Evaluation of Effective Bridge Deck Repair Maintenance Methods

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16. Abstract		

As there are a large number of existing aging bridges in need of maintenance, Ohio Department of Transportation is seeking safer, better, and efficient approaches for patch-repair concrete removal on bridge decks. The current practice to remove concrete is by using pneumatic breakers, which presents a danger to operators and damages to the sound concrete and rebar. Building on an extensive literature review, this study evaluates the current method and alternative methods that can address the limitations of the current method. Based on the findings, the recommendation is to use hydrodemolition robot to remove concrete, as it is time-efficient and does not create potential harm to the bridge deck or operator. In addition, hydrodemolition leaves a coarse finish cut to allow for a more effective and long lasting bond with the repair material, which is important for patch repair. Two potential robots are identified as most suitable for bridge deck concrete removal: Conjet Jetframe 101 Nalta and Conjet Robot 327. While the advantages of Conjet Jetframe 101 Nalta are easy transportability and low capital cost, Conjet Robot 327 has a higher productivity rate and has a built in debris barrier that is safer for the crew and on-going traffic. Lastly, based on the cost analysis, for project size larger than 100 SF, Conjet Robot 327 becomes a better option.

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Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

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Executive Summary

As there are a large number of existing aging bridges in need of maintenance, Ohio Department of Transportation is seeking safer, better, and efficient approaches for patch-repair concrete removal on bridge decks. The current practice to remove concrete is by using pneumatic breakers, which presents a danger to operators and damages to the sound concrete and rebar.

The objective of this study is to evaluate the current bridge deck concrete removal method and alternative methods which can address the limitations of the current method. A comprehensive literature review was conducted to synthesize exciting concrete removal methods. Historical work orders in ODOT District 11 was collected and cost analysis was conducted. Field demonstration of a recommended alternative method was arranged, observed and evaluation. It was found that:

1) Among existing concrete removal methods, blasting and peeling are not suitable approaches for patch repair since they are not able to control the cut depth; drilling should be only considered as a preliminary step for other concrete removal approaches (such as splitting and blasting). Suitable concrete removal methods for bridge deck repair include jackhammering, hydrodemolition, sawing, and splitting.
2) hydrodemolition is time-efficient and does not create potential harm to the bridge deck or operator; In addition, hydrodemolition leaves a coarse finish cut to allow for a more effective and long lasting bond with the repair material, which is important for patch repair. Therefore, hydrodemolition is recommended as the most effective and efficient concrete removal method for bridge deck repair.
3) Two potential robots are identified as most suitable for bridge deck concrete removal: Conjet Jetframe 101 Nalta and Conjet Robot 327.
4) While Conjet Jetframe 101 Nalta has advantages of easy transportability and low capital cost, Conjet Robot 327 has a better productivity rate and has a built-in debris barrier that is safer for the crew and on-going traffic. Lastly, based on the cost analysis, for project size larger than 100 SF, Conjet Robot 327 becomes a better option.

1. Background and Motivation

To ensure or extend the service life of bridges, Ohio Departments of Transportation (ODOT) is constantly seeking efficient maintenance/repair strategies for aging bridges. In particular, the bridge deck is a critical component for the bridge operational safety, and it experiences the most deterioration over time compared to other bridge components. The deterioration of bridge decks can be caused by various factors, such as corrosion of reinforcement, freeze and thaw cycles, chemical or biological attacks, poor construction quality, and accidents, resulting in poor skid resistance, poor ride quality, inadequate drainage, and even deteriorating structural reliability. As bridges are a vital part of the traffic network, bridge deck repairs that require closure or partial closure to traffic can cause major issues for the traveling public and increase congestion on other routes. Therefore, while ensuring the quality of the bridge deck repair and the safety of the work crew and public, it is critical to reduce negative impacts to traffic by reducing the time needed to perform repairs.

When deck surface area is found to be unsound, patch repair is usually applied, particularly in cases where removal of the entire deck and replacement is not economical. Untreated patches can grow larger and cause the roads and highways to be unsuitable for vehicles to safely drive on. Patch repair is consistent of 1) removal of unsound concrete; 2) preparation; 3) application of repair materials, and 4) curing and finishing of repair materials. In particular, concrete removal is a critical step. The ideal concrete removal is to remove only the unsound concrete without creating any disturbance/damages to the sounded concrete and rebar, also creating a finish cut that will bond well with the repair material. With the numerous amount of patch repairs need to be conducted around the state every year, it is imperative to implement a concrete removal process that can ensure the quality but also is time and cost efficient.

The ODOT District 11 (New Philadelphia) has maintenance responsibility for over five million square feet of bridge decks for approximately 950 bridges. The current method used to remove concrete for patch repair is pneumatic breaking, also known as jackhammering. Jackhammer is a pneumatic tool that combines a hammer directly with a chisel, powered by electric motors or compressed air. While the jackhammering is portable, economic, and easy to use, there are many disadvantages. This practice not only effects the laborers, it also negatively impacts the bridge. The vibration caused by the jackhammer weakens the sounded concrete and potentially damages the rebar, causing more cracks and holes to form around the newly fixed patch. The hammer blow with the explosive air exhaust makes jackhammering dangerously loud. The long exposure to jackhammering can lead to a few different bodily injuries including carpal tunnel syndrome and hand-arm vibration syndrome from the constant vibration of the jackhammer. The amount of dust produced from this method also exposes the operators to hazardous dust that contains crystalline silica. These risks limit the length of time a laborer can operate the equipment, which lead to longer time and more laborers needed to remove the concrete. In addition, this inefficient process exposes laborers to oncoming traffic for a long period of time. Therefore, the goal of this study is to aid ODOT to identify and implement an efficient solution to bridge deck concrete removal, which will result in higher safety, operation time reduction, cost savings, an increase in life cycle between repairs, and in general, the improvement of current operations and safety of the ODOT crew and traveling public.

