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Controlling Risk to Critical Infrastructure during Construction: Seine Riverbank Stabilization at the Branch 1 Aqueduct, Winnipeg, Manitoba

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ABSTRACT
The 100-year old Branch 1 Aqueduct is a critical part of the City of Winnipeg's water system, transporting 40% of the City's treated water. In recent years, undesirable riverbank movements were observed at the Seine River crossing which, if left unmitigated, could lead to complete catastrophic failure of the Aqueduct. The optimal method of stabilization was selected with consideration to the risk of construction induced movement and vibration adversely impacting the 100-year-old aqueduct, as well as environment, schedule, constructability and cost. A highly prescriptive construction methodology incrementally increased existing stability at each stage of the work. Construction began with a full-scale rockfill column field testing program to develop site-specific techniques. Real-time and cloud-based monitoring data were collected to facilitate refinements to the construction methodology, as necessary. All riverbank stabilization and erosion protection works were successfully completed during the winter of 2018. Pre and post-construction inspections revealed that the Branch 1 Aqueduct was not compromised by the construction.

RÉSUMÉ
L'aqueduc de la branche 1 est une composante essentielle du réseau d'alimentation en eau de la Ville de Winnipeg. Il existe depuis une centaine d'années et transporte 40 % de l'eau traitée de la Ville. Au cours de ces dernières années, la surveillance a détecté un mouvement des berges de la rivière Seine au croisement de l'aqueduc qui, sans intervention, aurait pu avoir entraîné l'échec catastrophique de l'aqueduc. Afin de rectifier la situation, une méthode de stabilisation optimale a été choisie en fonction des risques reliés au mouvement et aux vibrations provoquées par la construction sur l'aqueduc ainsi que l'environnement, le calendrier, la constructibilité et le coût du projet. Une méthodologie de construction hautement prescriptive a progressivement augmenté la stabilité existante des berges à chaque étape du travail. La construction a été entamée par un programme d'essais sur le terrain de colonnes d'enrochement à grande échelle afin de développer des techniques spécifiques au site. Des données de surveillance de Cloud en temps réel ont été collectées pour faciliter le perfectionnement de la méthodologie de construction, le cas échéant. Tous les travaux de stabilisation des rives et de protection contre l'érosion ont été achevés avec succès au cours de l'hiver 2018. Les inspections effectuées avant et après la construction ont révélé que l'aqueduc de la branche 1 n'a pas été compromis par la construction.

1 INTRODUCTION

Riverbank stabilization was necessary to preserve the structural integrity of the City of Winnipeg Branch 1 Aqueduct (Aqueduct) and provide long-term protection to the City's water supply. The urban location of the waterway and sensitive nature of the Aqueduct also posed unique environmental, design and construction challenges. Adding to the complexity of the project was the requirement to keep the Aqueduct operational during construction along an actively moving section of riverbank. Recent riverbank monitoring data revealed undesirable slope movements that, if left unmitigated, could lead to lateral displacement of the Aqueduct and subsequently damage the pipe joints, fracture the pipeline, or result in complete catastrophic failure, thus compromising the City's water supply. The Aqueduct crosses underneath the Seine River at a skewed angle increasing the likelihood that uncontrolled riverbank movement would have a detrimental impact on the integrity of the Aqueduct.

This paper describes the background and history of riverbank instability at the site, the development of the design, the highly prescriptive construction methodology to reduce risk, and lessons learned from the project.

2 BACKGROUND

2.1 History of Branch 1 Aqueduct at Seine River Crossing

The source of drinking water for the City of Winnipeg is Shoal Lake, located on the Manitoba/Ontario border, 145 km east of Winnipeg. The Shoal Lake Aqueduct was considered an engineering marvel upon completion of construction in 1919. Using the elevation difference between Shoal Lake and Winnipeg, water is transported entirely by gravity to the Water Treatment Plant on the east side of the City.

The Branch 1 Aqueduct is the 18.8 km long portion of the Shoal Lake Aqueduct that transports the treated water from the Water Treatment Plant to the MacLean and

McPhillips Pumping Stations. This portion is a critical component of the City of Winnipeg's drinking water supply, delivering 173 million litres of water (approximately 40% of the City's treated water) every day to homes and businesses. Figure 1 shows the original construction of the Branch 1 Aqueduct (Aqueduct) at the Seine River crossing from the east bank near the corner of Rue Notre Dame and Rue Maisonneuve in St. Boniface to the west bank in Lagimodière-Gaboury Park. The Aqueduct consists of a 1.67 m diameter reinforced concrete pipe constructed of 2.4 m long precast segments that are supported by a cast-in-place concrete cradle. Construction consisted of an open trench excavation supported by timber shoring and tightly spaced planks with cross bracing, shown in Figure 1. The shoring was left in place after construction to provide additional protection and to act as a barrier between the trench backfill and the existing poor soil conditions. Remnants of the timber shoring can still be seen 100 years later on either side of the Seine River.

