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Paper

UTILIZING WATERJET TECHNOLOGY TO MITIGATE SUBSTRATE DAMAGE WITHIN UNDERGROUND STRUCTURAL LINERS DURING REHABILITATION WORK

J. Bourgeois, H. Miller, E. Charrier
Colorado School of Mines
Golden, CO

ABSTRACT

Waterjet excavation has the potential to eliminate many of the technical and operating challenges associated with conventional shotcrete removal and repair. Evidence derived through empiric laboratory testing indicates that waterjets are capable of selectively removing damaged areas of support liners without structurally compromising the substrate and adjacent intact sections of the liner. This research illustrates the contrast between the excavation process associated with both conventional mechanical impact hammers and waterjet excavation methods during empiric testing. An analysis on the fracture mechanisms and operating parameters of each method was completed. Within this analysis, instrumented shotcrete panels were physically tested to quantify vibration during excavation and examined through visual and analytic processes to determine substrate damage and delamination. After testing was completed, this data strongly indicated that waterjet cutting causes less collateral damage to the surrounding intact liner and substrate when compared to that of conventional impact hammers. This research was conducted to provide a scientific basis for additional applied research in the rapid excavation and repair of shotcrete support systems. The intent is to develop a viable technology that will reduce the collateral damage caused to surrounding liners during excavation, improve the adhesion between shotcrete and the substrate for longer lasting ground support, and improve overall safety for workers in underground environments.

1. INTRODUCTION

The repair of concrete and shotcrete liners that have been structurally compromised or damaged is a common maintenance and rehabilitation activity in tunnels and other types of underground workings. In many cases, it is prudent to limit the repair to the isolated removal of the structural liner around the damaged area rather than the complete excavation of large sections of the support system. In these applications, traditional methods of liner removal include the use of hydraulic or pneumatic hammers that break and excavate the liner material through repetitive percussive impacts. In operating environments where working heights are less than twenty meters, these hammers are usually mounted to articulated booms attached to mobile rubber-tired or track equipment, such as a mechanical scaler. In applications that extend beyond the reach of conventional scalers, the height of the operating envelope usually necessitates the use of man-lifts, where workers manually remove the damaged areas from these elevated platforms using hand-held equipment.

There are significant drawbacks to the use of these traditional excavation methods. It is a long-held belief that the percussive impacts and vibration generated by hydraulic/pneumatic hammers while removing the compromised area of the liner also causes unintentional damage to the surrounding intact shotcrete and/or concrete because of the propagation of fractures and the delamination of the liner from the rock substrate, as well as any contained rebar or wire mesh/screen backing. In addition, there is a host of potential safety and health hazards commonly associated with the use of these traditional technologies. This is particularly true for work performed from elevated platforms, including the worker's close proximity to unstable roof/back, the potential of falling from these platforms, the man-lift tipping or overturning, and the limited ability for rapid egress.

In addition to these drawbacks, it is important to recognize that there is significant potential for growth in underground rehabilitation work due to current operating trends in both the mining and tunneling industries. Given the cumulative impact of increasing depth, age, in-situ stresses, and complex operating environments, higher demands on ground support, specifically through the use of shotcrete, are necessary to reduce instances of ground falls and support failure. The resulting high demand of ground support in the rehabilitation of existing underground workings will encompass new challenges that require the development of safe and efficient shotcrete rehabilitation practices and technologies that can be remotely operated in a wide range of work environments [1].

Building upon the success of previous Colorado School of Mines (CSM) research activities in underground rock scaling and scarification [2], evidence from this study indicates that waterjets are capable of selectively removing damaged areas of support liners without structurally compromising or adversely impacting intact material around the area being repaired. This hypothesis is partially supported using hydrodemolition on deteriorated concrete structures [3] with a specific focus on its application on bridge decks [4] [5]. However, due to the differences in excavation layout, operating characteristics, and environmental conditions between bridge deck removal and mine drift/tunnel liner rehabilitation, the intent of this research is to facilitate a baseline understanding of the excavation processes associated with liner repair in hopes of developing a future prototype system applicable for field testing.

