Lessons learned in vibration monitoring

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Introduction

Vibration monitoring is growing in popularity as a complement to geotechnical monitoring because infrastructure work generates noise and vibration that can have deleterious effects on structures and people. To ensure compliance with local ordinances and to protect sensitive structures, long-term vibration monitoring is more and more commonly used. The relevance of vibration monitoring was recently brought to the attention of the readers of Geotechnical Instrumentation News (GIN) by Turnbull in a March 2016 article entitled “The fundamentals of vibration monitoring - things to consider”. The article provides an overview of the technical requirements of vibration monitoring.

Our company has worked on several major projects in which vibration monitoring was a key component in addition to “traditional” geotechnical monitoring. In each of the projects detailed in this article, the first and perhaps most important thing to be decided was the goal of vibration monitoring. These goals led to the choice of the acceptable vibration limits and the appropriate sensors and data loggers. Finally, the method of data collection was determined according to the requirements of the client and the technological limitations of the equipment used. In addition to giving examples for each of the steps, we will explain how, despite following this basic methodology, unforeseen issues and human elements end up playing key parts in the lessons learned in vibration monitoring.

Project 1

Technical requirements

In this project, vibration monitoring was required for the construction of a tunnel linking a water treatment plant and Lake Ontario. Vibration had to be maintained below a certain threshold for several reasons: to ensure the wellbeing of residents; to protect private buildings and homes; and to protect a historical building that was identified as being more prone to vibration-induced damage. Near the historical building, peak particle velocity (PPV) of 2 mm/s at frequency below 100 Hz was chosen as the threshold not to be crossed. For other buildings, the threshold was 8 mm/s at less than 4 Hz, 15 mm/s between 4 and 10 Hz and 25 mm/s above 10 Hz. The threshold is varied as a function of frequency because low frequency vibration is much more damaging than high frequency vibration for any given PPV. Sensors and loggers were thus chosen according to these requirements.

Stations were installed at eight locations clustered around shafts and close to the historical building. The installation next to the historical building is shown in the picture of Figure 1. The assembled system is anchored to the concrete slab, and the old stone and mortar wall behind can clearly be seen. There are whiter parts in the wall where the mortar has been repaired before, showing that this building is indeed weakened and requires supplementary caution.

Fig. 1 : Picture of the geophone system and the historical building to be monitored.

To minimize long-term costs to the client, vibration data are uploaded daily, automatically to the client's server, where engineers can access it. This is achieved by hooking up a cellular modem to the logger and setting up scheduled data transfers. This passive method of data retrieval is well-suited for this application since we were confident that the generated vibration from tunnel construction would never exceed the threshold, thus eliminating the need for real-time alarms.

Lessons learned

Despite a smooth start, unforeseen equipment failures forced us to quickly review our setups and devise an action plant to ensure as little data as possible would be lost. Of the failures, the most common one was unreliable cellular modem communications. The modems would hang and generate issues in the transferred data, and create doubts regarding system reliability. There was a very real risk that tunnel construction would go on without our system continuously providing evidence that bylaws and other requirements were being followed. In this context, a well-prepared contingency plan is a necessity to ensure full protection for the client.

Beyond these hiccups, the main lesson learned from this project is not about choice of instruments, installation or data analysis. The main challenge proved to be communicating efficiently with the client. On several occasions, we have gone over with the client how the system works, how to configure it and how to extract data. Despite offering training sessions and providing several training documents, the client still had difficulty maintaining and using the vibration monitoring equipment.

There was a fairly high turnover rate for the people in charge of this equipment, and information would be lost from person to the next. Compounding this issue, the people in charge have often been temporary student workers, which almost guarantees their contract ends before their successor is hired and thus that they had not passed on their knowledge correctly before leaving. In the context of ensuring compliance to the project requirements, it is necessary to plan with the client how knowledge will be transferred from us to them and maintained within their team.

In short, the general outline of vibration monitoring was followed: vibration sources and limits were identified; instruments and measurement locations were chosen accordingly; and the system was set up according to the requirements. The main lesson drawn from this project is that for the system to work as intended, communication with the client and technological transfer are almost as, if not more, important than the technical aspects of the system.