Figure 1: Original Construction of Branch 1 Aqueduct.

In 1997, the City of Winnipeg began actively monitoring the east and west banks of the Seine River in the vicinity of the Aqueduct crossing. A follow-up conceptual design study assessed the stability of the crossing (UMA, 2000). The City subsequently stabilized the west bank with 286 rockfill columns in the winter of 2001 (Yarechewski and Tallin, 2003). As part of that assessment, the east bank stabilization was deferred until monitoring data indicated an unacceptable risk to the Aqueduct. Instrumentation was installed to monitor the riverbank movements and groundwater conditions.

After 2004, the rate of movement along the east bank noticeably increased (UMA, 2007) and prompted the City to undertake a conceptual design study accompanied by a regular slope monitoring program with additional instrumentation (AECOM, 2010). Subsequent monitoring data indicated that riverbank movements had continued and that riverbank stabilization of the east bank was now warranted in order to secure the long-term integrity of the Aqueduct (AECOM, 2016). Based on the monitoring results, the City planned in 2017 to proceed with a conceptual design that entailed a two-year construction timeline to stabilize the east bank.

The City of Winnipeg made it a requirement that the Aqueduct remains in service throughout construction. In addition to the technical challenges of preserving the Aqueduct, there were also social, ecological, and environmental sensitivities of working within a residential neighbourhood and within an urban waterway, resulting in significant local stakeholder interest. The City of Winnipeg understood these requirements and the need to incorporate them into the final design and construction work.

2.2 Stratigraphy

The riverbanks along the Seine River consist of soft, weak, high plasticity, Lake Agassiz lacustrine clay overlying glacial till. The clays are generally vulnerable to high rates of movements associated with deep-seated active bank instabilities. Residual shear strength parameters for the clay were back-calculated to be c' = 4 kPa and ϕ' = 10° within the zone where active riverbank movements were measured at the site. Post peak shear strength parameters of c' = 4 kPa and ϕ' = 14° were applied to the clay outside the zone of active riverbank movement. The underlying dense glacial till was applied shear strength parameters of c' = 0 kPa and ϕ' = 37°. These values are within typically accepted ranges from studies completed by Baracos and Graham (1981), Baracos et al. (1983), Tutkaluk (2000), Abdul Razaq (2007) and Thiessen (2011).

The height of the east bank is approximately 8 m as measured from the bottom of the river channel to the top of the slope, with the depth of water typically being less than 1.5 m. Measured riverbank movements extended from the ground surface near the crest of the slope to the deep-seated slide planes at the lacustrine clay/glacial till interface, exiting below the water level of the Seine River, as shown Figure 2.

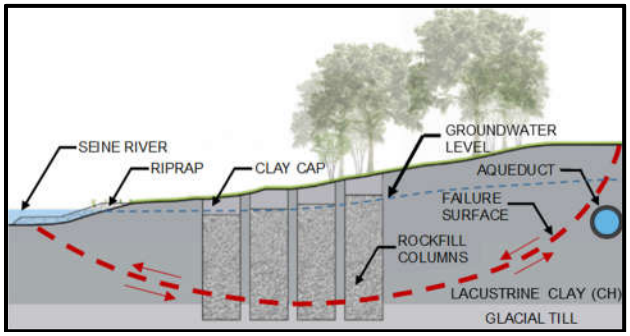

Figure 2: Cross Section of Deep-Seated Failure Plane.

3 DESIGN AND RISK MANAGEMENT

3.1 Selection of Optimal Riverbank Stabilization Design

Various potential riverbank stabilization alternatives were analyzed as part of preliminary design, including: riprap blanket, riprap berm, partial retaining wall, secant wall, soil mixing wall and light weight fill. The optimal method of stabilization was selected using an evaluation matrix that considered the risk of potential movement and vibrations induced during construction as well as the environment, required construction staging, schedule, complexity of construction techniques, and cost.

Advanced coupled stress-strain modelling was carried out using GeoStudio software to understand how the riverbank would react to riverbank stabilization works. In-situ pressuremeter testing was completed to directly measure the stress-strain behaviour of the clays for subsequent input into the stress-strain modelling.

As part of the modelling process, the riverbank response to other changes in stress state in the future was also examined, such as fluctuating river or groundwater levels including a rapid drawdown event, or the resulting stress state as artesian conditions in the bedrock increase (Bell and Neufeld, 2017).

