Reducing the Intrusion: Instrumentation and Monitoring for Urban Excavation with Non-Contact Technologies

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ABSTRACT
The Instrumentation and Monitoring Program (IMP) is becoming a critical aspect of project scope due to the increasing complexity and sensitivity of the environment surrounding deep urban excavations. The items monitored include the ground, shoring structures, adjacent buildings, roads surfaces as well as underground utilities. However, there are also constraints on the deployment of an IMP such as the congestion of the construction sites, the difficult access to the instruments, the (lack of) coordination among multiple players, the myriad of permits and clearances required, the continuous traffic of vehicles and of pedestrians, etc. It is very common that the implementation of the IMP gets delayed, that its scope gets reduced, or that the continuity of the monitoring data is jeopardized, increasing the overall geotechnical and structural risk associated to the project. This paper introduces state-of-the art IMP technologies. Focus will be on the advantages and limitations of those technologies by demonstrating how they can individually be beneficial for the success of the project (safety, reliability, productivity, competitiveness, etc..).

RÉSUMÉ
L'importance du Programme d'Instrumentation et d'Auscultation de travaux souterrains urbains accroit avec la complexification des villes et la volonté croissante à limiter les nuisances pour la population. De tels programmes permettent de conserver en état les bâtiments adjacents, les routes, les réseaux enfouis. Ils génèrent cependant des nuisances (interruption de la circulation, accès à des propriétés privées, etc.) et sont soumis à des contraintes de site (permis, préservation du patrimoine, etc.) qui rendent leur déploiement laborieux. Cela peut induire des délais, voire une réduction du programme, au détriment de sa pertinence et de sa performance. Dans cet article, nous présentons des solutions innovantes d'instrumentation pour des travaux urbains souterrains, qui ont l'avantage de réduire les nuisances tout en améliorant la performance du programme (sécurité, précision, intervalle de mesure, temps de réponse, résolution spatiale).

1 CHALLENGES OF URBAN EXCAVATIONS

1.1 You said intrusion?

Underground work happens frequently in urban environments: excavations for vertical constructions, utility work, micro-tunnels, extensions of buildings below ground, transportation and transit tunnels, sewers and combined sewers/overflows (CSO), etc. In most cases, the disruption of the ground induces collateral movements involving deformations of adjacent structures (buildings, aerial structures, vaults, etc.), of the surrounding ground (road surfaces, rails tracks, airports runways, subgrade, utilities, etc.), of existing underground structures (underground spaces, tunnels, sewers and collectors) and of the temporary retaining structures (shoring walls, supports of excavations, etc.).

Because urban environments are structurally dense and sensitive, they often require numerous monitoring devices, combining different types of technologies to ensure redundant collection of information from the site. The number and the concentration of measurement points, as well as the time interval between consecutive readings, increases with the geotechnical risk and the level of controversy of the project and risk-mitigation culture of the project team. The process is usually intense and invasive.

The more sensors on the ground combined with a higher frequency of readings results in a higher rate of intrusion caused by the project. This applies to private spaces, public spaces and construction sites. By intrusion, reference is made to recurrent lanes closures, traffic interruption or rerouting, random access to private buildings for the collection of readings (manual probes, survey points), co-activity on construction sites, synchronization of critical path construction activities, damages to pavements and buildings for the installation (and removal) of sensors or reflectors, and routine calibrations or maintenance of those sensors and reflectors.

1.2 Reassure but don't cause discomfort

There is no question about the relevance of an Instrumentation and Monitoring Program (IMP) for urban underground work. The program provides accurate information in a timely manner to mitigate the geotechnical, environmental, and structural risks. This also constitutes a very efficient tool to adjust the working methods or design criteria in the field. Changes are based on the response of the ground, structures, and environment under continuous measurement.

The serenity provided by the IMP is also used by projects owners, to demonstrate that the project is conducted with care and full control. It is therefore important to find the proper balance between the added value of the IMP and the nuisance caused by its installation, its maintenance, and its removal.

Figure 1. Vehicle towed for the installation of geotechnical instrumentation

Rather than reduce or constrain the scope, it is recommended to opt for wireless, remote or non-contact technologies whenever possible. These technologies generally can be partly or fully automated. They tend to limit damages caused during installation (if any) and eliminate most of the random human disturbance for data collection, routine maintenance, and trouble shooting. In most cases, they improve the performance of the IMP (accuracy, temporal resolution, spatial resolution). These solutions improve safety by reducing the need to send workers to hazardous areas such as driving lanes and shoulders, edges of excavations, confined spaces, unsafe neighborhoods, etc. This paper will describe four examples of wireless, remote, or non-contact technologies, applicable to the monitoring of urban excavations and urban underground work.