2. MATERIALS AND METHODS

This analysis is founded on empiric cutting tests performed on engineered and instrumented shotcrete panels designed to facilitate qualitative comparison of fracture propagation, substrate delamination, and collateral damage associated with waterjet and impact hammer excavation. Under the testing methodology, seven individual composite panels comprised of a steel reinforced concrete substrate with a 10-centimeter (4-inch) shotcrete layer were developed at the Earth Mechanics Institute (EMI) at the CSM in Golden, CO.

As part of the research testing plan, six composite panels underwent physical testing; where three of these panels were cut by a twin-orifice, rotating waterjet and three panels were mechanically excavated by a pneumatic percussive impact hammer. One panel was held in reserve for precautionary reasons. For all testing scenarios, the panels were excavated until the tool cut through the entirety of the shotcrete layer, reaching the interface between shotcrete and concrete. Each panel was instrumented with accelerometers attached to the rebar that reinforced the concrete to collect vibration data during testing. After testing, panels were visually examined to identify instances of surface fracture networks, delamination, and split aggregate from the excavation tool. Non-destructive structural analysis of the panels was performed before and after empiric testing using ground penetrating radar (GPR). The data collected through GPR will not be discussed in the context of this paper, however it can be referenced in Josef Bourgeois' dissertation "Characterizing the excavation Process Associated with Removal of Shotcrete Reinforced Underground Structural Liners Using Waterjet Technology" [6].

2.1 Engineered Test Panel

The test panels measure 76 centimeters (30 inches) by 61 centimeters (24 inches) by 25 centimeters (10 inches) thick, weighing approximately 226.8 kilograms (500 pounds) per panel. The concrete substrate is 15 centimeters (6 inches) thick and reinforced with #3 rebar (0.95 centimeters or 3/8 inches). The rebar is positioned in the middle of the concrete layer in a cross pattern on 20-centimeter (8-inch) spacing. Three segments of rebar are oriented along the short-axis, while two rebar segments run along the long-axis in each sample. The concrete/shotcrete and steel reinforcing materials are housed by a wood panel form. Holes were drilled in the sides of the wooden panel form to hold the rebar at the appropriate location within the panel, 7.6 centimeters (3 inches) up from the plywood bottom. The rebar was placed in the holes and protruded out of each panel siding to mount the accelerometers for vibration measurements. The concrete is type I/II 31 MPa (4,500 PSI (min)) commercial ready mix with 2-centimeter (¾-inch) aggregate. The batch was mixed and delivered by a local ready-mix company to the EMI and poured in the seven wood panel forms. A standard electric vibrator was used on the concrete after it was poured to eliminate the potential for air voids in the batch within each panel.

After the concrete cured for four weeks, the shotcrete layer was poured. The shotcrete layer is 10 centimeters (4 inches) thick with a 4-gauge welded wire mesh positioned 5 centimeters (2 inches) above the substrate. To facilitate the use of GPR in damage assessment and provide uniform shotcrete layering on the test panels, Quikrete sand/topping mix was used as a shotcrete simulant. This was necessary because the size of the test panels does not allow for consistent placement of shotcrete from a pneumatic sprayer. The steel (rebar and wire mesh) placement and density as well as the materials used in the substrate and shotcrete simulant were selected to replicate design parameters consistent with underground support liners. Panel dimensions (in inches) are shown in Figure 1 and panel properties are outlined in Table 1.