2. Research Objectives

This study is the Phase 1 of the project, and it mainly involves literature review, an in-depth analysis of current processes adopted by ODOT and other state DOTs, and field evaluation of the recommended solutions through demonstration.

The specific objectives for Phase 1 are to:

1. Evaluate the current method that ODOT District 11 uses for bridge deck repair.
2. Conduct an extensive literature review to develop an understanding of existing strategies for bridge deck repair.
3. Perform an analysis on current products and technologies available for bridge deck repair.
4. Create charts and graphs to identify method most suitable for patch repair. Considering the safety, cost benefit and efficiency of to remove concrete.
5. Recommend the most suitable approach for concrete removal to ODOT for a Phase 2 study.

3. Literature review

In this study, several methods are taken into consideration for the removal of concrete from bridge decks. The most common methods to remove concrete are breaking, hydrodemolition, sawing, drilling, splitting, blasting, and peeling.

3.1 Concrete Removal Methods

Breaking/ Jackhammering

Breaking is the commonly known method of jackhammering. Sometimes using a machine is mounted on jackhammer to break concrete. This pneumatic method breaks the concrete into smaller pieces that can then be removed by a shovel or other construction equipment. Jackhammering creates loud vibration and also emits a substantial amount of dust around the jobsite.

The benefits of jackhammering are the ease of being able to use this method on any size of project, the short setup time, and the low capital cost of the equipment. However, this method has detrimental impact on the deck and also the operators. In particular, during jackhammering the bridge deck undergoes high compressive stress on both the sound and unsound concrete. The damage on the sound concrete can cause future failure around the patch undergoing repair. The vibration of the jackhammer causes bodily injuries including carpal tunnel syndrome and hand-arm vibration syndrome.

Hydrodemolition

Hydrodemolition is a method that breaks concrete by using water at a high pressure. This method can be used both with a hand-held lance or a hydrodemolition robot. The hydrodemolition equipment is connected to a high pressure pump that regulates the pressure of the water that is being provided to the equipment. The pressure that is needed to cut is dependent upon the concrete strength. The flow rate of the water can be controlled by the size of the nozzle head and the pressure of the water. The production rate (i.e., the speed of the removal) depends on the flow rate of the water: the higher the flow rate the faster the cut.

One of the major benefits of hydrodemolition is that it only cuts the unsound concrete, leaving the sound concrete undamaged. This allows for a better bond with the new patch material for the repair and protects rebar from undergoing any damage. In addition, hydrodemolition produces no dust or vibration. Best of all, using hydrodemolition robot does not cause physical harm to the operators. Some of the disadvantages are the set up time for the robot and debris control, the amount of ancillary equipment needed on the jobsite (e.g., water tank, pressure pump, vac truck), the high initial capital cost for the equipment, treatment of the waste water, and special trained operators.

Sawing

Sawing is the technique of saw cutting the bridge deck into sections and removing those sections with an overhead crane or different type of vertical lift. There are two types of saws: the diamond blade saw and the diamond wire saw. The diamond blade saw can either be used for dry- or wet-cutting. This saw has segmented blades which produces smooth and fast cutting speeds and provides a long blade life. The diamond wire saw is made out of steel beads with electroplated diamonds that. They are typically mounted on a drive wheel, which can slide to maintain tension in the wire by using either hydraulic or electric power.

Sawing is a method that is a quick way to remove concrete at any angle with minimal vibration. If wet-cutting is used it can reduce the amount of dust and noise and can also avoid the equipment overheating. Other factors that determine the cutting speed and blade life are the hardness of the concrete and the amount of reinforcement. One of the downsides of sawing is the cost to replace the blades [1].

Splitting

Splitting is a method that uses tension on a pre-existing path within the concrete to rupture the concrete it in a controlled way. There are two primary types of splitting, mechanical splitting and chemical splitting. Mechanical splitting is the process of inserting a mechanical splitter in a predrilled hole. Mechanical splitters are typically hand-held tools that are hydraulically powered. When the piston is pressurized, it pushes the wedge forward and applies forces on the feathers which then push against the sides of the hole causing the concrete to rupture [1]. Chemical splitting uses expansive chemical agents to create pressure in holes. The main chemical used for this splitting is calcium oxide, which expands to roughly three times its original volume when mixed with water [1]. Mechanical and chemical splitting are both beneficial due to the minimal amount of noise and vibration needed to break the concrete. However, the downside to this method is the inability to control the depth of the cut.

Drilling

Drilling is commonly used to prepare a bridge deck for concrete removal. It is not typically used to remove large amounts of concrete. Drilling is the process of creating voids where splitting or blasting agents may be placed. Drilling can be used to establish cutting directions or to weaken a component. The process drilling is quiet, inexpensive and produces little vibration and dust. However, drill bits may cause damage to the rebar or blowout the bottom of the deck if not used carefully [1].

Blasting

Blasting is the method of using explosives inside of holes to fracture the concrete in a controlled setting. This method has been used in bridge demolition with its rapid ability to remove concrete. This method is more suitable for removing an entire bridge than for patch repair work [1].

Peeling

Peeling is a method that applies a vertical force on the concrete to break it free from the bridge girder. This is a newer technique to remove concrete. An excavator is used along with a slab crab and a machine mounted bucket. This is a quick process; however, it causes substantial vibration, noise and dust. There is also no way of controlling the desired depth of the cut [1].