The stresses and strains from the advanced coupled stress-strain model of the riverbank were then applied to computer simulations to estimate its effect on the Aqueduct. The applied riverbank stresses and strains were analysed using spColumn and Midas Civil 2018 software, respectively. The analyses identified critical structural locations along the Aqueduct and consequently guided the placement of slope inclinometers and vibration monitors, which were vital in monitoring the potential impact of construction on the Aqueduct.

Given the urban location of the waterway, KGS Group reconciled the needs and interests of nearby residents as well as the sensitive ecological environment. Public engagement included an open house to gather feedback to incorporate into the design. Hydraulic and environmental studies were completed to analyse the impact of the stabilization works on the Seine River with relation to water levels, erosion and aquatic life, both upstream and downstream of the site.

The selected stabilization method reduced the construction schedule from two years to just one year and resulted in significant cost savings. The final design, shown in Figure 3, consisted of:

- A strategic array of 79 lower to mid-bank rockfill columns installed through the clay into the underlying till with a total depth ranging from 10 to 13 m. The rockfill columns increased the stability of the potential deep-seated slide planes that extended to the base of the clay and till interface.
- A 0.6 m thick riprap blanket along the toe of the bank consisting of 150 mm to 450 mm diameter crushed clean limestone. The riprap protects against shoreline erosion and provided marginal resistance to slope movement by buttressing the toe of the slope.

The riverbank stabilization works were designed to provide a minimum factor of safety of 1.5 under normal groundwater and river level conditions, and 1.2 under a rapid drawdown from the flood protection level at elevation 230.0 m to the normal summer river level. Construction sequencing was designed to maintain a minimum factor of safety of 1.3 during each phase of construction.

A nominal friction angle of 45° was selected for the vibrocompacted rockfill column backfill. Studies completed by Abdul Razaq (2007) and Thiessen (2011) measured friction angles of rockfill ranging from 37° to 64° depending on the density of the rockfill and effective normal stress.

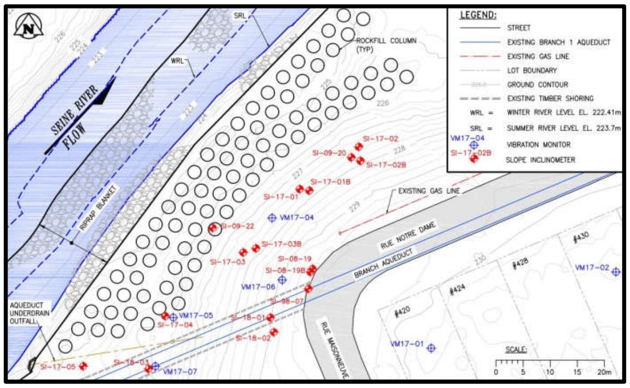

Figure 3: Site Plan Showing Stabilization Works.

3.2 Controlling Risk with a Prescriptive Construction Methodology

The main objectives of the construction methodology was to (1) prescribe an efficient and safe sequencing of construction activities to maintain the integrity of the Aqueduct, (2) minimize disruption to the surrounding residents, and (3) allow for the continuous operation of the Aqueduct.

To achieve the objectives, a series of tasks were considered or completed in the development of the construction methodology. Potential and active slip surfaces that could threaten the Aqueduct in the upper bank area were identified prior to construction using monitoring data and the advanced coupled stress-strain models. The models were also used to carefully model the construction sequencing, assessing the impacts of all construction equipment on riverbank stability at each phase of construction.

The resulting construction methodology was highly prescriptive and reduced risk by controlling potential movement and vibrations during construction. The approach also relied heavily on observation in the field, closely monitoring instrumentation strategically placed at critical locations during construction. This allowed the risk to be shared amongst the Contractor, Consultant and the City of Winnipeg.

Each step of construction was developed to incrementally increase stability. The location and operation of all heavy equipment were prescribed at each step. Heavy equipment was either supported by thick timber mats to effectively distribute the load or operated directly over the completed rockfill columns on the stabilized section to avoid loading the actively moving riverbank.

Initial riverbank stability improvement was achieved in three steps. First, the upper bank was offloaded to construct the access ramp. Second, a riprap blanket was permanently installed along the shoreline. Third, a temporary rockfill berm was placed in the river to provide immediate toe support as well as access and staging across the site during construction. Once the berm was in place, the heavy equipment could be safely brought down the riverbank. The material from the temporary berm was then used as backfill for the rockfill columns which significantly reduced noise, traffic congestion and infrastructure wear resulting from trucks hauling material. Removal of the berm that was buttressing the active construction area was controlled to provide a buffer around the operating drill and crane.

Riprap placement and the temporary rockfill berm construction started on the north end (away from the active riverbank movements) and advanced south towards the Aqueduct (closer to the active riverbank movements). Consequently, the stability of the riverbank increased as the distance from the active construction area to the Aqueduct was reduced. The placement of the permanent riprap blanket and temporary rockfill berm are shown in the Figure 4.