Project 2

Technical requirements

Large cracks running along several hundred meters in a large wastewater sewer compromised security during infrastructure work in the vicinity of the tunnel. A collapse of the sewer could lead to flooding with wastewater in a very densely populated area. Given the length and the width of the cracks (over 5 cm), very stringent vibration criteria were set: vibration should never exceed 2 mm/s for low frequency. Similarly, cracks should not open or close at all during infrastructure work in the vicinity. In consequence, two main types of instruments were used: 12.5 mm-range vibrating-wire crackmeters and geophones. In both cases, data are retrieved in a trailer where an engineer continuously monitors vibration and crack deformation. The vibration dataloggers are linked to a cellular modem which can transfer data to a server. Special software monitors incoming data and sends out alarm e-mails as needed. In most projects an alarm e-mail sent out within 15 minutes of vibration exceeding the threshold is considered satisfactory. The major public safety risk that a collapse would cause made it preferable that an engineer would monitor the data in real-time to make any work stop in under a minute.

Lessons learned

The unique work conditions of a large wastewater sewer pose significant difficulties. Work in sanitary sewers is accompanied by a slew of worker safety rules. Installation of instruments was conducted by workers accustomed to confined spaces who had never installed geotechnical instrumentation. The first step was to prepare a course to teach them how to install the instruments in the tunnel. This was achieved with hands-on demos that had the workers install instruments on a concrete jersey (a modular road barrier) and with preparation of drilling templates with every tool needed properly identified. Despite thorough preparation, we rapidly came to the conclusion that it was necessary to be available during installation should any issue arise. It would be very difficult and costly to fix an improperly mounted or damaged instrument and we made sure to provide whatever help we could through an unreliable radio link. In addition to these considerations, working in a sewer raised logistical issues. Workers wear a special combination with respirators, heavy boots, a rubber dry suit, a radio, and three pairs of gloves that hinder their freedom of movement.

Due to the high water level and flow, protective equipment for the instruments had to be designed. After installation of each geophone, a metal cover was bolted on top to protect it from impacts from smaller debris and to deflect heavy debris carried by water. Geophone casings were also filled with epoxy resin to make them fully waterproof and their cables were fed into a flexible metal conduit that was bolted to the wall. This is illustrated in the picture of figure 2, where a geophone installed inside the tunnel, with the protective cover, the conduit for the cable, and one of the large cracks running alongside are displayed. Similar protection was provided to the crackmeters. This was all done because maintenance would have proven challenging: access is difficult and restricted; cables are bolted to the wall; and vision and dexterity are severely limited in the tunnel.

Fig. 2 : Picture of a geophone installed in a wastewater tunnel.

Flowing water during rainstorms did not significantly affect vibration measurements. Water flow barely registered on the geophones and was not anywhere near the 2 mm/s threshold. Finally, crackmeters showed that the cracks expand and contract as the tunnel heats up and cools down. The main goal of this project was to ensure that the tunnel would remain stable during construction work. It did remain stable and no crack opening or contraction were observed beyond thermal effects.

Project 2 brought up a plethora of challenges that needed very careful planning. In this project, as a follow up to project 1, we have seen the value of putting a deliberate effort into communications with the client from the very beginning of the planning stages. Doing so ensured rapid and correct installation of the instruments. To sum up, conducting a successful vibration monitoring project goes beyond simple technical considerations.

Project 3

Technical requirements

The last project is a new 5 km long sewer tunnel being constructed underneath a densely populated area. Similar to project 1, vibration had to be monitored around the shafts and along the tunnel route. In addition to vibration monitoring, “traditional” geotechnical instruments were installed (inclinometers and multipoint borehole extensometers) to measure the effects of tunneling and to ensure that no convergence or settlement would threaten the surrounding structures. Lastly, noise monitoring was also undertaken to ensure compliance with bylaws concerning noise emissions.

Lessons learned

It was estimated that the blasting schedule would pose almost no risk of damaging buildings. Indeed, 25 mm/s is the accepted threshold for modern buildings and the blasting schedule was designed to keep vibration much lower for any single event. Monitoring was thus mostly meant to reassure residents, because humans feel vibration up to ten times less intense than those that normally pose a threat to buildings. Having this system in place also ensured that if any blasting event was higher than expected, it would be quantified and any resulting damage could be assessed subsequently.

