Vibrations monitoring for the blasting of a 70m deep shaft in an urban environment – challenges and lessons learned

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C. Trottier, M.Sc. Phys., O. Champagne, P. Eng., B. Walker, P.Geo, and J. Cubillos, Geol.
Geophysics GPR International Inc., Longueuil, Québec, Canada

ABSTRACT

The construction of Montreal’s REM light rail project includes the excavation of a 70m shaft and galleries in the bedrock of Mount Royal to create the Édouard-Montpetit train station. This multi-level blasting program poses many challenges with regard to vibration and movement monitoring. The future station is adjacent to a University of Montreal building, the Édouard-Montpetit subway station, a densely populated residential area, and main water, sewer, electrical, natural gas and telecommunication utilities; the site was excavated in three phases from July 2018 to fall 2020. This paper discusses the challenges of the monitoring program, equipment installation and monitoring of rock blasting. Aspects of the monitoring program studied include coordination with various stakeholders (client, engineering, contractors, workers, personnel and public), the use of state-of-the-art instrumentation to meet the project needs, on site installation and monitoring challenges, and the implementation of a sophisticated data management, communication, and visualization platform. We also discuss the lessons learned from carrying out this project, which include documenting various technical, environmental, and budgetary constraints, to be used as a roadmap for future projects.

RÉSUMÉ

Le projet de Réseau Electrique Métropolitain inclut l’excavation des conduits et galeries dans le soubassement du Mont Royal pour la construction de la station du train Édouard-Montpetit. Ce programme de sautage multi-niveau met plusieurs défis en ce qui concerne la vibration et surveillance des mouvements. Cette train station qui est adjacent au bâtiment de L’Université de Montréal, la station du métro Édouard-Montpetit, des zones résidentiels densément peuplée, et différents services d’utilité publique, a été excavé en trois étages depuis Juliet 2018 jusque automne 2020. Cet article discute les défis du programme de surveillance, l’installation des instruments et le monitoring des sautages. En collaboration avec différents participants (client, ingénierie, entrepreneurs, travailleurs, personnel, et publique), l’usage du dernier cri d’instrumentation pour parvenir les besoins du projet, défis d’installation et surveillance sur le terrain, et l’implémentation d’un platform sophistiqué pour le maniement des données, communication, et visualisation. Nous communiquons aussi les leçons appris à partir du ce projet qui inclut plusieurs restrictions techniques, environnementaux, et budgétaire vers la documentation afin de promouvoir la récurrence de résultats désirables.

1 INTRODUCTION

The Quebec Government, via its CDPQ Investment branch, has invested in a 67 km long light rail train system to provide the greater Montreal metropolitan area with a fast, electrified public transportation service (referred to as the REM – Réseau Electrique Métropolitain, or Electrified Metropolitan Network). The rail system extends from the south shore of Montreal to the north shore, connecting suburban areas to city hotspots like McGill University, University of Montreal, and the International Pierre-Elliot-Trudeau Airport.

Amongst the many locations connected to the network, the University of Montreal will have its own station. Located near the top of Mount Royal, the Edouard-Montpetit station is already a subway stop for university students and supporters of the Carabin varsity football team. The REM project will add services to the most frequented French University in North America.

The connection to the REM rail system had to be made via an existing tunnel that passes directly through the mountain, from downtown Montreal to the city of Mont-Royal. Built between 1912 and 1918, the tunnel is still in use today for the commuter train to Deux-Montagnes. With the tunnel located some 70m below the chosen location for the Edouard-Montpetit station, the connection requires the excavation of a shaft directly through the hard, 125 million year old metamorphic rock of the iconic Montreal Mountain.

The creation of the shaft could only be accomplished using explosives to get through the rock. What could have otherwise been a blast (literally and figuratively) becomes a daunting challenge given the sensitive environment.

Surrounding the work site are University buildings, major Montreal infrastructure, hundred years old watermains, a water reservoir servicing over 800,000 citizens, the tunnel of the subway’s blue line, and a densely populated area.