Rockfill columns were installed in four stages as shown Figure 5. Steel sleeve casings were installed in every column to minimize lateral movement. Casings were vibrocompacted and removed from the excavation using a vibratory hammer hoisted by a crane as shown in Figure 5. Excess clay remaining in the casings were removed prior to backfilling with the clean, crushed limestone. Installation of the 79 rockfill columns began in February 2018 and was completed in one and a half months' time in March 2018.

To prevent groundwater infiltration and to promote positive surface drainage, completed rockfill columns were capped with 0.6 m of compacted clay. Once the frost was out of the ground, the slope was regraded to provide a smooth and positively graded ground surface.

3.3 Rockfill Column Full-Scale Field Testing Program

Construction began with a full-scale field testing program to evaluate the contractor's means and methods, which included drilling, sleeving, backfilling and vibrocompaction of the rockfill columns while closely monitoring real-time riverbank performance. Three test rockfill columns were installed on the north end of the site to help determine the most suitable, site-specific installation methods that achieved proper relative densities, especially when critical infrastructure is in close proximity. Both the rate of casing retrieval and applied vibrocompaction were optimized to achieve the maximum rockfill densification while limiting inherent risk to the Aqueduct as determined by the monitoring data, specifically tolerable limits of construction-induced vibrations.

The contractor had both a vibratory hammer (HPSI 500XL Exciter) intended to install the casings as well as a vibrating lance (PTC 400HL Vibrolance) historically used to vibrate and compact rockfill columns. In this case, the vibrating lance only nominally increased the relative density of the rockfill columns compared to the vibratory hammer. As a result, subsequent rockfill columns were compacted using only the vibratory hammer attached to the steel sleeves.

After initial placement, the relative density of the uncompacted rockfill was considered generally loose to medium-dense based on expected relative densities for similar rockfill as shown in Table 1 (Abdul Razaq, 2007). Following vibrocompaction, the relative density of the rockfill generally increased to dense. The dry density of the compacted rockfill from the testing program ranged from 1,850 to 1,915 kg/m^3.

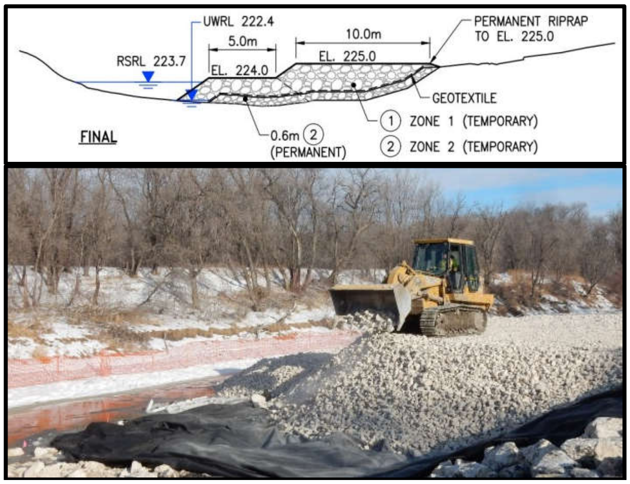

Figure 4: Permanent Riprap Blanket and Temporary Rockfill Berm.

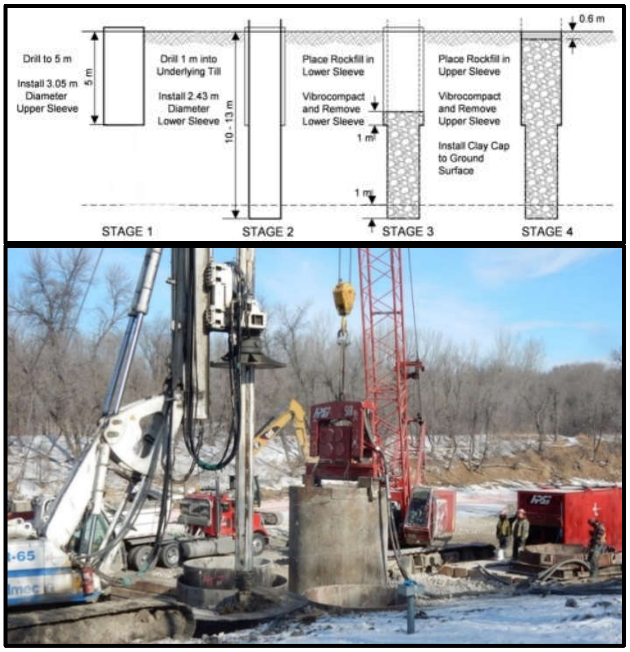

Figure 5: Rockfill Column Installation Method.