2 EXAMPLES OF NON-INVASIVE MONITORING TECHNOLOGIES

2.1 Wireless Integrated Sensors

Newly emerging technologies such as IoT (the Internet of Things) and wireless sensors have been adopted and popularized in the past few years in our industry. Deploying conventional geotechnical, environmental, and structural sensors can quickly become challenging with numerous cable connections used for communication and/or power. Cables running from the sensors to the data acquisition box are prone to damage by construction activities. This also poses constraints in locating the data acquisition device with the goal of limiting the length of cabling.

2.1.1 Description

Wireless integrated sensors are turn-key devices encompassing the sensors (tiltmeters, extensometers, etc.), the battery, and data transmission unit in a compact and ergonomic assembly. Built upon low-power, wide-area network (LPWAN), one of the fastest growing IoT technology, an alternative solution is provided to reduce intrusion on site.

2.1.2 Advantages

LoRa, one of the prevailing LPWAN technologies (Semtech Whitepaper, 2017), enables up to 15 kilometers of wireless communication distance while maintaining battery operation for over 10 years. This significantly outperforms most of the existing standard radio communication technologies usually implemented for IMPs in the last two decades. LoRa's long-distance capability results from its unique wireless modulation, called chirp spread spectrum modulation, and its communication protocol. Such long communication distance might seem unnecessary as it greatly exceeds the scale of a typical urban excavation site. However, this feature improves the deep penetration in dense urban/indoor environments, encountered in most urban excavation sites. To reach long distances, LoRa operates by increasing the message travel time in the air. This is described by a parameter known as the spreading factor (SF). Low SF indicates faster data transmission and is used for short distance communication, while high SF indicates slower data transmission with better immunity against interferences, but also requires more power for long distance communication. A mechanism called ADR (Adaptive Data Rate) allows the node to automatically negotiate the lowest possible SF with the gateway based on the signal strength and balance the signal resolution, transmission rate, and power consumption.

Due to its superior point-to-point communication distance, the LoRa network utilizes a star topology, which does not require a node in the network to receive and forward information from other nodes as is required in a mesh topology network. Therefore, it reduces the network complexity and increases its robustness. The nodes in a LoRa network are asynchronous and communicate only when they have data ready to be sent, which is different from a synchronous network, such as cellular, in which the nodes must frequently 'wake up' and consume more power.

2.1.3 Limitations

The sensors for IMP applications usually have a much higher sampling rate than other IoT devices, and tend to shorten the battery life. However, they can operate without changing the battery for the duration of most urban excavation projects (1 to 2 years).

2.1.4 Applications

Wireless integrated sensors simplified the installation of structural sensors (predominantly tiltmeters) located inside buildings, galleries or caverns. They do not require any permanent power outlet in their vicinity and their small size makes them very discreet. Furthermore, they do not require cables or the installation of radio relays to transmit the data to the central server. As a result, installation is faster and less invasive.

Wireless integrated sensors are also used inside boreholes monuments (inclinometers, extensometers, observation wells), specifically when their access is restricted (driving lanes, parking lots, etc.). The ability of LPWAN technologies to penetrate through cast iron lids or concrete covers, enables transmission of data from the borehole/vault without the need for a trench to string cables between the logger and sensor.

2.2 Automatic Motorized Total Stations (AMTS)

Conventional optical survey methods have been used successfully to monitor excavations and underground work, regardless of the environment. They generally involve the setup of a complex geodetic traverse, which prevents survey crews to run survey loops with very high frequencies during construction. Manual surveys for tunnels projects are typically conducted at intervals greater than 24 hours, most of which occur weekly, for practical reasons. As a result, the response time of the monitoring program is slow and the redundancy of the readings (single reading per loop) is not guaranteed.

Moreover, the presence of a survey crew in the project's environment induces safety concerns, creates some intrusion, and can imply costs related to traffic control or access restrictions on sidewalks. In most cases, the operator must enter properties to initialize the survey rod at each monitoring point. This method constitutes a constant reminder for the public that construction is occurring in their environment.