2 RISK ASSESMENT

The first step in this colossal undertaking is a thorough risk assessment study. Given the sensitive nature of explosive usage in urban area, we need to understand the main issues with performing the required work

2.1 Goals of geotechnical surveillance

The purpose of conducting vibration, noise and movement monitoring is twofold: protect the neighboring structures from damages and reduce the inconvenient to the neighborhood residents. While the former is mainly concerned with technical issues and based on established standards, the latter is dependent on the individual sensitivity the affected citizens. The importance of the second part cannot be underestimated in designing a surveillance program, and those who have conducted any sort of monitoring understand that lending an ear to the local populace goes a long way to ensuring a smooth progress throughout any project.

2.2 Surrounding structures

With an excavation of 70m using explosives in the middle of a densely populated area, many surrounding structures are susceptible to potential damages as shown on Figure 1.

The excavation removed a major part of the parking lot in front of the Marie-Victorin building that is property of the University of Montreal. The building is frequented by students and university personnel and remained open throughout the entire operation. To the west of the shaft is the Vincent-d'Indy Avenue, under which is located 2 important sewers, and a major watermain. The watermain is a 100-year-old cast iron pipe connected uphill to the Outremont reservoir and a pumping station; together, they provide drinking water to over 800,000 persons. All these utilities are withing 20m of the excavation western wall.

The neighbors to the North are an elementary school yard, the school itself and a church. Across the Vincent-d'Indy Avenue are many residential buildings. One hundred meters west is the UdM ice rink and sport pavilion.

Last but not least, the Edouard-Montpetit subway station is located directly under the intersection of Edouard-Montpetit Blvd. and Vincent-d'Indy Avenue. The station is connected by a pedestrian tunnel to the Marie-Victorin building and will be connected directly to the REM via an elevator. The subway tunnel itself passes under the Edouard-Montpetit Blvd., and the excavation will bring the wall of the shaft within 15m of the tunnel.