3.2 Comparisons and Recommendation

Apparently, while drilling should be considered as a preliminary step for other concrete removal approaches (such as splitting and blasting), the last two approaches described above (i.e., blasting and peeling) are not suitable approaches for patch repair since they are not able to control the cut depth. Therefore, it is worth to compare the other four approaches (i.e., jackhammers, hydrodemolition, sawing, and splitting) in terms of suitableness for concrete removal in patch repair. Table 1 provides a comparison of the potential four approaches, concerning the quality control to the patch repair, and possible damages to the operators. As shown in Table 1, using hydrodemolish robot has the least damages to the sound concrete and rebar, creates good bonding surface for the patch repair, and causes no body harm to the operators. Therefore, we recommend using hydrodemolition robot for the patch-repair concrete removal.

Table 1. Comparison of Concrete Removal Methods

	Jackhammers	Hydrodemolition		Sawing	Splitting
		Hand held water-jet	Hydro-demolition Robot		
Creates microcracks	***Yes***	***No***	***No***	***Yes***	***No***
Keeps rebar intact	***No***	***Yes***	***Yes***	***No***	***No***
Reaches under rebar	***Yes***	***Yes***	***Yes***	***No***	***Yes***
Pre-set depth	***No***	***No***	***Yes***	***No***	***Yes***
Good bonding surface	***No***	***Yes***	***Yes***	***No***	***No***
Requires periodical rest	***Yes***	***Yes***	***No***	***Yes***	***Yes***
High risk of injury	***Yes***	***Yes***	***No***	***Yes***	***Yes***

4. Evaluation of Hydrodemolition

A review of the hydrodemolition technique led to the discovery of numerous manufacturers that provide the robots for this method. The hydrodemolition manufacturers that have been investigated in this study are Conjet, Aquajet, NLB and Stone Age.

4.1 Manufacturers

Stone Age

Stone Age is a Colorado based company that was founded in 1979. They originally developed for the mining industry, but have since reached a multitude of industries including hydrodemolition. Stone Age currently has one robot used for hydrodemolition, the Blackhawk BHK-100.

Blackhawk BHK-100

The Blackhawk BHK-100 shown in Figure 1, is a small sized robot. The robot is 5 feet 7 inches tall 7 feet 4 inched long and has a cutting width of 4 feet. The robot can handle a flow rate up to 50 gpm and a pressure of 22,000 psi [2]. The Blackhawk is not a self-operated machine; it needs to be connected to a skid steer to function properly.

Figure 1. Blackhawk BHK-100 [2]

NLBCorp.

NLB Corp is a Michigan based company that was founded out of a garage in 1971. They have become known across the world as a leader in water jet productivity [3]. NLB provides services for product removal, surface preparation, pavement marking and rubber removal, tube and pipe cleaning, tank cleaning, tube bundle cleaning, concrete hydrodemolition, and pipe cutting. NLB only has one hydrodemolition robot, 6600-2 Concrete Buster.

6600-2 Concrete Buster

The 6600-2 Concrete Buster, shown in Figure 2, is a large sized robot. This robot is 7 feet 6 inches tall and 14 feet 8 inches long. The cutting width of this robot was not disclosed. The concrete buster can handle flow up to 60 gpm and pressure up to 20,000 psi. The system is powered by a 32 HP John Deere diesel engine [3].

Figure 2. 6600-2 Concrete Buster [3]

Aquajet

Aquajet is a Swedish based company that began in 1988 after forming from a hydrodemolition contracting company [4]. Aquajet provides cutting edge hydrodemolition robots that are able to work on every size of project. In this research there are two robots that are looked into. The robots are described as follow:

Cutter 410A

The cutter 410A robot shown in Figure 3 (left), is one of Aquajets medium sized robots. The robot is 3 feet 5 inches tall, 6 feet 9 inches long and has a cutting width of 4 feet 9 inches. Data is not provided for the flow rate and pressure limits for the robot. The robot is electrically powered by a generator; however, generator specifications are not provided.

Cutter 410V

The cutter 410V robot shown in Figure 3 (right), is one of Aquajets large sized robots. The robot is 3 feet 2 inches tall, 7 feet 4 inches long and has a cutting width of 4 feet 9 inches. Data is not provided for the flow rate and pressure limits for the robot. The robot is electrically powered by a generator; however, generator specifications are not provided neither.

Figure 3. (left) Cutter 410A [4]; (right) Cutter 410V [5]

Conjet

Conjet is a Swedish based company that began in 1983 to provide a new method to cut out concrete on bridge decks Conjet provides a wide range of robots that can do a vast majority of projects from large overlays to patch repairs and everything in between. There are three robots that are focused on in this research. The robots are described as follow:

Jetframe 101 Nalta:

The Jetframe 101 Nalta, shown in Figure 4(a), is Conjet's most compact robot. The frames area can be adjusted to be different lengths or widths depending on the size of the hole needing to be cut. The height is also adjustable. The cutting width is adjustable by driving the robot on connected sections that are 3 feet 3 inches wide. The Jetframe weighs a total of 245 pounds. The flow can handle up to 37 gallons per minute (gpm) and pressure of 22,000 pounds per square inch (psi), although it is typically used at a rate of 13-17 gpm and pressure of 15,000-20,000 psi. This robot is powered by a hydraulic unit that comes with the included. The hydraulic unit is electrically powered by a generator that provides 240 volts in single phase and 480 volts in 3 phase or a 6,500 watt generator can also work for the Jetframe [9]. The Jetframe can work both vertically or horizontally. Note that Figure 4(a) shows a vertical configuration. For bridge deck concrete removal, a horizontal configuration is desired and can be easily achieved by adjusting the frame on site.