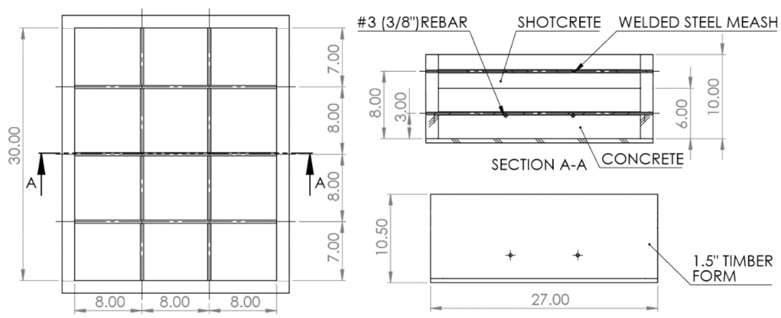

Figure 1. Composite panel dimensions (shown in inches)

Table 1.Composite panel properties

Panel Component	***Material Volume, cm³ (in³)***	***% of Panel***
Type I/II 4,500 PSI Concrete	70,553 (4,305.4)	59.8
Quikrete Sand/Topping Mix	47,111 (2,874.9)	39.9
#3 (3/8”) Rebar	239 (14.6)	0.2
Welded Steel Mesh	84 (5.1)	0.1
Sum	**117,987 (7,200)**	**100**

*Welded steel mesh nominal diameter of 4 gauge – 4.7 mm (0.187”)

2.2 Mechanical Excavation

Mechanical excavation was conducted at the EMI using an electric rotary hammer. The sample was turned on end, so the exposed concrete face was vertical in order to better simulate repairs to the rib. A Bauer 40-millimeter (1-9/16-inch) rotary hammer (1643E-B) was used. It was rated at 3,780 impacts per minute with a force of up to 6.6 foot-pounds per impact. Excavation was conducted using a 2.54-centimeter (1-inch) concrete spade chisel. Bit rotation was disabled to allow for better operator control of the chisel location and orientation and to simulate common repair practice. A rectangular cavity was cut in the center of each panel and excavated to the top of the concrete layer. The mechanical excavation process is shown in Figure 2.


Figure 2. Process of mechanical excavation using impact hammer

2.3 Waterjet Excavation

The panels that underwent waterjet testing were placed on a manually operated hydraulic lift to be positioned similar to that of the panels tested by the impact hammer. This provided vertical movement of the sample and was utilized to elevate the panel relative to the jet assembly. Horizontal movement during sample cutting was accomplished by a pneumatic actuated linear slide. The pressurized fluid flow for waterjet testing was generated by a KOBE high-pressure triplex, positive displacement pump. This pump was a Size-4 model with 180 nominal HP and 15.9-millimeter (5/8-inch) diameter plungers. It possessed a designed maximum operating pressure of 207 MPa (30,000 PSI) as well as a theoretical fixed displacement of 28.1 lpm (7.4 gpm). The KOBE was powered by a 150 HP electric AC motor. During testing, the system operating pressure was 189.6 MPa (27,500 PSI), which was measured at the pump discharge manifold. Due to the occurrence of slippage internally within the pump at pressure, the actual nozzle flow rate during testing was approximately 21.3 lpm (5.6 gpm) rate. During operation of the waterjet system for testing, a low-pressure priming pump was used to supply the Kobe pump at a flow rate of 22.8 lpm (6 gpm) at 0.45 MPa (65 PSI). The system also included a 950-liter (250-gallon) water storage tank and inlet line filters. The waterjet system diagram is shown in Figure 3.