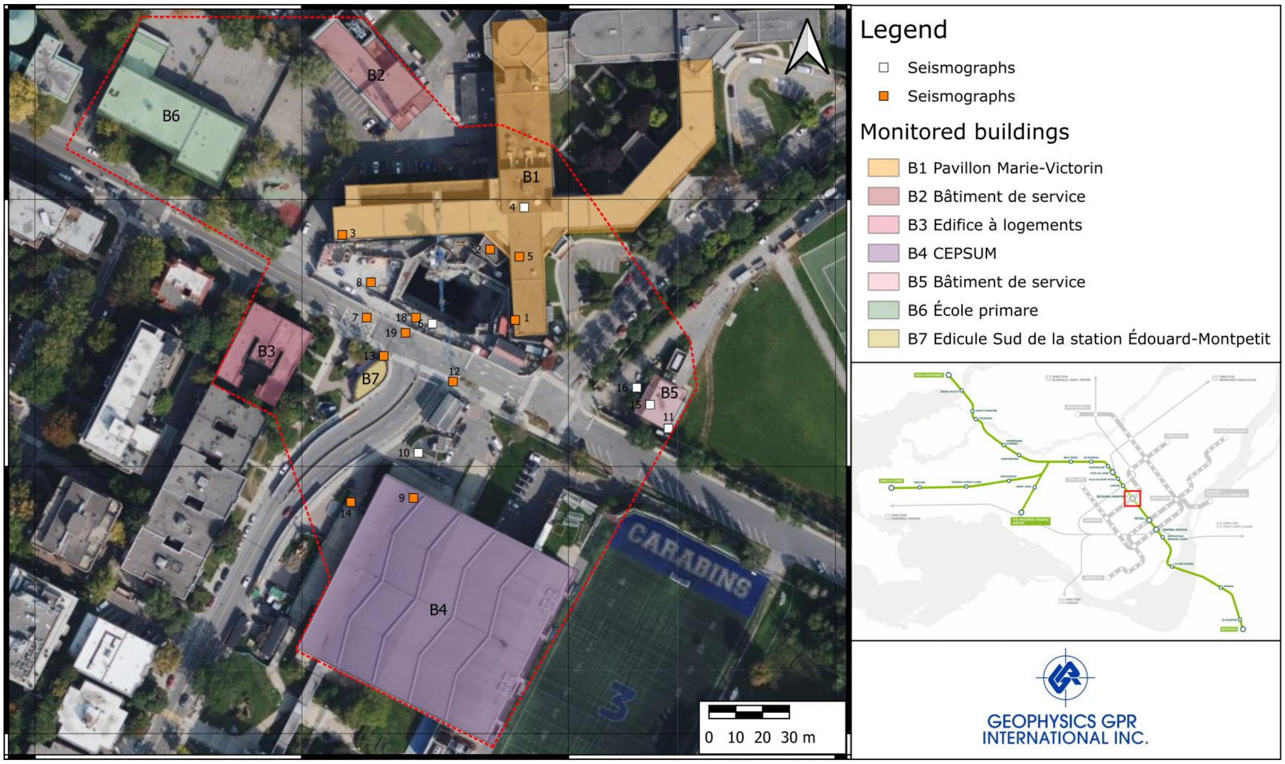

Figure 1. Monitored buildings and seismographs' location.

2.3 Risk assessment: evaluation of potential impact

The first and most obvious impact of the work will be the inconvenience to the neighbors and the users of the different public spaces surrounding the work site. The vibrations produced by the various steps of the excavation (blasting, rock breaker, work site heavy traffic, etc.), as well as the noise, need to be monitored and controlled. The public opinion and the perceived inconvenience generated by the construction are very important to manage if the project is to reach completion.

That means that vibrations need to be monitored for building protection but also to reduce the disruption to the populace. Indoor occupants will feel the vibrations more strongly than those outside, in part because of the ground born noise generated by the vibrations of the structure itself; that "noise" is generally of lower frequency, giving the impression of a lower tone "thump".

The vibrations can also impact the surrounding structures directly, especially the aging infrastructures. The old watermain services a large portion of the Montreal population. The cast iron makes it resistant to vibrations, as well as the fact it is mostly surrounded by rock, but its proximity to the blast zone and age turns it into a major concern.

Buildings are also at risk for damages from vibrations. Standards exist in the industry regarding the effect of vibrations on buildings (Siskind, 1980). Vibrations had to be monitored at the structure the closest to the shaft, the Marie-Victorin building.

The subway tunnel passes within 15m of the wall of the excavation. Just as with the other surface buildings, the concrete covering the inside of the tunnel is susceptible to damage if it is subjected to high level of vibrations. The operations of the trains are crucial since the blue line services the University of Montreal and cannot be disrupted. All precautions were taken to limit the vibrations that lead to debris falling on the tracks during operation hours. As a result, blasting was avoided during peak traffic hours, and seismographs were installed directly on the inside walls of the tunnel.

The other aspect of the monitoring includes monitoring of displacement of adjacent structures. The removal of a large portion of ground imposes significant changes to the soil conditions, meaning that the strain of vibration might cause settlement of ground, thought to have settled a long time ago. This means that both structures and infrastructures near the excavation site must be monitored for movements.

Other than the impact caused by vibrations, the blasting work can potentially release carbon monoxide gases, which are susceptible to infiltrate residencies and cause important health issues to the neighboring populace.

2.4 Risk assessment: tools at our disposal

In urban environments, it is generally accepted that blasting work impacts an area with a minimum of 100m in radius. That consideration stems from a concern about the well-being of citizens located near the work site.

In terms of actual effect on structures and buildings, it is a well-known fact of physics that the intensity of vibration, be it noise or ground vibration, diminishes with distance. The fact that there is attenuation of the amplitude of vibrations with distance means that there is a spatial limit to the impact of the construction work.