Robot 327

The Robot 327, shown in Figure 4(b), is Conjet's medium sized robot. The robot is 3 feet 10 inches tall, 7 feet 8 ½ inches long, and the cutting width is 5 feet 5 inches. The robot weighs a total of 2,293 pounds. The flow can handle up to 69 gpm with pressure up to 34,900 psi. The robot is typically used at a rate of 20-30gpm with a pressure of 15,000-20,000 psi. The robot is powered by an electrical generator that provides 3 phase 380-480 volts, 16 Amp, 50-60 hertz or 3 phase 200 volt, 32 amp, 50-60 hertz [7].

Robot 557

The Robot 557, shown in Figure 4(c), is one of Conjet's largest robots. The robot is 5 feet 3 inches tall, 11 feet 2 inches long and has a cutting width of 6 feet 11 inches. The robot weighs a total of 5,500 pounds. The flow can handle up to 72 gpm with a pressure up to 37,900 psi. The robot is diesel engine powered so it does not need a generator (6).

(a) (b) (c)

Figure 4. (a) Jetframe 101 Nalta [6], (b) Robot 327 [7], (c) Robot 557 [8]

4.2 Comparison and Recommendation

Table 2 shows a comparison of the robots mentioned above, in terms of size, pressure capability, robot price, and performances. The Stone Age only robot, the Blackhawk BHK-100, is a cost affordable robot and is suitable for small and medium sized projects, such as patch repair. However, it is not recommended to ODOT, as it needs to be connected to a skid steer in order to operate. This may cause the potential of longer cut durations due to the time it will take to verify the robot is cutting to the desired depth, as it is controlled by the skid steer not a remote. The potential low efficiency is the major concern for this robot. The only robot from NLB, the 6600-2 Concrete Buster, is also not recommended to ODOT because of its size and cost. This is a large robot that is more suitable for medium and large sized projects. In addition, the Concrete Buster is very expensive and needs a large expensive pump to operate.

Aquajet is a manufacturer that has state of the art robots that can efficiently cut all project sizes. This manufacturer is not recommended solely because of the price. Aquajet robots are much more expensive in comparison to the other manufacturers. On the other hand, Conjet has many different robots suitable for a wide range of sizes of projects, including patch repair. Based on this comparison, Conjet is recommended for further study based on the price, efficiency, and the vast selection of robots. As shown in Table 2, Conjet has affordable robots that reach as low as $45,000. They are all remote operated to control to ensure the efficiency of the cut. With the numerous amount of robots that Conjet provides, this study further investigates three robots: Robot 327, Jetframe 101 Nalta, and Robot 557.

Table 2. Comparison of Hydrodemolition Robots

Manufacturer	Model	Size	Pressure Range	Robot Price	Performance
Conjet	Robot 327	Height: 3’10” Length: 7’8.5” Cutting Width: 5’5”	Flow: Up to 69gpm Pressure: up to 34,900psi	$112,000	Vertical or horizontal
	Robot 557	Height: 5’3” Length: 11’2” Cutting Width: 6’11”	Flow: Up to 73gpm Pressure: up to 37,900psi	$200,000	Vertical or horizontal Further reach than 327
	Jetframe 101 Nalta	Height: Adjustable Length: 3’3” Cutting Width: Adjustable	Flow: Up to 37gpm Pressure: up to 22,000psi	$45,000	Vertical or horizontal It is suitable for patch-repair
Acuajet	Cutter 410A	Height: 3’5” Length: 6’9” Cutting Width: 4’9”	Flow: Up to N/A Pressure: up to N/A	$165,000	Good for patch-repair or large project
	Cutter 410V	Height: 3’2” Length: 7’4” Cutting Width: 4’9”	Flow: Up to N/A Pressure: up to N/A	N/A	Good for patch-repair or large project
NLB	6600-2 Concrete Buster	Height: 7’6” Length: 14’8” Cutting Width: ?	Flow: Up to 50gpm Pressure: up to 22,000psi	$250,000	Suitable for medium size project
Stone Age	Blackhawk BHK-100	Height: 5’7” Length: 7’4” Cutting Width: 4’	Flow: Up to 50gpm Pressure: up to 22,000psi	$75,000	Suitable for medium size project, and needs to be operated with a Bob Cat

4.3 Data Collection and Cost Analysis

Once Conjet is selected as the manufacturer of choice for this research, an extensive study of the three robots is conducted. The performance characteristics used to select the best robot are: the overall concrete removal cost (including needed equipment and labor), the efficiency of concrete removal, the safety, and the easiness of the operation. These criteria are also used to compare with the current practice of jackhammering.

To understand the labor and equipment cost of using jackhammering, first, we compile the past two years (2016 and 2017) work orders of the patch repair projects from ODOT District 11, as shown in Table 3. The last row of Table 3 provides the average project size, average project duration, and average equipment and labor cost for the current practice of jackhammering. This data reveals that the average project size is 247.6 Square Feet (SF) which takes an average of 12 laborers working 5.7 days, and the average project cost $15,532.67. In terms of project size, Figure 5 shows the histogram of area size of the project, indicating that 16 out of the 23 projects (nearly 70%) are under 250 SF. Please note that these work orders include the time for both the removal of concrete and the repair of the exposed patch. The time to solely remove concrete by the method of jackhammering cannot be directly extracted from the work order data. While ODOT owns all the equipment in the projects, the cost of equipment reflects the cost of wear and tear.