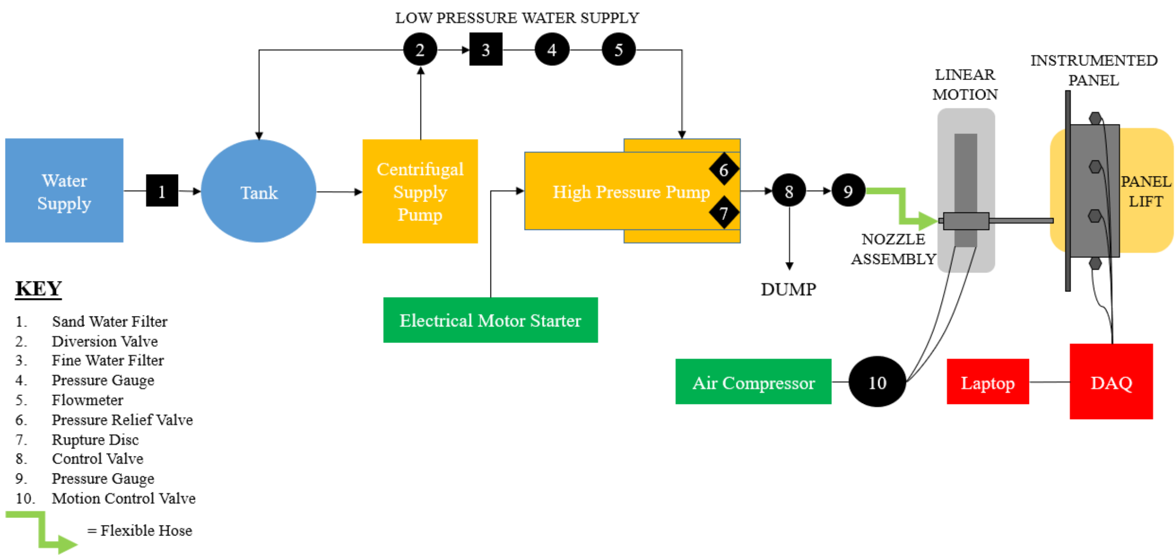

Figure 3. Waterjet instrumentation and cutting setup

A twin orifice rotary nozzle assembly was utilized with two commercially purchased 0.74 millimeter (0.029 inch) diameter stainless steel leach walker type nozzles with vane flow straighteners. These nozzles were chosen based on their pressure and flow ratings of 151.7 MPa (22,000 PSI) and 12.9 lpm (3.4 gpm) respectively. Overall, the size and design of the nozzles used for this research was chosen based on empiric experience and the need to maintain jet stagnation pressures above the potential threshold pressures of the target material. The nozzle assembly was connected to the pump accumulator via a 3.7-meter (12-foot) long, 5.1-millimeter (0.2 inch) ID, 275.8 MPa (40,000 PSI) high pressure flexible hose. The system includes a bypass valve at the pump which was designed to regulate flow and pressure. For safety considerations, a pressure relief valve and rupture disc assembly were plumbed into the system. System pressure was measured using a gauge located at the pump accumulator. The pump required an organic lubricant in the form of a soluble gear oil mixture, which was mixed into the water supply (2% by volume). It is assumed that the addition of the oil into the system possessed negligible effects on the thermal and dynamic properties of the fluid. A summary of operating parameters used during continuous waterjet impingement on the test panels is outlined in Table 2. The cutting system used during waterjet testing is shown in Figure 4.

Table 2. Continuous waterjet testing parameters

Jet Parameter	Value	Units
Fluid Pressure at Pump	27,500	PSI
Fluid Pressure at Nozzle	25,966	PSI
System Pressure Loss	1,534	PSI
Pump Flow	5.6	GPM
Nozzle Diameter	0.029	in
Nozzle Exit Velocity	1,768	ft/s
Standoff Distance	3.5 – 7.5	in
Traverse Rate	1.0 – 6.0	in/s
Impingement Angle	10	deg
Rotation of Nozzle Assembly	300	RPM

Figure 4. Waterjet excavation – Laboratory set-up (upper left) start of slot in panel (upper right) kerf in panel (bottom left) close-up of kerf in panel (bottom right)

2.4 Visual Inspection

Visual inspection was performed after excavation was completed on each panel. This process was accomplished in sections to analyze the entirety of the excavation profile including the left, upper, right, and bottom walls, as well as the face where exposed aggregate was located. Before inspection took place, each panel's excavation profile was rinsed thoroughly with water to provide a clean, wet surface which aided in fracture/failure visibility to the naked eye. When each section was examined, areas of fracture/failure were noted. These areas either had a single fracture or a network of failure which were manually measured in millimeters using measuring tape. All these areas were identified, measured, and summarized for each excavation section. During inspection of a particular section, if damage to wire mesh was present, it was noted for final comparison between each testing method. Delamination was also measured in millimeters if it was present in the analyzed division of the excavation profile. Finally, for the face section, split aggregate was counted and divided by the total exposed aggregate to give a percentage of split aggregate at the face due to testing.

