 (10.8)	14 (20)	7 (10)	49
3.6 (11.8)	20	3.8 (12.5)	12 (17)	4 (6)	68
4.6 (15.1)	16	4.8 (15.7)	13 (19)	5 (7)	59
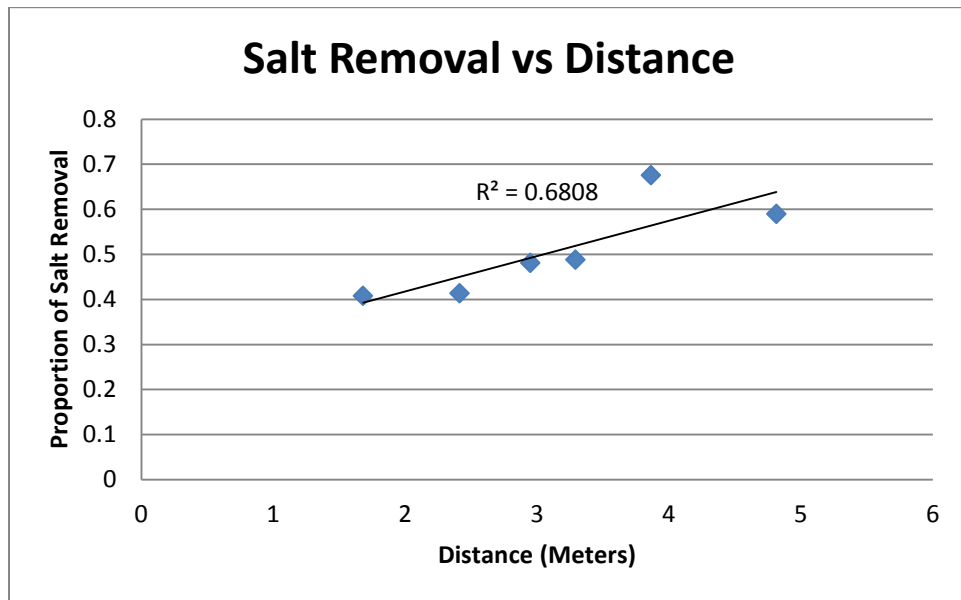
Figure 29: 40th St. Bridge, Test A: Salt Removal versus Distance

It appears that there is not a strong relationship between increasing distance between the washer and the target area being washed and decreasing effectiveness of the salt removal. This could be the result of either the salt concentrations were too low to show a significance or that the pressure used was significantly high that the distances selected were not sufficiently large to be statistically significant. The proportion of salt removal in locations 1 and 3 is plotted against the washing angle in Figure 30.
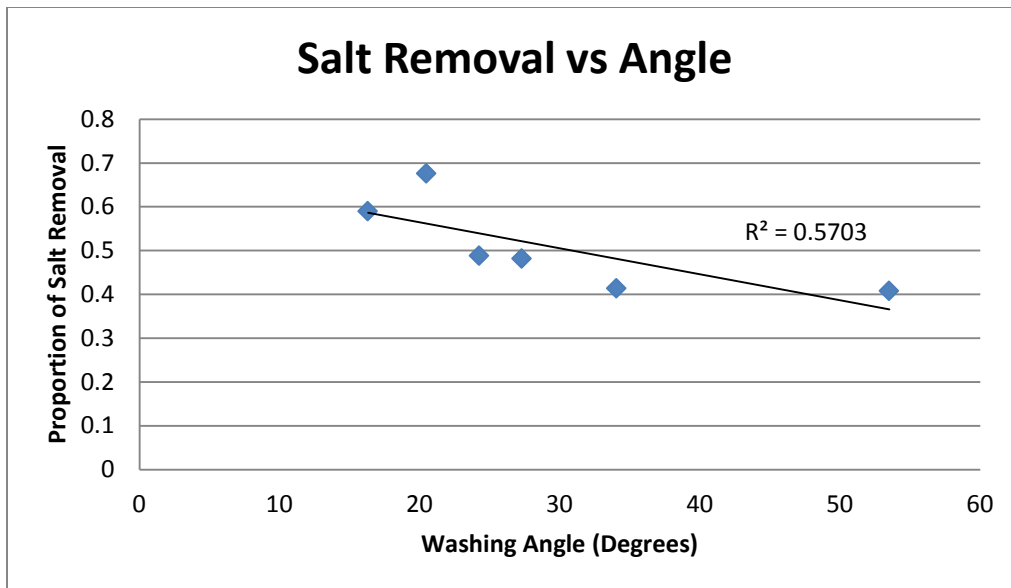
Figure 30: 40th St. Bridge, Test A: Salt Removal Versus Washing Angle