It is then possible to evaluate the radius from the source of vibrations at which the impacts mentioned above become negligible. First, we consider the general formula for the attenuation of the energy of vibration with distance.

$$I_1 = I_0 \left(\frac{r_0}{r_1}\right)^n e^{-\propto(r)*(r_1-r_0)} \qquad [1]$$

where

I_0 = Intensity of the vibrations at the source (or at the point of measurement considered as the « source »)
I_1 = Intensity of the vibrations at point of measurement r_1
r_1 = point of measurement « 1 », distance of r_1-r_0 from source point
$A_\omega I$ = attenuation factor from the medium of propagation of the wave
n = geometric attenuation factor, based on the geometry of the propagation of the wave (with the most basic considerations, n =2 for body waves, 1 for surface waves)

Simply put, the very general Equation 1 states that as you move further away from the source of vibration, the energy from the wave, generated by the source, becomes smaller at each point, and the vibration amplitude is similarly lowered. This is broken down in two (2) contributions: the geometrical factor "$\left(\frac{r_0}{r_1}\right)^n$", which accounts for the conservation of energy, and the ground factor I(r)", which accounts for the dissipation of energy from the medium through which the wave travels.

The geometric factor is always present, even in a perfectly elastic medium. While the details are outside the scope of this paper, the exact value of the exponent "n" depends on the source of the wave and the medium or type of wave considered (Gutowski & Dym, 1976).

While Equation 1 would technically enable us to predict the amplitude of vibration at every point in space around the blasting site, the ground factor needs to account for the absorption of the medium because of its nature and the dissipation due to reflection and transmission at each interface the wave travels through. In any case, 'real' ground is practically impossible to model with numerical simulation. Therefore, empirical models are used to determined propagation of waves with distance. In the case of blasting, the following equation is widely used:

$$v_i = H_i \left(\frac{D}{W^{\propto}}\right)^{\beta_i} \qquad [2]$$

where,

v = particle velocity
H = Intercept particule velocity
D = Shot to gage distance
W = charge weight
α = exponent
β = decay exponent (or slope; see below)
and *i* refers to the axis component

H and β refer to graph parameters. The decay exponent β is a negative number, illustrating the previously mentioned fact that vibrations amplitudes get weaker with distance, and is adjusted to fit the data by linear regression in a log-log graph. β takes care entirely of both the geometrical and ground attenuation factors.

This procedure requires real data from the site to design a model that will account the local conditions. Also, while some construction activities, like pile driving and dynamic compaction, have known energy at the source, the size of the source in blasting depends obviously on the amount of explosives used.

3 OPERATIONAL REQUIREMENT

In a residential environment people are concerned about their well-being, especially if blasting operations are carried out close to where they live. The fact that these structures are constantly monitored gives comfort to the residents and construction workers.

3.1 Monitoring devices and monitoring platform integration

A total number of 21 seismographs were deployed in the surrounding area of Edouard-Montpetit station. The three component (tri-axial) seismographs, with a maximum measuring range of 135 mm/s, a frequency range of 1-350 Hz, could be horizontally or vertically mounted.

In addition, 7 Utility Monitoring Points (UMP) at varying depths were installed together with 31 Surface and Building Monitoring Points (SMP and BMP).

All the information was stored and displayed in an online application where the client could verify in real time if the instruments were functioning and closely follow the civil work progress. This innovative monitoring platform was an indispensable tool for all the participants because of its ease of use, its accessibility from any from any computer or cellphone and the convenience provided by compiling all information in one format, and delivering through one point of access.

The workflow for monitoring is not particularly complex: the data is collected in the field, then it's automatically uploaded in a cloud service that sends the data to the monitoring platform web server, where the user can generate reports, check instrument status, verify alarm status and make decisions based on this information (Figure 2).