Table 3. Summary of ODOT District 11 Patch-repair Work Order

Project Number	Size of Project (SF)	Work days (days)	Total Equipment Hours	Cost of Equipment	Number of Laborers	Total Labor Hours	Cost of Labor	Total Cost
1	3	1	30	$556.38	4	31	$1,739.69	$2,296.07
2	0	9	132	$1,448.77	11	187.3	$12,351.88	$13,800.65
3	886	10	232.5	$2,345.77	14	364.5	$23,221.75	$25,567.52
4	94	5	103	$1,406.16	12	161	$8,465.27	$9,871.43
5	426	8	148	$2,085.50	18	217	$12,911.88	$14,997.38
6	81	5	105	$2,250.09	12	172.5	$10,210.80	$12,460.89
7	881	3	40	$524.18	6	95.5	$5,149.86	$5,674.04
8	168	7	91	$5,339.26	21	189	$9,825.26	$15,164.52
9	400	4	88	$2,318.21	10	170.5	$9,803.55	$12,121.76
10	567	8	242	$4,135.37	10	339.9	$19,223.97	$23,359.34
11	215	5	129.5	$2,506.98	9	222.7	$12,714.50	$15,221.48
12	109	2	48	$1,084.43	4	46.7	$2,204.53	$3,288.96
13	418	9	249	$2,614.46	20	254.6	$20,773.73	$23,388.19
14	162	5	134	$1,475.44	12	126.5	$6,792.36	$8,267.80
15	17.89	6	136	$1,160.88	9	196.5	$11,179.32	$12,340.20
16	45.8	7	243.5	$2,714.73	22	205	$20,638.66	$23,353.39
17	230.88	12	995	$8,509.46	16	746.9	$44,315.08	$52,824.54
18	21.4	2	106	$979.70	9	106.3	$5,374.46	$6,354.16
19	518.02	2	105	$956.56	10	143	$5,789.77	$6,746.33
20	95	2	160	$1,410.95	11	142	$7,237.81	$8,648.76
21	55.8	11	672	$7,393.85	22	513	$28,847.75	$36,241.60
22	8	1	59	$448.74	9	67	$3,606.76	$4,055.50
23	44.44	7	505.5	$3,958.32	11	286.6	$17,248.51	$21,206.83
Average	**247.60**	**5.70**	**206.70**	**$2,505.40**	**12**	**216.74**	**$13,027.27**	**$15,532.67**

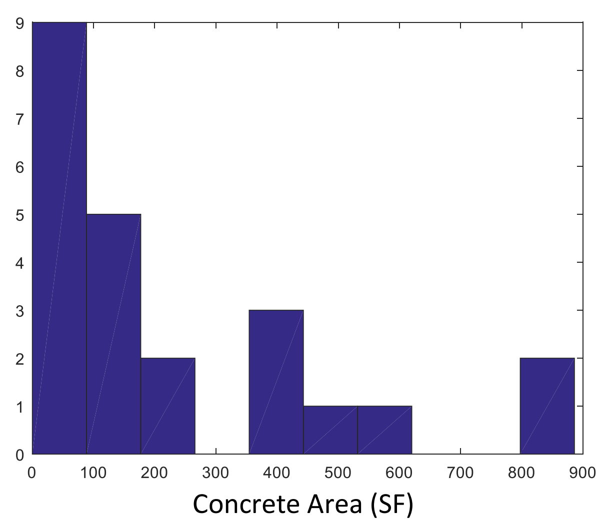

Figure 5. Project Size Histogram

Table 4 lists out the labor/equipment needed for using Jackhammering or hydrodemolition robots. The dash line in the table indicates that equipment is not needed for that corresponding removal approach. Considering the size of robots and the generator and pump that are needed, for Robot 327 and 557, one needs an 18-wheel truck and a pickup truck for the robot, pump, and generator. On the other hand, when using Jetframe Nalta, a crack truck will be able to carry these three pieces of equipment.

It is reasonable to assume that the labor unit cost should be the same regardless the removal approaches. Here the average labor unit cost obtained from Table 3, \$55.50 is used. Based on the discussion with ODOT district 11, we estimate 8 employees for concrete removal using jackhammering. For hydrodemolition, we contacted contractors and representatives that have years of experience in this field. Considering hydrodemolition operation regardless robot model only requires 2 employees [9], and the employees needed to transport equipment and potential extras, we assume a total of 5 employees needed for hydrodemolition.

The work orders obtained from ODOT district 11 is able to provide us the unit cost of the equipment. However, to obtain the unit cost for the hydrodemolition equipment is not straightforward, since the equipment unit cost (C_u) refers to the cost associated with the wear and tear and we only have the capital cost (C_C) for most of hydrodemolition equipment. In this study, we utilize the available information: the known unit cost and capital cost of the jackhammering equipment, from which we able to obtain the correlation between C_u and C_C through a relationship, $C_u = \alpha \cdot C_C$. It is found that $\alpha \approx 5\%$ when $C_C \leq \$40{,}000$; and $\alpha \approx 8\%$ when $C_C \leq \$40{,}000$. Thus using this α value, the unit cost of the hydrodemolition equipment is obtained.