2.2.1 Description

Automatic motorized total stations (AMTS) are survey robotic total stations (RTS) that are fully automated and operated remotely. They monitor the 3D displacement of optical reflectors (prisms) attached to the ground or to structures being monitored. AMTS are installed on a pedestal (ground level, roof tops – see Figure 2, platforms) or on a bracket attached to a vertical structure (wall, pillar, beam, etc.) for the duration of work. They are usually positioned underneath a light roof to protect them from adverse weather conditions, ultraviolet light, and animal disturbance. When the ground or structure supporting the AMTS is potentially unstable, it is recommended that an automatic leveling device (ALD) is included to keep the instrument vertical, within tolerance of its internal compensator. The unit is composed of a control box including a battery, data transmission unit (wired or wireless), and computer (dependent upon whether the RTS has its own IP address; with an IP address no field computer is required which reduces the power consumption). The AMTS can be powered by a permanent power source (if available) or solar powered. The use of solar panels may limit the ability of the AMTS to operate around the clock, specifically in near-polar latitudes or if reflectorless readings are performed.

Figure 2. Typical AMTS installation on a roof top. Monitoring of an adjacent urban excavation for vertical construction

Once an AMTS is installed and commissioned, it collects monitoring data (angles and distances) automatically 24 hours a day. The RTS can locate the optical center of the prisms by using the automatic target recognition (ATR) feature which ensures that the same physical point is measured consistently.

There is no technical limitation to the number of points that one AMTS can measure. However, the higher the number of points, the longer the time interval between two consecutive readings. The number of points measurable by one AMTS is determined on a case by case basis from the monitoring interval and the accuracy specified in the contract (typical rates are between hourly to four times per day for urban construction) along with the site conditions (obstructions of sightlines).

For monitoring applications, the operational range of an AMTS is typically between 100 m and 150 m, depending on the accuracy required and the RTS model used. Monitoring points must be located within this range and have direct line of sight to the RTS.

AMTS can be located within the settlement zone provided they can measure enough reference prisms located beyond the settlement zone. In that case, at recurrent intervals, the AMTS will measure those benchmarks and recalculate its own position and orientation by least square adjustment of a 3D triangulation.

The output of an AMTS system is a time series of {X, Y, Z} coordinates for each prism. AMTS generally provide those coordinates with an accuracy down to ±1mm (1σ) within the operational range. Typically, an AMTS can measure 100 points and deliver monitoring results on an hourly interval, with an accuracy of ±1mm (1σ).

The monitoring results can be uploaded in any standard integrated database management system (IDMS) to provide near-real time information to stakeholders involved with the project, and raise automatic alarms if movements exceed threshold levels.

2.2.2 Reflectorless Monitoring

Most AMTS now offer the possibility to perform reflectorless measurements with the same instrument. Instead of sighting a prism, the AMTS sights the ground surface directly. There is no artificial reflector used in this case. The AMTS relies on the natural reflectivity of the ground material (concrete, asphalt, etc.) to reflect the signal of the electronic distance meter (EDM). Points are defined by vertical and horizontal angles that the AMTS will use orient itself.

As the ATR feature is irrelevant in this case (there is no optical center for the impact point), there is no guarantee that the AMTS always sights the same physical location, especially if the AMTS is located within the settlement zone. Therefore, AMTS in reflectorless mode do not monitor the 3D displacement of individual points. Instead, the mesh of reflectorless points is used to interpolate a digital surface model (DSM). The vertical deformation of the DSM is the result of the reflectorless monitoring of the ground. This output is uploaded to standard IDMS and displayed using vertical displacements for a grid of points or using isolines displaying movements.

Because of the limited reflectivity of the ground material, the operational range of AMTS in reflectorless mode is usually limited between 50 m to 80 m. The vertical accuracy of the deformation model can be accurate to ±1.5mm (1σ) if the system is used under proper conditions.

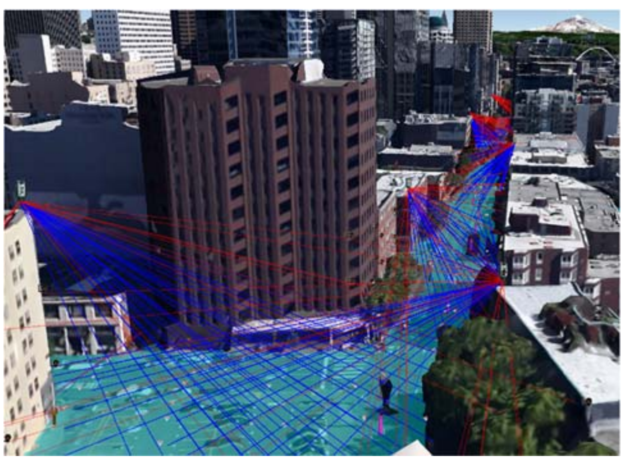

Figure 3. AMTS used in reflector mode (red lines) and reflectorless mode (blue lines) to simultaneously monitor building movements (prisms) and ground deformation (reflectorless points). 1st Avenue in Seattle, WA during the construction of the Alaskan Way tunnel

2.2.3 Advantages

AMTS are silent, optically safe, and compact. They are inconspicuous once installed and do not constitute a substantial disruption to the public environment.