Table 1: Relative Density of Limestone Rockfill (Abdul Razaq, 2007)

Relative Density	Loose	Medium	Dense
Density [kg/m^3]	1,499	1,733	1,896

3.4 Real-Time and Cloud-Based Instrumentation Program

The instrumentation and monitoring program was the most comprehensive program ever undertaken by the City of Winnipeg for a project related to riverbank stabilization. Selected instrumentation was installed, prior to construction including additional slope inclinometers (SIs), vibrating wire (VW) piezometers and seismographs to complement existing slope inclinometers at the site. The location of all instrumentation is shown in Figure 3.

The advanced instrumentation program using real-time, cloud-based monitoring reduced risk to the Aqueduct as well as to the nearby residential homes to a tolerable level by increasing the likelihood that potentially damaging riverbank instabilities and vibrations would be detected prior to structural damage occurring. Early detection allowed for proactive risk mitigation measures to be immediately implemented, in particular modifications to the rockfill column installation method. Monitoring data and the results were openly communicated to all parties including the owner, contractor and designer for transparency and to promote open dialogue. The SIs and VW piezometers will also be monitored for two years post-construction to validate performance.

Seismographs were installed and continuously monitored construction induced vibrations at and near the work site. Deep vibration monitors along the top of the Aqueduct pipe at key pre-determined locations provided early warning and prediction of vibrations as the installation of the rockfill columns progressed towards the Aqueduct. Since construction was within a residential neighbourhood, vibration monitors were also mounted directly on the foundations inside three nearby houses.

Each monitor continuously recorded the peak particle velocity (PPV) value within a five-minute block of time. The monitors installed on nearby homes continuously recorded PPV values and transmitted the readings to a cloud-based data storage system in order to minimize the disturbance to the residents. The monitors installed at the work site near the Aqueduct recorded PPV values throughout the workday and were manually downloaded at the end of each workday. The resident site inspector provided constant visual monitoring of the actual vibration monitor displays during all critical activities.

Slope inclinometers were installed to monitor riverbank movement both inside and outside the existing trench shoring. These supplemented the existing, functional SIs that had been baselined prior to the start of construction. All SIs were routinely monitored daily during construction.

Vibrating wire monitored groundwater conditions before, during and after construction. Piezometric levels were continuously monitored to provide early warnings of movements due to the vibration induced generation of excess pore water pressure in the riverbank. Also, they effectively served to detect possible leakage from the Aqueduct.

3.5 Vibration Monitoring

Vibration monitoring focused on PPV and the corresponding frequency measured during the vibrocompaction of rockfill columns as shown in Figure 5. Peak accelerations were measured on one occasion at radial distances of 11 and 24 m from the center of the rockfill column being installed to understand the impact of vibrocompaction further.

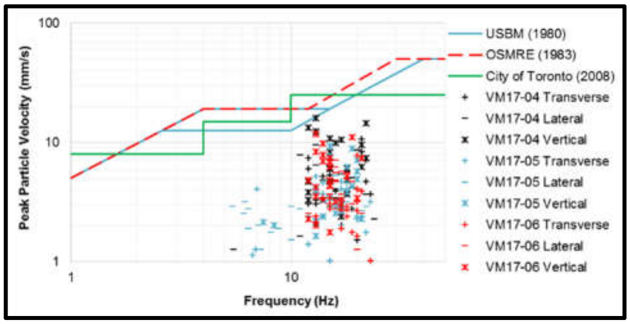

Figure 5: Peak Particle Velocity versus Frequency during Vibrocompaction of Rockfill Columns.

As shown in Figure 6, higher velocity, lower frequency vibrations were experienced briefly during the initial start-up of the vibratory hammer that generally lasted for less than five seconds, followed by more regular and continuous vibrations with a lower strength.

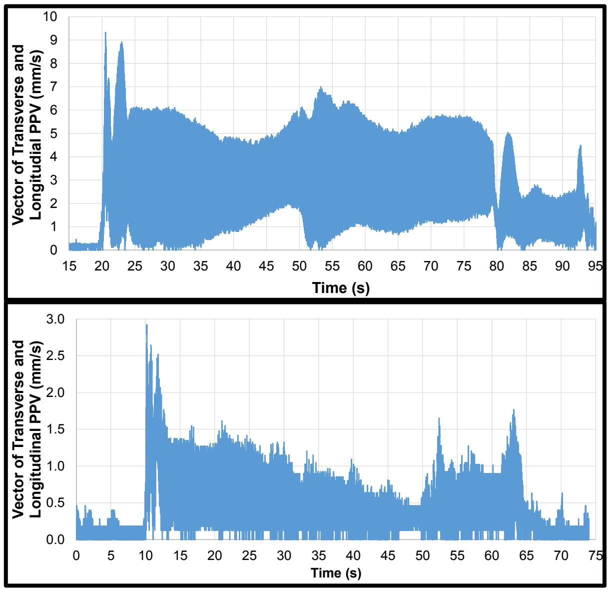

Figure 6: Vector Transverse and Longitudinal PPV at Radial Distances of 11 m (top) and 24 m (bottom) from the Rockfill Column Installation.