2.5 Vibration Data Acquisition

The data acquisition system (DAQ) recorded vibration readings from seven accelerometers. The accelerometers were mounted on the exposed ends of the rebar in the test panels. A USB DAQ and LabVIEW were used to process and save the collected data to a laptop. The accelerometers used were a prosumer product from Sparkfun, the ADXL337, which is a triple axis analog accelerometer with a range of +/-200 G. The X, Y, Z, ground and +3.3 V connections were soldered to the wiring harness. The ground and +3.3 V were supplied by the National Instruments USB-6211 DAQ. The Z axis and the X axis were used on each accelerometer due to the limited number of analog channels available. The Z axis was normal to the sample surface with +Z pointing towards the excavation equipment. The X axis ran parallel to the edge of the sample.

The accelerometers were mounted in enclosed 3D printed ABS sensor mounts. The ADXL337 was attached to the accelerometer mount by four screws. A cutaway was left in the base of the sensor mount for the wiring harness. The sensor mounts were pressed onto the rebar. To ensure a tight fit, the rebar was wrapped with electrical tape. The hexagonal tops of the sensor mounts were parallel to the surface of the panel. Seven sensor mounts were used during testing. These were arranged in a counterclockwise pattern around the sample starting with accelerometer 1 on the bottom right rebar end. There were three accelerometers on the right side of the sample, two on the top of the sample, and two on the left side of the sample. The sensor arrangement is shown in Figure 5.

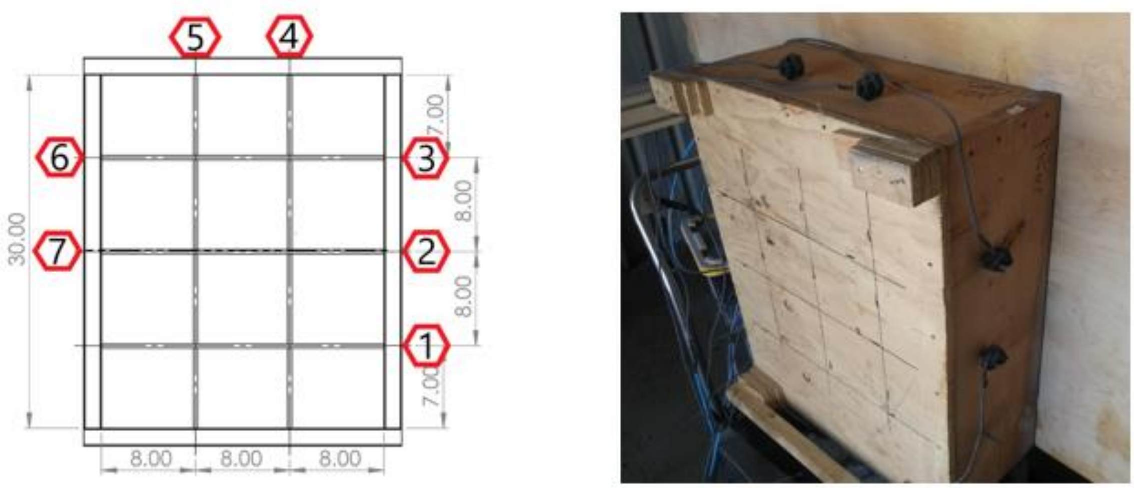

Figure 5. Accelerometer locations (left) accelerometers on actual panel (right)

A National Instruments USB-6211 DAQ was used to read the analog signals from the accelerometers. This DAQ supported sixteen analog channels. Fourteen of the channels were used for accelerometer data, one was used to monitor the accelerometer power supply voltage, and the remaining analog channel was not used. The specified maximum impact rate of the Bauer rotary hammer (1643E-B) was 3900 impacts per minute (65 HZ). Thermal and operating considerations lead to the hammer being operated at frequencies well below the maximum (below 50 HZ).