As they operate continuously and automatically, AMTS measure points with a high frequency (typically every twenty minutes to hourly). Several measurements can be performed by the AMTS within one monitoring interval (usually hourly to daily). This inherent redundancy gleans the results by filtering the data (median or average) and improves the overall accuracy of the monitoring data.

AMTS usually have their own QA/QC features integrated in the work flow. They can immediately identify erroneous or suspicious data

Recent AMTS have integrated cameras in the RTS (Figure 4). This feature is very useful for troubleshooting the system remotely, without sending a crew to site for an inspection. This improves safety on site, the reaction time of the team and helps document events on the job site.

Figure 4. A close-up image taken by an AMTS camera showing a prism covered with grout at the top of a support of excavation.

AMTS are fully automated, operated and reconfigured remotely. They significantly reduce the exposure of workers to construction hazards and burdens related to coordination of activities. At any point in time, they can be reconfigured to intensify the monitoring in a specific area of interest, with limited or no additional cost. The cost of the system is not related to the number of readings taken. This is useful when incidents happen on site and contractors ask for additional or faster readings temporarily.

A large part of the costs for an AMTS comes from the initial setup. The subsequent rental and service is usually very competitive compared to manual surveys, based on hourly, daily and even weekly readings. On average, it is estimated that AMTS are more cost efficient than conventional survey after a period of 4 to 8 months. The savings increase with the increase of the duration of the job.

Reflectorless readings also have major advantages. They are non-destructive and very inexpensive. They do not require a physical installation which eliminates exposure to many hazards. Therefore, it is easy and painless to use them to optimize the spatial resolution (or the temporal resolution) of the monitoring program.

2.2.4 Limitations

AMTS are not very versatile because their initial setup is complex. They are not intended to require regular relocation. In that sense, AMTS are not suitable for very congested construction sites with frequent reorganizations of the site layout. AMTS may not be suitable for mobile or fast-moving projects such as micro-tunnels. For those projects, conventional survey may be more appropriate because survey crews can easily re-route their traverse to accommodate changes in site conditions and new obstructions.

AMTS are sensitive to adverse weather conditions. The ATR requires reasonable visibility of the prism and the laser signal of the EDM is absorbed by stagnant water. Measurements may fail for prisms installed low on the ground and covered with morning dew. Reflectorless measurements may fail on wet pavements prior to the drainage of stagnant water. Readings will fail or be erroneous on snow pack. A lot of those circumstances can be anticipated, and remedial measures exist to a certain extent. For example, prisms can be protected to prevent the accumulation of snow and rain drops on the glass.

Finally, AMTS cannot monitor features enclosed in a vault or in a monument, such as subgrade or utility monitoring points. Those points require an operator to expose the point physically. There are designs providing a rigid connection of the monitoring point to a point at the surface, but they are not applicable in all circumstances. Another approach in this scenario is to replace one subgrade or utility monitoring point, by a mesh of reflectorless points at the surface. An AMTS will then provide a wider and faster monitoring of the surface near the utility (or subgrade), with high spatial resolution, which can be beneficial in some cases, but which can possibly be inefficient if the utility (or subgrade) and the surface behave independently.

2.2.5 Applications

AMTS are now commonly used in urban excavation projects or urban tunnels projects. On the Alaskan Way tunnel project, a 3 km tunnel bored with a 19 m diameter EPB-TBM underneath downtown Seattle, WA, 41 AMTS units have been used from 2012 through 2018 to continuously monitor more than 160 buildings with prisms, 1500 reflectorless points spread along the streets within the zone of influence, an existing BNSF tunnel and several iconic structures such as the monorail and the Pike Place Market. The reflectorless points were not specified in the RFP but adopted as an improvement to the performance of the monitoring program by increasing the spatial resolution and reducing the response time of the monitoring plan. Similarly, the monitoring of the existing BNSF tunnel was intended to be performed with conventional survey and borehole extensometers drilled from inside the tunnel. That would have created a lot of conflicts with the operations of BNSF. A single AMTS unit superseded the complete scope and provided suitable monitoring information during construction of the tunnel.