It appears that there is a slight correlation in that the shallower the washing angle the more effective the washing is at removing soluble salts. This goes against what was observed in the previous site visits when a very shallow washing angle caused a decrease in washing effectiveness. The trend is not very strong and is not statistically significant at a 95 percent confidence level, with an R^2 of 0.57 and a P value of 0.082. As previously stated, the prewash salt levels were relatively low which may have made it difficult to identify a significant trend. It could also be that the washing effectiveness could decrease at angles smaller than 16 percent, the smallest angle washed as part of this experiment. An evaluation of this would be best performed in a controlled setting where the salt concentration across all target locations prior to washing was held constant. It does show that these factors are not important when salt concentrations are small.

4.2.2. The Effect of Elevation Change on Bridge Washing Effectiveness

The purpose of test B was to determine how a difference in elevation between the nozzle of the pressure washer, and the target area changed the effectiveness of bridge washing. Pre-washing measurements were taken on the second, third and fourth vertical member (from south to north) in the middle span of the bridge. The first vertical member on the span was not used because any members near joints would most likely contain a

higher prewash soluble salt concentration. The vertical members were all tested where the ornamental arch intersected the member to ensure that the tests were performed at a constant distance below the deck. The prewash surface salt concentrations at these locations were also relatively small, below 20 mg/m^2 (29x10^{-3} grains/ft^2), as shown in Table 15. The height of the nozzle of the pressure washer during cleaning was 1.5 m (4.9 feet) below the target area, which was at the intersection between the ornament and the arch, for the third vertical member. It was 3 m (9.8 feet) below the target area for the fourth vertical member on the span and 4.5 m (14.8 feet) below for the second vertical member. The contractor then washed the beams with the nozzle of the pressure washer approximately 1.5 m (4.9 feet) away from the vertical member in the horizontal direction. The pressure was maintained at a constant 10 MPa (1500 psi) for the duration of the cleaning. The setup is shown below in Figure 31.
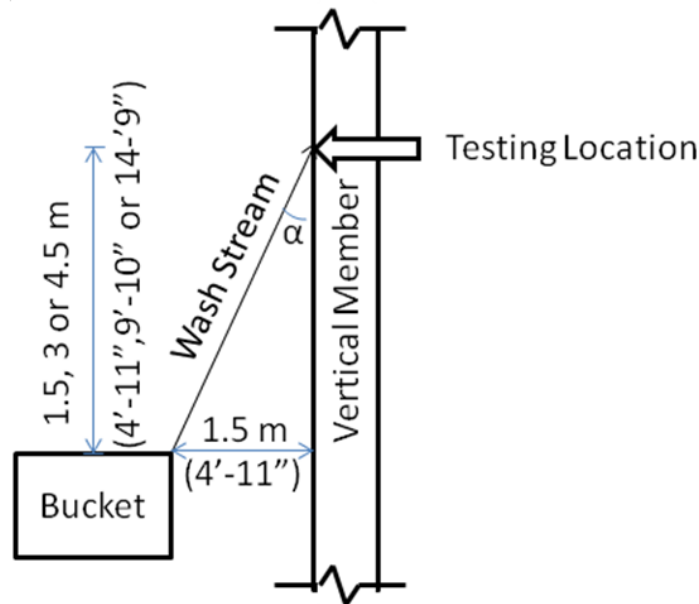

Figure 31: 40th St Bridge, Test B: Side View of Sampling Locations

The postwash surface salt concentrations at these three locations were not significantly reduced due to washing, as can be seen in Table 16.