The sample rate of the DAQ was 100 HZ which translates to a recorded reading for each accelerometer in the X and Z direction every 0.01 seconds. This was sufficient to exceed the Nyquist frequency of the hammer at plausible operating conditions. Due to the recording sample rate, most cutting runs lasted approximately 210 seconds at which point recording stopped and the values for the readings per every 0.01 second were output in excel format. With this time constraint per run in the DAQ, each panel required multiple testing runs in order to excavate through the entirety of the shotcrete layer until reaching the shotcrete/concrete interface. For example, it took seven runs to reach the shotcrete/concrete interface in Panel 2, which was excavated using the impact hammer.

3. RESULTS

The following research results validate the hypothesis that waterjet removal of concrete/shotcrete liners will result in less collateral damage than conventional methods through comparison of visual inspection and processed GPR scans. For clarification purposes, the designed panels, along with their testing method, are shown in Table 3.

Table 3. Panel number and associated testing method

Panel	Testing Method
2	Impact Hammer
3	Impact Hammer
4	Impact Hammer
1	Waterjet
7	Waterjet
TEST	Waterjet

3.1 Visual Inspection Comparison of Kerfs and Damage of Steel Infrastructure

Visual inspection was performed after excavation was completed on each panel through analysis of the entirety of the excavation profile including the left, upper, right, and bottom walls, as well as the face where exposed aggregate was located. Figures outlining the inspection process of each excavation section can be found in Appendix C of Josef Bourgeois' dissertation [6]. Panels 2, 3, 4, 7, and TEST were examined at the EMI. Panel 1 was not visually inspected as it is currently being held at the SAI/RAMAX laboratory in California. Results of visual inspection measurements for all panels is shown in Table 4.

Table 4. Results of fracture/failure count and measured distance, measured delamination, and percent split aggregate (exposed)

Panel	Excavation Method	Fracture/Failure Count: Left Wall	Upper Wall	Right Wall	Lower Wall	Excavation Face	Outside Excavation Profile	Total Fracture / Failure Count	Total Measured Fracture / Failure Distance (mm)	Total Measured Delamination Distance (mm)	Percent Split Aggregate (Exposed)
2	Impact Hammer	3	1	3	2	1	3	13	66.5	0	62.7
3	Impact Hammer	7	3	6	4	0	2	22	165	131.5	62.5
4	Impact Hammer	4	3	2	0	0	2	11	57.5	92	80.7
7	Waterjet	1	0	0	0	0	1	2	19	0	0
TEST	Waterjet	1	1	1	0	0	1	4	23.5	0	-

3.2 Vibration Comparison from DAQ Results

During both forms of testing, acceleration in the Z direction typically exhibited higher magnitudes as a consequence of the Z direction being normal to the panel surface. Some of the higher magnitude acceleration values in the X direction during impact hammer testing could be contributed to when the angle of the chisel was changed from perpendicular to the excavation surface to having an attack angle in order to remove material in the X direction with relation to the panel face. Accelerometer results of waterjet testing generally appear as static noise with consistent vibration when excavating surfaces that do not have irregular geometry. Comparatively, results of impact hammer testing show frequent peaks in all accelerometers at values never once reached during waterjet testing, and thereby showing far less consistency with much higher vibration.

Positive and negative peak acceleration (g) values reached during testing on each panel are shown in Figure 6. Within this figure, the labeling of each panel that underwent excavation is preceded by the testing method used where “IH” stands for “Impact Hammer” and “WJ” stands for “Waterjet”. For Panel 7, acceleration readings during waterjet excavation never reached above 6 g. With Panel 1, there were instances when accelerations between 10 and 20 g were recorded when the jet stalled at the end of a traverse before reversing direction or when the nozzle traversed across areas of kerf geometry where additional free surfaces existed because of adjacent kerfs. The longest period of time that the nozzle assembly stalled at the end of a traverse was approximately 15 seconds. This could be avoided in future applications by utilizing hydraulics to traverse the nozzle assembly rather than air compression. Overall, even with these relatively infrequent spikes in recorded acceleration, values never exceeded 20 g during waterjet testing.