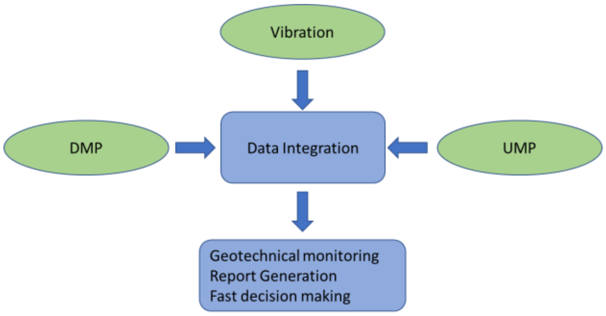

Figure 2. Édouard-Montpetit monitoring workflow

3.2 Need to react quickly

All observations recorded in the study area were obtained with calibrated seismographs, with parameters configured for the type of structure to monitor (house, building, etc.). These parameters define the alarm limits; when the vibration amplitude passes the defined threshold, the software sends a notification immediately to the people in charge at the site but also to people in charge of the operations in the civil work. The fast communication between hardware and software, shown schematically in Figure 3, makes an efficient real time transmission of information. All information is saved in case it is ever necessary to check previous readings for a long-term evaluation of impact.

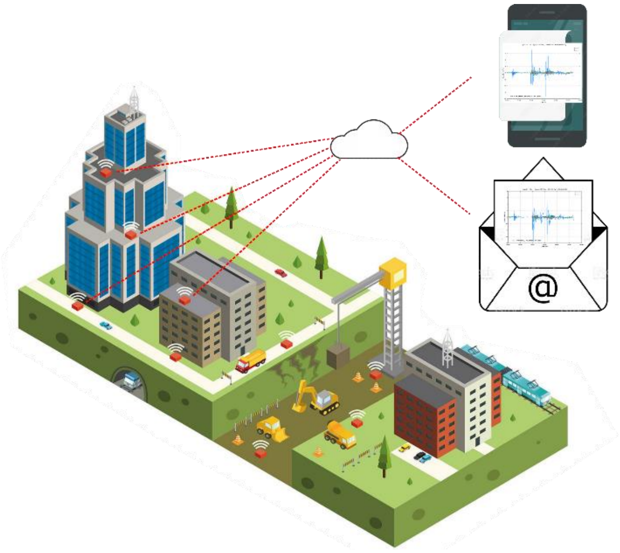

Figure 3. Seismographs network schematic operation (Modified from Syscom-Instruments, 2019)

The instruments used for vibrations and overpressure (from blasting) acquisition performed well, autonomously recording and communicating data. The integrated modem facilitated remote configuration of the devices, and data transmission.

3.3 Excavation depth and monitoring adjustments

As the work progressed and the excavation got deeper, the vibrations were felt less and less at the surface. The monitoring was slowly scaled back, removing units located farther away, where the vibrations were barely felt. Units were then kept mostly in frequented areas, where vibrations were detectable by occupants, even it the impact on buildings were negligible.

3.4 Blasting events signature

Blasts usually have many low amplitude compressional wave arrivals at the beginning of the record and finish with a long-lasting reverberation at the end of the time series (Figure 4.a.). Nevertheless, the defining feature for blasts is made obvious when we apply Fast Fourier Transform (FFT) to extract the dominant frequency of the vibrations. While other types of seismic work have frequencies that range between 0-50 Hz, blasts will have higher frequencies, usually well above 100 Hz (Figure 4.b).