With event-based and general monitoring of blasting in mind, an automated data collection system with cellular modems was put in place to ensure that data were transmitted rapidly to the server. Specifications required that the blasting foreman must be alerted within 15 minutes by the construction contractor if any vibration crossed the threshold. To this end, the specifications written by the city engineers required alarms to be sent out to the construction contractor upon 2.5 mm/s peak vector sum (PVS) for any frequency. This type of arrangement is fairly common to ensure that work cannot continue while generating harmful levels of vibration.

Peak vector sum is defined by the following equation: $PVS = \sqrt{tran^2 + vert^2 + long^2}$ (1) in which *tran*, *vert* and *long* are respectively the transverse, vertical and longitudinal PPV. However, the datalogger could only relay alarms on the PPV and not on the PVS. This raises the issue that each axis could be below 2.5 mm/s PPV while their PVS is above 2.5 mm/s, and no alarm e-mail would be sent out. As a compromise, alarms are relayed if any one of the axes are above 1.8 mm/s, which leads to a maximal possible peak vector sum of 3.11 mm/s according to equation (1). Lower values could have led to too many false positives and hampered progress of the tunnel construction. Figure 3 shows the measured *tran, vert, long* and PVS values over a one-month period. The green line at 1.8 mm/s shows the alarm threshold. It can be seen that the measured vibration are typically much lower than the 1.8 mm/s threshold, blasting events have created PPV as high as 11 mm/s. There are also clear lulls during weekends where little to no vibration is measured.

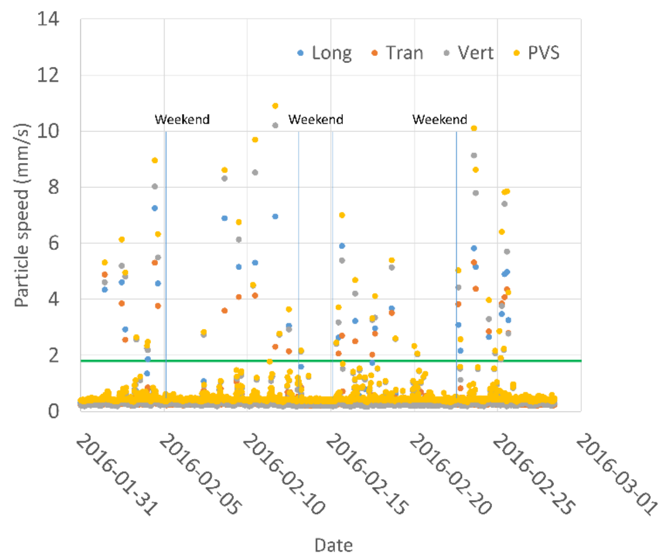

Fig. 3 : One-month sample of vibration measurements near a shaft.

The automated system was required and expected by the client to be functioning twenty four hours per day. Clients and construction contractors expect this to be a cheap and straightforward affair that requires little to no maintenance. However, the large number of components (batteries, casing, logger, sensors, and cellular modems) make these goals difficult to reach. The loggers and cellular modems are finicky and sometimes unreliable, occasionally requiring to be reset on-site. Having staff available to check on the systems weekly and to replace batteries and recharge units, made vibration monitoring much more involved than originally planned.

This project proved to be fairly straightforward once the technical issues were settled. A lesson to be drawn from this project is that, vibration criteria can be chosen for their effects on residents rather than only to protect buildings and infrastructure, and systems were designed to provide automated alarm e-mails.

Conclusions

In every vibration monitoring project, technical requirements come first: frequency range, sensitivity, measurement range, etc. Choosing thresholds according to the specific needs is possibly the most critical decision for this type of monitoring. Other important considerations include that humans are much more sensitive to vibration than structures. Also that there can be older, more sensitive structures. However, creating a good monitoring project that fulfills its duty also requires deliberate planning and communication with the client, from the planning phase to its final execution. This is an often overlooked point that proves to be very important in vibration monitoring, perhaps even more so than in “traditional” geotechnical monitoring because it is chiefly implemented for safety, legal and wellbeing reasons.

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