The measurements from the seismographs were key in developing a safe radius of influence from the rockfill column being installed (vibration source) as shown in Figure 7. The benefit of vibrocompaction was weighed against the risk of damaging the Aqueduct from vibrations and resulting riverbank movement as the installation of the rockfill columns approached the Aqueduct. Based on the radius of influence, the Aqueduct would have likely experienced vibrations and riverbank movements in excess of tolerable limits if the rockfill columns closest to the alignment were vibrocompacted. Consequently, the rockfill column installation method was modified while working immediately adjacent to the 100-year old Aqueduct pipe. Construction induced vibrations were all kept below the specified threshold for maximum PPV, and in turn, preserved the integrity of both the Aqueduct and the nearby houses.

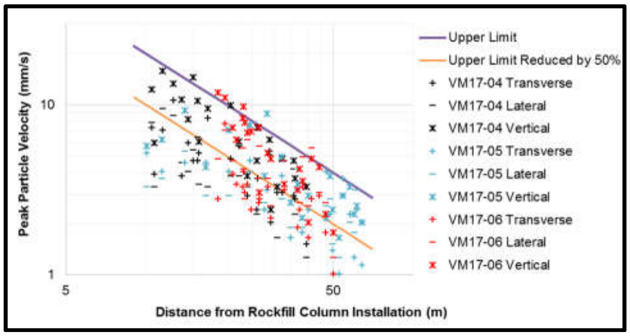

Figure 7: Radius of Influence of PPV at Distance during Vibrocompaction of Rockfill Columns.

The attenuation of vibrations through soil is dependent on the frequency of the vibration source, as well as the soil parameters including: grain size, degree of consolidation, density, moisture content and temperature (Wiss, 1967 & Woods and Jedel, 1985). The attenuation of vibrations for the simplified upper limit measured during initial start-up, shown in Figure 7, was calculated according to the method developed by Wiss (1981):

$$V = kD^{-n} \qquad [1]$$

Where:

V = Peak Particle Velocity (mm/s)
k = Measured Peak Particle Velocity at a Unit Distance from the Source (mm/s)
D = Distance from the Source (m/m)
n = Attenuation Rate

An attenuation rate of n = 1.0 was found to provide a strong fit to the measured results. This attenuation rate was lower than anticipated, as the findings from Woods and Jedele (1985) generally suggest attenuation rates of n = 1.5 and 1.1 for clay and glacial till, respectively. The lower attenuation rate observed during construction can be partially attributed to frozen soils which attenuate vibrations less than thawed soil (Barkan, 1962).

Understanding of the vibrations induced by the vibratory hammer during construction allowed for the initial PPV threshold of 6 mm/s at the Aqueduct (as set out in the bid opportunity) to be increased to 10 mm/s. This change was based on the observation that very short periods of higher PPV with lower frequencies occurred when the vibratory hammer was started, thereby being of less concern in respect of causing damage to the Aqueduct. PPV generally decreased by 40 to 60% of the initial peak for the remaining time the vibratory hammer was in operation as shown in Figure 6.

3.6 Slope Inclinometer Monitoring

Slope inclinometers (SIs) on the mid-bank generally measured the highest magnitude of movement at Elev. 218 m and 219.4 m above the clay/till interface. An example of key full depth slope inclinometer readings from SI09-20 on the mid-bank is presented in Figure 8, depicting movement along the clay/till interface during construction. Maximum vector displacements from select slope inclinometers are presented in Figure 9.

The SIs on the riverbank recorded small rates of displacement until construction of the rockfill columns began immediately downslope of the instrumentation. The magnitude of the riverbank movements was significant along the northeast end of the site away from the aqueduct to the corner of Rue Notre Dame and Rue Maisonneuve where the critical riverbank section existed. Riverbank movements southwest of the critical section towards the aqueduct were considerably lower as the rockfill column installation method was modified as construction approached the aqueduct, as well as the riverbank being flatter and less susceptible to instability.

The rate of construction induced riverbank movements slowed rapidly following the completion of the rockfill columns downslope of the instrumentation as shown in Figure 8. Post-construction movements on the east bank during the first four months after the completion of the rockfill columns appear to be consistent with post-construction movements following stabilization of the west bank in 2002. In 2002, monitored displacements along the west bank were observed at 40 to 58 mm/year one year after completion of the stabilization works (Yarechewski and Tallin, 2003). East bank displacements ranged from 2 to 13 mm from April to mid-July 2018.