A section of Panel 4 was excavated using hand hammering with the chisel and a sledge hammer, instead of using the Bauer tool, to draw a comparison of different impact techniques. During hand hammering, acceleration peaks between 17-72.5 g were recorded which were comparatively lower than typical peaks reached with the Bauer tool however, still higher than that of the waterjet system. The higher vibrations induced through impact hammer testing are likely the cause of delamination at the interface of the shotcrete/concrete layer as noted in Table 4.

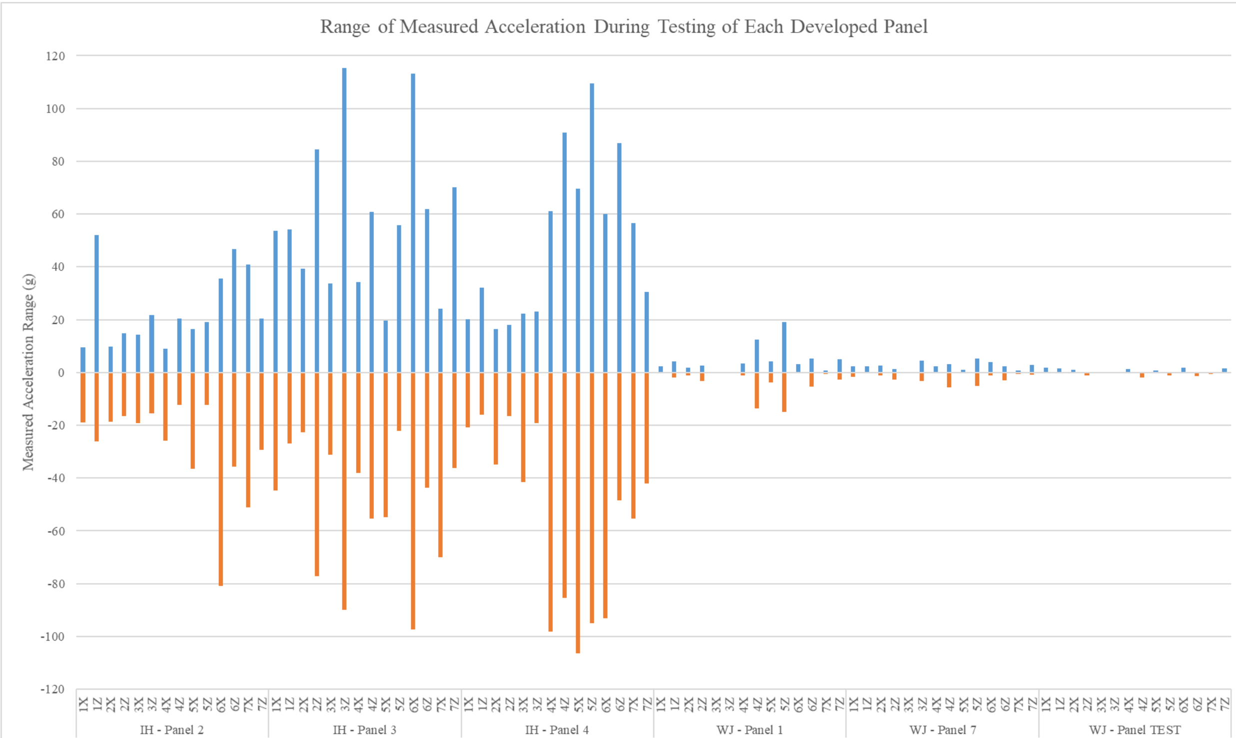

Figure 6. Range of measured acceleration during testing of each developed panel

4. DISCUSSION

This section summarizes completion of the research objectives through empirical comparison of excavation methods, as well as an analysis of the proposed hydro-excavation technology.