Table 4. Equipment Cost per Hour

Equipment	Jackhammering	Robot 557	Robot 327	Jetframe
Labor	$55.50 x 8	$55.50 x 5	$55.50 x 5	$55.50 x 5
Skid Steer	$16.09	-	-	-
Air Compressor	$15.75	-	-	-
Dump Truck	$45.14	-	-	-
Jackhammer	$0.07	-	-	-
Utility Truck	$17.65	-	-	-
1 Ton Stake	$23.84	-	-	-
Generator	$1.27	$9.78	$9.78	$1.27
Pickup Truck	$13.40	$13.40	$13.40	-
18 wheel truck	-	$38.26	$38.26	-
Crash Truck	-	-	-	$16.88
Robot	-	$169.87	$95.13	$38.22
Pump	-	$212.34	$212.34	$135.90
Water tank	-	$2.93	$2.93	$2.93
Vac Truck	-	$117.74	$117.74	$117.74
Total labor & Equipment Cost (Per Hour):	**$577.21**	**$841.84**	**$767.10**	**$590.45**

With the unit cost described above, the concrete removal time for each removal method needs to be estimated in order to calculate the total cost. For jackinghammering, there is no firm data on the length of time it takes to remove concrete for a given size. This is because the time heavily depends on the presence of the overlay, and the soundness of the hole in need of repair. Based on the conversation with ODOT district 11 maintenance crew, to remove concrete to a 4 inch (in) desired depth it will take roughly 1 hour to remove 1.5 SF of concrete [10]. This estimation was calculated into multiple project sizes, ranging from 25-500 SF, to form a correlation between project size and removal time.

To determine the concrete removal time for hydrodemoliation, the hydrodemoliation production rate table is used. Table 5 shows the a production rate table provided National Hydro [9] for various target concrete depth, where the production rate refers to the removal speed and is estimated based on a concrete compressive strength of 4,000 psi and a flow rate of 50 gpm at a pump pressure of 20,000 psi. As the flow rate is proportional to the volume of the concrete removed per unit time, the productivity for different flow rates can be determined based on Table 5. Table 6 shows the calculated production rates when using various flow rates. To calculate the depths larger than 4 in., a trendline generated based on Table 5 is used for estimating the rates for the depths of 5 in and 6 in.

For a target removal depth of 4 in. and considering the minimum productivity rate of the hydrodemolition, Table 7 shows the removal time needed when using jackhammering or hydrodemolition at different flow rates for various sizes of the project. As shown in Table 7, the hydrodemolition removal time is much smaller than jackhammering, particularly for larger size project. For hydrodumolition, the removal time is proportional to the flow rate as expected.

Table 5. Production Rates @ 50 gpm Flow Rate Provided by National Hydro [9]

Depth	Rate (SF/hour)
0-3/4in	360-540
1in	315-450
2in	180-315
3in	135-225
4in	90-180

Table 6. Productivity Rates Calculated for Various Flow Rates

Depth (in)	Rate (SF/Hour)		
	@ 40 gpm	@ 30 gpm	@ 15 gpm
1	252-360	189-270	95-135
2	144-252	108-189	54-95
3	108-180	81-135	41-68
4	72-144	54-108	27-54
5	47-101	35-76	18-38
6	31-75	24-56	12-28

Table 7. Removal Duration

Project Size (SF)	Jackhammering (Hours)	Hydrodemolition (Hours)		
		@ 40 gpm	@ 30 gpm	@ 15 gpm
25	8.33	0.35	0.46	0.93
50	16.67	0.69	0.93	1.85
100	33.33	1.39	1.85	3.70
175	58.33	2.43	3.24	6.48
250	83.33	3.47	4.63	9.26
500	166.67	6.94	9.26	18.52

4.4 Comparison of Conjet Robots

With the unit cost (shown in Table 4) and the removal time needed (shown in Table 7) for jackhammering and three hydrodemolition robots, one can calculate the total project cost associated with concrete removal by multiplying the unit labor and equipment cost (cost per hour) and the total removal time (hours). The total costs of concrete removal for various size of projects are shown in Table 8. Note that two extra hours are added to the hydrodemolition removal time, which refers to the setup time of prepping the hydrodemolition robot (e.g., adjusting the pressure and flow rate, setting up the debris control etc.). In addition, the flow rate of 40 gpm are assumed for Robot 557 and 327, and the flow rate of 15 gpm is assumed for Jetframe 101 Nalta, based on the current practice used in the field (Steve Tomes?).

As shown in Table 8, the cost of jackhammering is much higher than any of the hydrodomolition robots. The bigger the project is, more obvious the cost effectiveness of using hydrodemolition becomes. When comparing the three Conject robots, the costs are very similar for the project size is less or equal to 100 SF; for the bigger project, using Robot 327 becomes more cost-effective. The comparison of the removal cost of using the three Conject robots is also graphically displayed in Figure 6.

Figure 6 graphically indicates that with the increase of the project size, the increase in the cost of using Jetframe is faster than the other two Robots. Since Jetframe has a lower unit cost but also low production rate, from the cost point of view, Jetframe is only suitable for smaller projects with size less than 100 SF.