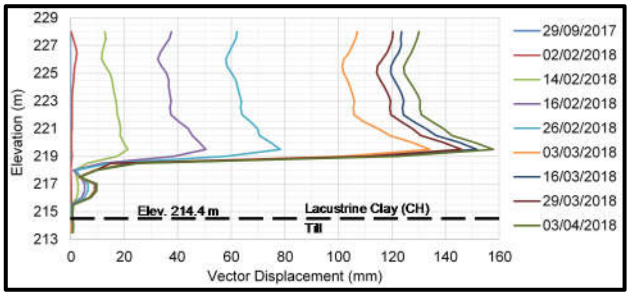

Figure 8: SI09-20 Vector Displacement with Depth

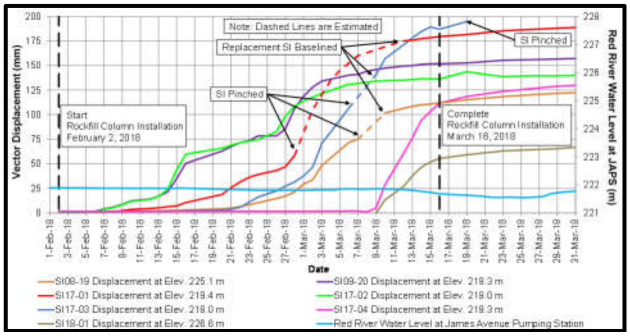

Figure 9: Maximum Vector Displacement

4 OBSERVATION METHOD

The benefit of vibrocompaction was weighed against the risk of damaging the Aqueduct from vibrations and resulting riverbank movement as the installation of the rockfill columns approached the Aqueduct. Vibrocompaction increased the density of the rockfill which resulted in increased shear strength and stiffness (Abdul Razaq, 2007; Thiessen, 2011). It was decided to modify the installation method of the last 14 rockfill columns closest to the Aqueduct alignment as the offset distance was less than 15 m. It was anticipated that resulting vibrations and riverbank movements would have exceeded tolerable limits if vibrocompaction was completed within 15 m of the Aqueduct alignment. This prediction was based on measured attenuation of vibrations from the source and the estimated reduction of riverbank stability, discussed later. Not vibrocompacting the backfill resulted in lower rockfill density, shear strength and stiffness but enabled successful construction of the columns, while mitigating the risk of damage to the Aqueduct.

Modifying the installation method of the rockfill columns was a successful application of the observational method. Actively monitoring instrumentation results during construction allowed for the prediction of when risk to the Aqueduct exceeded an acceptable level, triggering the modification to the installation method. The decision to not vibrocompact the rockfill columns within 15 m of the Aqueduct was made through consultation with the City of Winnipeg, Designer and Contract Administrator.

5 STABILITY ANALYSIS

Slope stability analysis was completed to examine the effect of construction-induced vibrations during vibrocompaction of the rockfill columns versus the short-term reduction of riverbank stability. Back analysis of the existing conditions at the start of construction was first completed in order to determine the shear strength parameters of the soil to result in an estimated factor of safety (FS) of 1.0, based on groundwater and river level conditions with a reasonable probability of occurrence.

Based on the vibration monitoring, a peak ground acceleration ranging from 50% to 60% of the measured maximum value was applied to the riverbank in the pseudo-static slope stability analysis. The applied peak ground acceleration was estimated to be 0.06 g at a distance of 11 m and 0.02 g at 24 m. A sensitivity analysis was completed for peak ground accelerations ranging from 0 g to 0.1 g, as shown in Figure 10. The reduction in the FS along the critical section was estimated to be approximately 25% at a distance of 11 m and 10% at a distance of 24 m.

The combination of the permanent riprap blanket and the temporary riprap berm resulted in a 30% increase in the riverbank stability during construction. It is estimated that at a distance of 11 m, the reduction in the FS was 25% based on the sensitivity analysis. Therefore, it is plausible that from the edge of the rockfill column to an estimated distance of 8 m upstream of the rockfill column, riverbank stability would have reduced by over 30% due to vibration. This vibration most likely resulted in the movements that were observed and measured during construction.

The estimated reduction in the FS at the location of SI17-02 during the construction of the rockfill columns is shown in Figure 11. The estimated vibrations and reduction in FS was the highest (24-30%) when installation of the rockfill columns occurred immediately downslope. This timeframe corresponded directly with measured large riverbank movements at the location. The reduction to riverbank stability was limited in scale and continuous monitoring results did not indicate any threat to the integrity of the Aqueduct.