Table 16: 40th St. Bridge, Test B: Salt Removal versus Washer Elevation

Test B Salt Removal					
Elevation Difference, m (ft)	Wash Angle (degrees)	Wash Distance, m (ft)	Pre-wash SSC, mg/m^2 (x10^{-3} grains/ft^2)	Post-wash SSC, mg/m^2 (x10^{-3} grains/ft^2)	Wash Efficiency (%)
1.5 (4.9)	45	2.1 (6.9)	14 (20)	17 (24)	-20
3 (9.8)	27	3.4 (11.2)	10 (14)	15 (21)	-45
4.5 (14.8)	18	4.7 (15.4)	13 (19)	13 (18)	0

There does not appear to be any trend between the washing height/angle and the cleanining effectiveness. This could be the result of the low concentrations of salt before washing. It might with also be that when cleaning with a water pressure of 1500 psi, the distances and angles evaluted do not effect the cleaning effectiveness.

Although this study did not show a tend between the the distance (either vertical or horizontal) and angle of the power washer from the target area and cleaninging effectiveness, these results should be evaluated for a larger range of spray pressures and salt concentrations. This evaulation would be best performed in a controlled laboratory setting were the salt concentrations could be kept constant and the distance/angle of the power washer with resepct to the targe area could be controlled. This evaluation should be performed for a range of pressures comonly encountered for the power washers used in the field.

5. Conclusion

5.1. Recommendations Regarding PennDOT Procedures

There are several ways identified to improve the effectiveness of the bridge washing program based on the information gathered in the literature review, observations of PennDOT procedures and the field trials.

The CMMT and PennDOT Publication 55 are not in agreement on the frequency in which bridges are to be washed and should be changed so that they are consistent.

This study revealed that portions of steel bridges beneath leaking expansion joints contain very large concentrations of soluble salts. It is recommended that the area of a steel bridge directly beneath an expansion joint that is leaking should be washed frequently until the expansion joint can be repaired. The joint itself should also be flushed to remove any residual salts, which are typically accumulating in the joint and could be reintroduced to the steel structure during rain events.

The current PennDOT specifications (CMMT and Publication 55) do not require horizontal members extending above the roadway to be cleaned. However, it was found that the members that are close to the roadway (6.5 m or 21.5 feet) contain some of the highest salt concentrations observed in this study. I appears that washing overhead members extending above a roadway, within 7 m (23 feet) of the roadway surface would be beneficial.

Locations in the vicinity of connections exhibited high salt concentrations and washing of these areas would appear to be beneficial.

Washing with the specified pressure is ineffective in cleaning areas with a failed coating that are exhibiting corrosion.

There are also some changes that can be made from a procedural standpoint. From the observation of PennDOT procedures and the field trials it appears that pressurized water between 12 and 16 MPa (1750-2000 psi) is capable of removing a large portion of the soluble salts. Therefore, exploring the use of chemicals is not recommended.

It was also found that the pressure supplied by the compressor is critical for effectively removing soluble salts. The contractor crews were able to remove salts using the pressure of 10 MPa (1500 psi), which is actually below the range set forth in the

specification. However, when bridges are washed with a pressure washer that operated at a much lower pressure, salt removal will not be effective. A pressure gage should be installed on the compressor whenever possible and checked to ensure that the washing occurs at the specified pressure range.

Washing efficiency could be compromised if the elevation of the washing nozzle is even 1.5 m below the targeted washing area. If at all possible, bridge members should be washed with the nozzle that is even or above the area to be washed. It was also observed that very shallow washing angles may diminish the efficiency of the washing. However, the field trials showed that, at least on areas with low surface salt concentrations, the washing efficiency actually increased as the angle got shallower up to the shallowest angle tested of 16 degrees. More testing is needed to determine the effect of washing angles on the washing efficiency.

5.2. Further Research

This study revealed several areas where further investigation would be beneficial. A challenge with this study was that it was very difficult to control all of the variables. The initial salt concentration, roughness of the surface, inconsistencies in time spent washing each area and difficulties in accessing bridges and certain bridge areas made it difficult to control all possible variables. It was also difficult to get a robust data set in the field trials without bringing the washing operations to a standstill. These variables could be isolated with a laboratory study using steel sections with uniform coatings sprayed with a salt brine in a manner such that a uniform surface salt concentration can be achieved. Washing could then be performed in a systematic manner such that the effects of the wash angle, water pressure, distance between the target area and the washer nozzle and wash time could be accurately evaluated.