Table 8. Total Cost of Removal

Project Size (SF)	Jackhammering	Hydrodemolition		
		Robot 557 (@ 40 gpm)	Robot 327 (@ 40 gpm)	Jetframe 101 Nalta (@ 15 gpm)
25	$4,810.05	$1,975.98	$1,800.55	$1,590.93
50	$9,620.10	$2,268.29	$2,066.90	$2,000.96
100	$19,240.20	$2,852.90	$2,599.61	$2,821.02
175	$33,670.34	$3,729.81	$3,398.67	$4,051.12
250	$48,100.49	$4,606.73	$4,197.73	$5,281.22
500	$96,200.98	$7,529.78	$6,861.26	$9,381.55

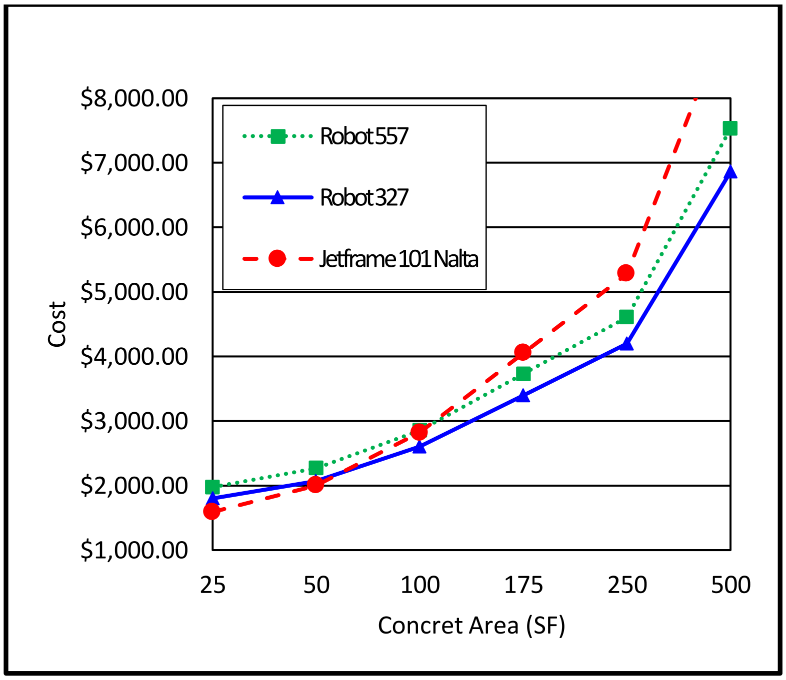

Figure 6. Total Removal Cost of Using Three Different Hydrodemolition Robots

The Jetframe is the smallest robot that Conjet offers. This robot has ability to reach flow rates of 25 gpm and above and 15 gpm, which is the flow rate often used in practice. The initial cost of this robot is the lowest among the three, which is $422,723, and is roughly two-thirds the cost of the Robot 327 and Robot 557. The Jetframe is also compact, which allows storage of the robot even in the back of a regular pickup truck. The other equipment (e.g., pump and generator) needed for the Jetframe is small as well, which allows for a small footprint on the project site.

However, safety is a concern with the Jetframe due to the fact that this robot uses an open frame, so the debris and water is not contained as it is with Robot 327 or 557. Also the flow rate used in Jetframe is about only half the value that is usually used in Robot 327 and 557m , thus the removal duration with this robot is doubled in comparison to Robot 327 and 557.

The Robot 557 is among the largest robot that Conjet offers, while the Robot 327 is Conjet a medium sized robot. For both robots, the flow is able to reach rates of up to 69 gpm (and 40 gpm is the typical value used in the field), thus the duration of the project can be shorten dramatically. For example, to remove a 4 in depth of 500 SF of concrete, the duration is just a few hours when using Robot 557 or Robot 327 with 40 gpm, compared with more than 100 hours when using jackhammering, as shown in Table 7. The amount of equipment needed for both robots is similar to the Robot 327, however; the capital price of Robot 527 causes the equipment unit cost to be higher than Robot 327. As shown in Table 8 and Figure 6, Robot 527 has a higher cost than Robot 327. As the same flow rate (i.e., 40 gpm) is typically used for both Robot 527 and Robot 327, Robot 327 coming with a smaller size and the lower removal cost is more suitable for patch-repair projects.

Due to the low cost (particular for small size project) and compact size, Jetframe 101 Nalta also has a great potential to be used in the field for patch-repair concrete removal. While the demonstration of Robot 327 has been conducted by another ODOT research project, the demonstration of Jetframe 101 Nalta is conducted in this study in order to further examine its performance.

Demonstration of Jetframe 101 Nalta

On March 26th 2018 a demonstration using the Jetframe 101 Nalta took place on a bridge near state route 36 & US 250. Structures Inc. from Colorado preformed the demonstration. The equipment used on the site included: Jetframe 101 Nalta with hydraulic unit, high pressure pump, generator, vac truck, 1,800 gallon water tank, and Plywood used for debris barrier. The robot frame was set up at 6 feet by 10 feet, as shown in Figure 7.

The jetframe flow rate was 15 gpm and the pump provided pressure of 16,000 psi. In the field we timed the length of the project from start to finish, keeping track of the setup time, the duration of each cut, transition time between cuts, and the amount of concrete removed per cut.

The setup time for the Jetframe took 1 hour. The total area removed was about 75 SF at a 5 in depth, which was took six separate cuts. The total removal time is 3 hours and 20 minutes with about 15-minutes transitions between each cut.

The first and second cut took 1 hour 48 min and removed 12 SF for each cut, the third cut took 17 minutes and removed 12 SF, the fourth cut took 11 minutes and removed 12 SF, the fifth cut took 13 minutes and removed 12 SF, and the sixth cut took 12 minutes and removed 12 SF. The first and second cut took much longer time due to the calibration of the robot to determine the pressure and flow needed to cut the concrete to the desired depth. Once calibrated, the process sped up. Averagely, the first two cuts resulted in productivity rate of 12 SF/Hr, while the last four cuts resulted in productivity rate of 48 SF/Hr, which is within the range for a 4in depth removal provided in Table 7.

Figure 7. Jetframe 101 Nalta Demonstration Setup

As a summary, two matrices are developed to compare different concrete removal methods (Table 9) and different hydrodemolition robots (Table 10).