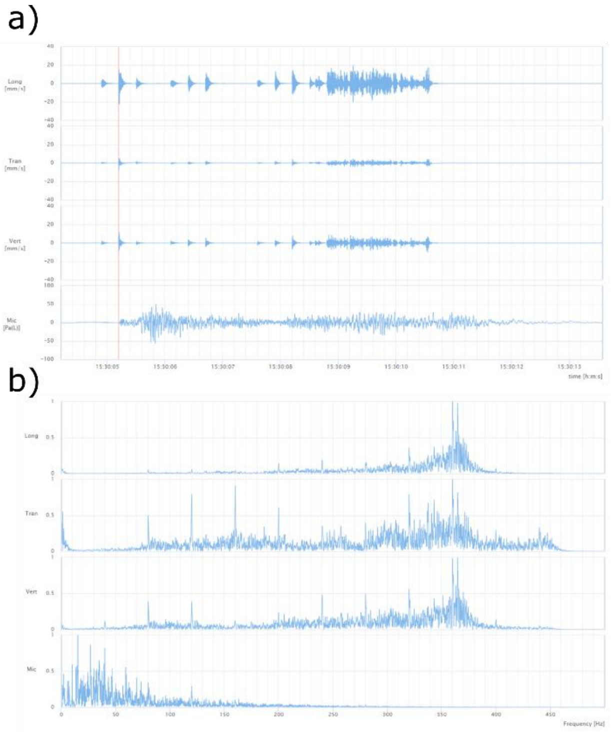

Figure 4. a) Blast event seismograph in Édouard-Montpetit b) FFT for blast event shown in Figure 4.a)

4 CHALLENGES

4.1 Limitation with vibrations

Even when the vibration monitors are precisely configured for the structures they are monitoring, there are external factors that can impact their operation. One frequent example is the interruption of communication between the devices and the software, because the mobile phone network connection can be weak or drop from time to time. For this reason, it is necessary to regularly verify if the data is being pushed by the instruments. Furthermore, the monitoring software allows for the implementation of alarms, which can later be cross reference to the data, to ensure completeness.

The signals must be analyzed subsequently by a specialized professional with knowledge in vibrations, for the possible causes that triggered the alarms. That person should have some field information about the sources that could exist in the monitoring area, especially to be able to identify true events related to civil works, from those that are not associated with blasting or construction, among others. In the near future, an automatic and independent analysis would be the next step for this research using Machine Learning (ML) methods to classify and identify different sources quickly and efficiently with a reduced error margin.

4.2 Communication

As we mentioned before, the devices send the data through a cellular phone network. In closed/remote spaces, where the signal quality is poor (e.g., tunnels, sewers, among others), the transmission becomes more limited. Consequently, it is necessary to modify the sensor antenna with a wired extension until the antenna reaches the surface or any location with sufficient mobile network strength.

4.3 Different participants with different requirements

Many entities were [potentially] impacted by the blasting and construction work. The University has sensitive equipment, like the motion capture lab located in the Marie-Victorin pavilion, as well as a large population of students and teachers. The subway system is frequented by a considerable amount of people. The city infrastructure is located around the work site. Every neighbor had a representative who was interested in the construction project information, particularly the vibration levels.

However, it was not desirable to share the issues of a single resident with the entire community. Therefore, each resident needed access to just their own data. One of the advantages of the system that was used was the great flexibility in creating access for various users, limiting the information to only the information related to their own property; each neighbor received reports of the vibrations from monitoring devices installed in their facilities only.

5 CONCLUSION

Thanks to the latest IOT technologies, we were able to deploy and develop a vibration monitoring network that recorded continuously, efficiently, and precisely the vibrations related to civil works made in Édouard-Montpetit. This network was able to recognize different types of sources and adapt to the particular requirements of the neighbors involved in the project.

The hardware and software integration through an online monitoring platform made for easy and convenient access, allowing both the client and the contractor in charge of the vibration analysis and inspections to develop a strong and efficient, real-time observation and communication channel that could adapt easily to project stakeholders demands.

Enough data was collected to develop a vibration analysis algorithm using ML, which will allow to classify and identify different events for their sources.

A robust and first order approximation was conducted to look out for civil structures integrity and soil changes due to changes generated, not only as a result from the blasting but also from the soil reworking.

The application of high quality and well calibrated geotechnical instruments, together with latest communication technology, optimized the monitoring task, such that all of the stakeholders had the peace of mind that their infrastructure was not impacted by the construction.

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