As discussed in the literature review, there is no reliable information regarding the effect of different salt concentrations on the exterior of a coating on the failure of the coating, or corrosion of the member. Currently WSDOT and the University of Washington are conducting a study on the effect of bridge washing on the longevity of bridges based primarily on the field data. There have also been extensive laboratory studies on how soluble salts introduced to a steel surface before coating affect the life of

the coating. A laboratory study on the effect of salt introduced on the outside of the coating on the longevity of the coating would provide further insight on the levels of surface salt concentration that are acceptable, and what is the effect of bridge washing on the longevity of bridge members and their coatings.

Finally, it is unknown how quickly the surface salt concentration on bridges increases after washing. Even though bridge washing can effectively reduce the surface salt concentration on a steel member, if the salt concentration return to the pre-wash level the next time deicing salts are applied to the bridge, life cycle benefits of bridge washing may be minimal. By monitoring the surface salt concentration on a member throughout the year for several years, further information on the effectiveness of the washing cycle could be gained.

To summarize, the following additional follow-up work would be beneficial for the PennDOT bridge maintenance program:

1. Monitor the increase in salt concentration throughout the year for several years for selected bridges washed in 2013 to establish criteria on timing and frequency of washing that would maximize life cycle benefits for these bridges. This could be performed in areas where traffic control would not be needed.

2. Perform a laboratory-scale study under relevant process and operating conditions to: (a) quantify the effect of salt concentration on the longevity and effectiveness of surface coating and (b) assess methods for effectively cleaning bridge regions were the coating has been compromised and the use of water alone was ineffective in removing surface salts.

6. References

Ann, K. Y., & Song, H. (2007). Chloride threshold level for corrosion of steel in concrete. *Corrosion Science*, *49*, 4113-4133.

Appleman, B.R. (2002). Advances in technology and standards for mitigating the effects of soluble salts. *JPCL*, *May*, 42-47.

Appleman, B. R., Weaver, R. E. F., & Bruno, J. A. U.S. Department of Transportation, Federal Highway Administration. (1995). *Maintenance coating of weathering steel: Field evaluations and guidelines* (FHWA-RD-92-055). Pittsburgh, PA: Steel Structures Painting Council.

Bayliss, D.A., and K.A. Chandler. (1991) *Steel Work Corrosion Control*. Essex, England: Elsevier Science Publishers Ltd.

Bhattacharjee, B., & Pradhan, B. (2011). Rebar corrosion in chloride environment. *Construction and Building Materials*, *25*(5), 2565.

Bowers, M. C. and Hesterberg, J. H., 1976, Environmental implications of highway agents on white pine in Marquette County, Michigan, *Michigan botanist* 15(2), pp. 75–89.

Broomfield, J. (2007). *Corrosion of steel in concrete*. (2nd ed.). New York: Taylor and Francis.

Chlor*rid announces soluble salt remover is 100% green. (2009, November 16). *Health & medicine week*, 3161.

Corbett, W. D. (Presentor) (2010, November 10). Methods for the detection of soluble salts. *SSPC-JPCL Education Series*. [Webinar]. Retrieved from http://www.paintsquare.com/webinars/?fuseaction=archive&action=view&webinarID=28

Corus, (2005). *Corrosion protection of steel bridges*. North Lincolnshire, England: Orchard Corporate Ltd.

de la Fuente, D., Chico, B., & Morcillo, M. (2005). The effects of soluble salts at the metal/paint interface: Advances in knowledge. (2006).*Portugaliae Electrochimica Acta*, *24*, 191-206.

Environmental Protection Agency Water quality Research, 1971, Environmental Impact of Highway Deicing, *Water Pollution Control Research Series*, 11040 GKK 06/71.

Environmental Protection Agency (EPA). 2007. Aquatic life ambient freshwater quality criteria - copper. EPA-822-R-07-001, U.S. Environmental Protection Agency, Washington, D.C.

Etenadi, M. (2013, April 10). Interview by K.D. Alland [Personal Interview]. Discussion of IDOT District 2 bridge washing procedures.

Frenzel, L. National Shipbuilding Research Council, Surface Preperation and Coatings Panel. (2011). *Study to determine the level of salt mitigation as related to the accuracy of the measurement and cost benefits* (2010-385). Charleston, SC: Advanced Technology Institute.