Table 9. Matrix for Concrete Removal Methods

Options	Comparison Criteria			
	Cost	**Safety**	**Efficiency**	**Advantages/ Disadvantages**
Breaking/ Jackhammering	1. The estimated cost varies based on the area being cut. 2. Estimated to cost $48,100 for a project with an area of 250 SF. 3. Does not always go beneath rebar which causes the use of the more expensive repair material (e.g., Tech-Crete)	1. Damages sound concrete and rebar, which causes future repairs. 2. The sound and vibration can cause health damages to the operators; and it exposes Labor to oncoming traffic.	1. Estimated to take 83 hours on projects with an area of 250 SF. 2. Many times repair needs to take place more than once because of damaged rebar. 3. Requires a few operators to work in rotation	Advantage 1. Initial cost for equipment is low. 2. Easy to use. 3. Easy to transport. Disadvantage 1. Causes bodily harm to labor. 2. Damages the sound concrete & rebar. 3. Can be noisy and cause a lot of dust on jobsite. 4. An estimated 8 employees are needed.
Hydrodemolition	1. The estimated cost varies based on the area being removed and the robot type. 2. Estimated to cost $5,110, on average, for a project with an area of 250 SF. 3. Is able to cut beneath the rebar allowing the cheaper repair material. 4. Capital cost of equipment is high, varying with robot type selected.	1. Keeps laborer safe from bodily harm of using equipment and oncoming traffic. 2. Does not damage rebar and sound concrete. 3. Needs a debris barrier to block water and debris generated from the removal.	1. Time efficiency is dependent upon the flow rate of the robot. At a flow rate of 40 gpm and with a 250 SF project area it is estimated to take only 3.5 hours. 2. Does not damage the rebar, rather it cleans the rust on the rebar. 3. Requires less crew for operation	Advantage 1. Safe for laborer and bridge. 2. Ability to remove concrete faster than jackhammering. 3. The unit cost per project is lower than jackhammering. Disadvantage 1. Higher initial cost. 2. More equipment needed on the jobsite. 3. Needs a debris barrier to protect oncoming traffic.

Table 10. Matrix on Comparison between "Do nothing" and "Using hydrodemolition robots"

Options	Comparison Criteria			
	Cost	Safety	Efficiency	Advantages/ Disadvantages
Do Nothing	None	Unrepaired Patches will lead to unsafe roads for Civilians.	No time is taken.	Advantage 1. No cost Disadvantage 1. Does not fix damaged patches. 2. Causes potential harm to vehicles and civilian.
Robot 557	$200,000	1. Has a debris barrier built in. 2. Allows workers to use remote to control concrete removal.	1. Can reach flows up to 73 gpm. 2. Removes 250 SF of concrete at a 4 in depth in 3.47 hours.	Advantage 1. Fastest robot. 2. Has a built in debris barrier. Disadvantage 1. Is very large and requires bigger equipment. 2. The initial cost is the highest.
Robot 327	$112,000	1. Has a debris barrier built in. 2. Allows workers to use remote to control concrete removal.	1. Can reach flows up to 69 gpm. 2. Removes 250 SF of concrete at a 4 in depth in 3.47 hours.	Advantage 1. Fast and also efficient for smaller sized projects. 2. Has a built in debris barrier. Disadvantage 1. Has a high initial cost 2. Requires larger equipment.
Jetframe 101 Nalta	$45,000	1. Does not have a debris barrier. 2. Allows workers to use remote to control concrete removal.	1. Can reach flows up to 37 gpm. 2. Removes 250 SF of concrete at a 4 in depth in 6.94 hours.	Advantage 1. Small compact robot that is easy to transport. 2. Cheapest initial cost. Disadvantage 1. Does not have a built in debris. 2. Has a lower production rate compared to the other robots.

5. Conclusions and Recommendations

With a large number of bridges in District 11 and high demand of repair, an efficient concrete removal solution must be put in place to address the issues related to the current practice of jackhammering – the time efficiency and safety of the crew. In this study, extensive literature review is conducted and hydrodemolition robots are investigated by comparing with jackhammering. Using a hydrodemolition robot allows the operator to control the cut using a remote, which eliminates the safety concern. Hydrodemolition also substantial reduces the time in order to remove concrete and does so with no damages to the sound concrete and rebar. In particular, three Conjet robots are analyzed: Robot 557, Robot 327, and Jetframe 101 Nalta; and a field demonstration of Jetframe 101 Nalta is also conducted.

Based off of the criteria to select a robot that is suitable for small projects such as patch repair and cost effective, Robot 557 is not a good option. This is because this robot has very similar production rates as Robot 327, but it has the largest size and highest capital costs among the three. On the other hand, Jetframe 101 Nalta is a potential candidate, because this robot is compact and least expensive, even though the production rate is only half of Robot 327. However, based on the observations obtained in the demonstration, the Jetframe performance did not meet up to the expectations of the ODOT District 11 crew. There were concerns about the robot having the same productivity rate as jackhammering and the ability of the Jetframe to contain debris.

The medium size Robot 327, therefore, becomes a viable choice for District 11 crew. This robot has a higher productivity rate, which can reduce the duration of the removal in half, and also has a built-in debris barrier that creates a safer work site than the Jetframe. Although the initial capital cost for this robot is high, the unit cost calculated per project pales in comparison to jackhammering. To eliminate continued danger to the crew and improve the efficiency of repair, the implementation of hydrodemolition using the Robot 327 is highly encouraged. Once implemented, bridge decks will be repaired faster, safer and more efficiently with a better quality.

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