4.1 Visual Inspection

Visual inspection of Panels 2, 3, 4, 7, and TEST exemplified stark differences in the occurrence of fractures/failures, delamination, damage to steel wire mesh, and the incidence of split aggregate associated with each testing method. As previously stated, Panel 1 was not visually inspected as it is currently being held at the SAI/RAMAX laboratory in California. Table 4 shows that impact hammer excavation caused more counts of fracture/failure, compared to that of waterjet cutting, along the excavation profile and surrounding shotcrete layer with 13 (66.5 mm), 22 (165 mm), and 11 (57.5 mm) for Panels 2, 3, and 4 respectively. Panels 7 and TEST resulted in fracture/failure counts of 2 (19 mm) and 4 (23.5 mm). While the panels tested by the waterjet system did result in measured fractures/failures, there was no visual indication of delamination, damage to wire mesh, or split exposed aggregate. This is especially important because the panels tested using the impact hammer contained damaged wire mesh, measured delamination in two of the three panels, and measured over 50% split exposed aggregate for all panels. The highest measured delamination within the excavation profile of a panel subjected to impact hammer testing was 131.5 mm from Panel 3, which also had the highest recorded vibration from accelerometers.

4.2 Vibration Data Acquisition

Accelerometer data gathered during testing of Panels 2, 3, 4, 1, 7, and TEST illustrated significant difference in vibrations induced by the chosen excavation tools with the impact hammer consistently recording acceleration far higher than that of the waterjet. This data clearly demonstrates that use of a high-pressure waterjet systems will translate substantially less vibrations to the embedded steel reinforcement. The high readings of acceleration shown in Panel 1 can be reduced through adjustment of operating parameters, specifically avoidance of stalling the nozzle assembly while keeping a consistent traverse speed and avoiding standoff distances of less than 8.9 centimeters (3.5 inches). It's important to note that, while particularly high acceleration was recorded for Panel 3, experienced use of the impact hammer could result in lower readings like that of Panel 2, however, these are still considerably higher than data gathered for all waterjet panels.

5. CONCLUSIONS

The results obtained from visual inspection, and collected accelerometer data correlate with observations made in the literature favoring the use of hydrodemolition in bridge deck removal and repair work [4], specifically those identifying structural benefits to its use including:

- Providing a rough surface profile for excellent mechanical bond to repair materials;
- Eliminating surface micro-fracturing;
- Not fracturing exposed aggregates;
- Minimizing vibration; and
- Cleaning steel reinforcement and leaving it undamaged.

The data collected for this research project provides supplemental validation of the benefits of hydrodemolition. According to Asadi et al, the Federal Highway Administration reported that 11% of the bridges in the United States are rated as structurally deficient and over 30% of existing bridges have exceeded their 50-year design life [7]. This means that bridge deck analysis and rehabilitation work will substantially increase in the years to come. The findings from this research, specifically through the reduction of vibration to embedded steel reinforcement and avoidance of cutting the aggregate within the concrete layer for an improved bonding surface to the new overlay material, can be used to further advance the knowledge and use of high-pressure waterjet systems for bridge deck rehabilitation. The next step of this research agenda would be to adapt the waterjet system used from this study to an existing tunnel or mine site, where large sections of an existing support liner could be excavated as part of a full-scale pilot test. Based on the vibration analysis conducted in this study, accelerometers could be embedded into sections of support liner for continued collection of data during future empiric testing. Additionally, to enhance visual inspection of the excavation profile developed in a shotcrete layer, liquid penetrant inspection (LPI) could also be utilized for detection of impact failure/fracture.

Finally, the findings from this study could also be used to optimize the jet's specific energy for fragmentation. Through this process, the time required to remove a volume of shotcrete could be characterized in hopes of increasing the excavation rate as compared to conventional mechanical methods. For commercial application, a cost-benefit and safety analysis between waterjet systems and traditional tools, such as impact hammers, would be beneficial for advancing the commercial relevance of the technology in specific industrial applications.

6. ACKNOWLEDGEMENTS

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