Hara, S., Masazumi, M., Uchiumi, Y., Fujiwara, T., & Yamamo, M. (2005). Suppression of deicing salt corrosion of weathering steel bridges by washing.*Corrosion Science*, *47*, 2419-2430.

Hong, K., & Hooten, R. D. (2000). Effect of freshwater on chloride contaminated concrete. *Cement and Concrete Research*, *30*, 1199-1207.

Hoffman, G. Pennsylvania Department of Transportation, Pennsylvania Department of Natural Resources. (1994). *Bridge washing.*

Hopwood, T.II, Palle, S., Younce, R., 2003, Environmental impacts of bridge cleaning operations, Research Report, KTC-03-03/SPR 224-01-1F.

Hunkeler, F. Technical Research and Consulting on Cement and Concrete, (2005). *Corrosion in reinforced concrete: Proccesses and mechanisms*. Switzerland: TFB.

Hunt, H., Gidley, J., 1990, The toxicities of selected bridge painting materials and guidelines for bridge painting projects, Division of New Technology, Materials and Research, California DOT.

Illinois Department of Transportation, (2012). *Standard specification for bridge and road construction*

Johnson, et al. (1997) *U.S. patent number 5,609,692.* Washington D.C. US Trademarks and Patent Office.

Jones, P. H. and Jeffrey, B. A., 1992, Environmental impact of road salting, Chemical Deicers and the Environment, pp. 1–97.

Katayama, T., Tagami, M., Sarai, Y., Izumi, S., & Hira, T. (2004). Alkali-aggregate reaction under the influence of deicing salts in the Hokuriku District, Japan. *Material Charicterization*, *53*, 105-122.

Kavanah, B., & Garwood, P. Maine Department of Transportation, Maine Local Roads Center. (2011).*Bridge cleaning and washing best management practices*

Keenan, C. (2013, April 9). Interview by K.D. Alland. Discussion of WSDOT bridge washing program.

Kirkpatrick, P. J., Weyers, R. E., Anderson-Cooke, C. M., & Sprinkel, M. M. (2002). Probabilistic model for the chloride-induced corrosion service life of bridge decks. *Cement and Concrete Research*, *32*, 1943-1960.

Mayne, J. E. O. (1959). The problem with painting rusty steel.*9*, 673-680 inc.

Minnesota Auditor General, (1996). *Preventative maintenance*. St. Paul, MN: Retrieved from: http://www.auditor.leg.state.mn.us/ped/pedrep/9706-ch4.pdf

Myhr, G. (2013, April 12). Interview by X. Ma [Personal Interview]. Discussion on environmental impacts and regulations of bridge washing in Washington.

Nace Resource Center. (2010). Retrieved from http://events.nace.org/library/corrosion/AtmCorros/mapNA.asp

Nanayakkara, O., & Kato, Y. (2009). Macro-cell corrosion in reinforcement of concrete under non-homogenous chloride exposere. *Journal of Advanced Concrete Technology*, *7*(1), 31-40.

National Climactic Data Center. (2008, August 18).*Average relative humidity*. Retrieved from http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgrh.html

New York State Department of Transportation, Engineering Instruction. (2007). *Maintenance cleaning and washing of bridges-us customary* (EI-07-032)

Niogi, S; Wood, C.M., 2004, Biotic Ligand Model, a Flexible Tool for Developing Sit-Specific Water Quality Guidelines for Metals. Environmental Science and Technology 38 (23): 6177–6192.

Organisation for Economic Co-operation and Development, (1981). *Bridge maintenance*. Paris: Entreiten Des Ouvarages D'art.

Palle, S., Youce, R., & Hopwood, T. (2003).*Investigation of salts on kentucky bridges*. Informally published manuscript, Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky.

Palaniswamy, N., Rajagopal, K., & Vedalakshmi, R. (2008). Longterm corrosion performance of rebar embedded in blended cement concrete in macro cell corrosion condition. *Construction and Building Materials*, *22*(3), 186.

Parks, R. (2013, February 3). Interview by K. Alland [Personal Interview]. Phone call regarding soluble salt meter.