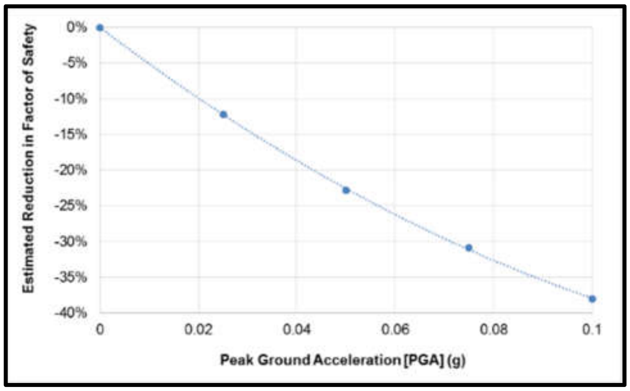

Figure 10: Sensitivity Analysis Reduction in Factor of Safety versus PGA during Construction

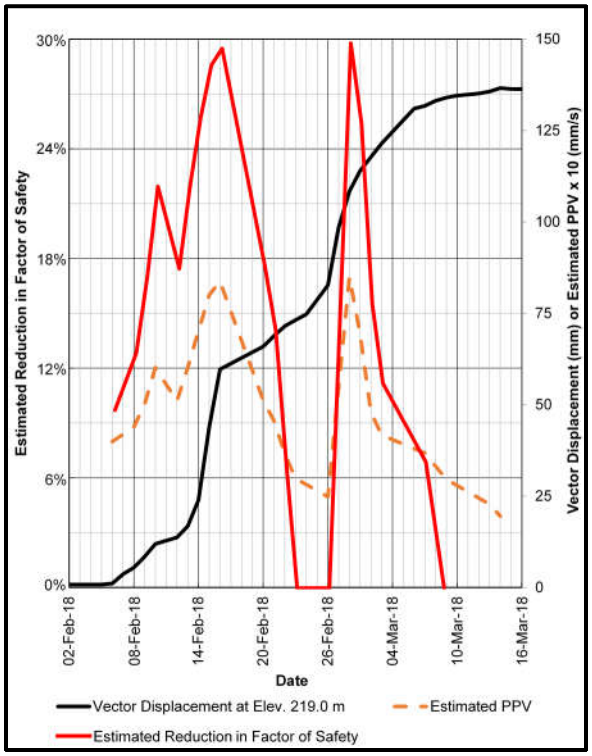

Figure 11: Estimated Reduction in Factor of Safety at SI17-02 during Construction of Rockfill Columns

6 RIVERBANK NATURALIZATION

Healthy riparian forests are by their nature resilient to environmental fluctuation and disturbance. A phased two-year re-vegetation plan was developed to create favourable conditions for riverbank naturalization by stimulating natural processes to preserve the long-term ecological health of the forest as shown in Figure 12. These naturalization measures generally improve shallow bank stability, restore ecological habitat, and minimize long-term maintenance. The augmented naturalization process and restoration of the heavily used granular active transportation path have greatly enhanced the user experience and left the site in a better condition than before construction.

Figure 12: Completed Stabilization Works and Phase 1 Riverbank Naturalization.

7 CONCLUSIONS

The Seine Riverbank stabilization at the Branch 1 Aqueduct required highly prescriptive construction methodology and sequencing, and the most comprehensive instrumentation monitoring program the City of Winnipeg had ever undertaken for a project related to riverbank stabilization. Advanced stabilization modelling and highly detailed sequencing and instrumentation monitoring were critical to maintaining the integrity of the Aqueduct under extreme conditions.

The riverbank stabilization and erosion protection works were successfully completed during the winter of 2018, with post-construction riverbank monitoring ongoing. Key to the overall success of the project was that the Aqueduct remained in operation throughout construction. There have been no indications of ongoing detrimental bank movement since construction was completed. Pre and post-construction inspections validated that the integrity of the Aqueduct was not compromised by the construction.

Similar instrumentation monitoring programs should be implemented for riverbank stabilization projects located near sensitive or vulnerable infrastructure. Vibration monitoring should consider peak acceleration, peak particle velocity (PPV) and frequency. The radius of influence from the vibration source should be monitored closely, with consideration given to the impact of short-term peaks during equipment start-up versus continuous longer term vibrations. Vibration hammers generate high velocity, low-frequency vibrations during initial startup. The attenuation of vibrations can be predicted accurately with distance using the method developed by Wiss (1981).

The observational method was successfully applied when instrumentation monitoring results showed high vibrations close to the Aqueduct, resulting in modification of the rockfill column installation method. Movements that occurred during construction were likely a result of the vibrocompaction of the rockfill columns, resulting in the short-term reduction of riverbank stability caused by induced vibrations. Slope stability analyses should consider the reduction in stability that results during the vibrocompaction of rockfill columns and the impact corresponding instability may have on the riverbank and infrastructure.

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