Paquin, P.R.; Gorsuch, J.W., Apte, S., Batley, G.E., Bowles, K.C., Campbell, P.G.C., 14. Delos, C.G., Di Toro, D.M., Dwyer, R.L., Galvez, F., Gensemer, R.W., Goss, G.G., Hogstrand, C., Janssen, C.R., McGeer, J.C., Naddy, R.B., Playle, R.C., Santore, R.C., Schneider, U., Stubblefield, W.A., Wood, C.M., Wu, K.B., 2002. The biotic ligand model: a historical overview. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology. 133 (1-2): 3–35.

Paullson-Tralla, J. (2001). Service life prediction of concrete bridge decks repaired with bonded concrete overlays.*Materials and Structures*, *34*(1), 34-41.

Pennsylvania Code, Chapter 93. Water quality standards, http://www.pacode.com/secure/data/025/chapter93/chap93toc.html (accessed on 2/10/2013).

Pennsylvania Department of Environmental Protection, 2013, http://www.dep.state.pa.us/dep/deputate/waterops/redesign/subpages/npdes.htm (accessed on 2/10/2013).

Pennsylvania Department of Environmental Protection, 2013, GP-11 Maintenance, Testing, Repair, Rehabilitation, or Replacement of Water Obstructions and Encroachments 3930-PM-WM0511, http://www.dep.state.pa.us/dep/efacts/generalpermitslisting.htm (accessed on 2/12/2013)

Pennsylvania Department of Transportation, (2012). *County maintenance measuring tool.*

Pennsylvania Department of Transportation, (2010). *Bridge maintenance manual* (Publication 55) Pennsylvania Department of Transportation: Harrisburg, PA.

Radlinska, A., Yost, J., McCarthy, L., Matzke, J., & Nagel, F. (2012). *Coatings and Treatments for Beam Ends* (No. FHWA-PA-2012-002-100402).

Russel, G., & Gesinski, J. (2013, March 19). Interview by K. Alland, X. Ma, J. Vandenbossche, R. Vidic [Personal Interview]. Interview on current PennDOT bridge cleaning practices.

Salt-A-Way (2012)*Salt-A-Way.* Material Safety Data Sheet. Retrieved from http://saltawayproducts.com/MSDSPage.htm

Serada, P. J. (1959). Atmospheric Corrosion of Steel. *Ind. Eng. Chem.*, *51*(9), 79A-80A.

Silfwerbrand, J. (2007, May). *Technical demands for preventative bridge maintenance: A critical review*. Concrete structures-Stimulators of development, Dubrovnik, Croatia.

Singh, D. D. N., Yadav, S., & Saha, J. K. (2007). Role of climatic conditions on corrosion characteristics of structural steels. *Corrosion Science*, *50*, 93-110.

Soltesz, S. Oregon Department of Transportation, Research Unit. (2005). *Washing bridges to reduce chloride* (SPR304-031).

Sorenson, P. A., Kiil, S., Dam-Johansen, K., & Weinell, C. E. (2009). Anticorrosive coatings: A review. *Journal of coatings technology and research*,*6*(2), 135-176.

Strehblow, H. and Marcus, P. (2012). Pitting corrosion mechanisms. In P. Marcus (Ed.), *Corrosion Mechanism in Theory and Practice* (Third ed., pp. 349-394). Boca Raton, FL: Taylor and Francis.

Tatalaski, T. (2013, April 10). Interview by K.D. Alland [Personal Interview]. Discussion of CDOT bridge washing program and 2011 survey.

U.S. Department of Transportation, Federal Highway Administration, (2011), Bridge preservation guide: maintaining a state of good repair using cost effective investment strategies.

Valenza, J., & Scherer, G. (2007). Mechanism for salt scaling of a cementitous surface. *Materials and Structures*, *40*, 259-268.

Washington State Department of Transportation, 2010, Bridge maintenance washing and cleaning monitoring protocols.

Washington State Department of Transportation, 2009, Fact sheet for NPDES permit WA 0039039.

Weldon, D. (2009). *Failure analysis of paints and coatings*. (Revised Edition ed.). West Sussex, United Kingdom: John Wiley and Sons. DOI: www.knovel.com

Weykamp, P. (2013, April 10). Interview by K.D. Alland [Personal Interview]. Discussion of NYSDOT bridge washing program.

Wolfosky, R. (2011). *Corrosion initiation of concrete bridge elements exposed to de-icing salts*. (Master's thesis, McGill University, Montreal, Quebec).