AMTS are increasingly used to supersede conventional survey for the monitoring of temporary shoring structures within urban excavations, as well as the adjacent buildings (Figure 5).

Figure 5. Use of an AMTS to monitor the shoring structures of an urban excavation, as well as adjacent buildings. Confidential project (downtown Los Angeles, CA)

On this project, the AMTS drastically reduced the exposure of workers to hazards such as co-activity and elevated works. The system also eliminated coordination on site with concurrent activities. After 6 months of monitoring, the use of AMTS became more cost effective than conventional survey. At two points during construction, the AMTS detected early stage abnormal deformations of the support of excavation, which enabled the contractor to stop the work in a timely manner and take precautionary measures accordingly.

2.3 Interferometric Synthetic Aperture Radar (InSAR)

The ground instrumentation (geotechnical, structural, environmental) provides accurate and subsequent near-real time information about the behavior of the ground and structures located within the anticipated zone of influence. Some of those instruments rely on benchmarks located beyond the assumed zone of influence.

For practical and financial reasons, the extent of the area covered by the ground instrumentation, and the spatial resolution of the monitoring devices within this area are limited. The ground instrumentation provides very reliable information with a fast response time but has two major weaknesses: implications when no devices are installed within the zone of influence, and various unknowns related to the area beyond that covered by the ground instrumentation. InSAR fills the majority of those two gaps.

2.3.1 Description

Various civil constellations of satellites carrying synthetic aperture radar (SAR) sensors orbit around the earth in polar orbits. Therefore, any point on the planet can be revisited every few days. Currently, the fastest revisiting times are slightly better than a week, depending on the constellation. Current developments of new constellations are forecasted to reduce the revisiting times to daily in less than five years (Aguttes J.P., 2001). It is possible to acquire SAR images of the ground surface, at regular intervals. SAR images record each pixel's travel time from the radar signal source to the impact point on the ground and scatter back to the radar source aboard the satellite. For civil commercial satellites currently used for monitoring purposes, the footprint of one pixel on the ground is approximately 3x3 m^2.

SAR interferometry (InSAR) is a monitoring technique measuring the deformation of the ground surface, in the direction of the line of sight (sub-vertical for most civil SAR constellations). InSAR algorithms compare those travel times between consecutive SAR images. For monitoring purposes, not all pixels are compared. InSAR monitoring algorithms only focus on pixels which have a systematic, stable and unique spectral signature. Those generally correspond to geometric physical objects on the ground, unmoving, reflective and distinct, such as building edges, rocks, pipelines, urban equipment, etc. They are called permanent scatters (PS-InSAR). They have a very clear, stable, and characteristic spectral response which is easily identifiable in all SAR images acquired and processed during the life of the project.

InSAR compares the evolution of travel time of the radar signal for each PS. Changes are translated into displacement along the line of sight. For monitoring purposes, only the vertical component of this displacement is considered in general. The monitoring information can be uploaded to any standard IDMS (Figure 6), either as a displacement map (mm), or as a deformation speed map (mm/yr). For each PS, it is possible to obtain a time series of the vertical component (displacement or velocity). Each SAR image acquired corresponds to one point in the series.

The accuracy of the monitoring data is ±2mm to ±3mm (1σ) for displacements and ±1mm/yr (1σ) for velocity with X band SAR sensors.

Figure 6. Example of InSAR data for urban projects

2.3.2 Advantages

SAR images cover wide areas (up to 40x40 km^2) and extend far beyond the zone of influence for most urban projects. They provide accurate monitoring information within the zone of influence of the project to validate monitoring results obtained from the ground instrumentation (usually with a higher spatial resolution). InSAR also provides accurate information on potential effects caused by the construction beyond the area covered by ground instrumentation. This information allows confirmation of the validity of the settlement study performed during the design phase and to identify actual construction influence extents beyond the anticipated zone of influence. InSAR has been used on the NZlijn metro project located in Amsterdam to dismiss a claim from a building owner claiming remediation costs from the city due to reported damages to his property located beyond the anticipated zone of influence. InSAR was able to clearly demonstrate that this specific building had not been affected by the metro project, but potentially by other dewatering activities simultaneously occurring on another private site in the area.

InSAR is a completely remote technology. There is no need for ground work, unless artificial PS need to be installed locally. This is a completely invisible activity to the public.

Urban environments in North America typically have 15,000 to 25,000 PS/km^2. This number decreases for vegetated areas or areas with high traffic (highways, ports terminals, parking lots, etc.). This density of monitoring points cannot be achieved with conventional ground instrumentation, specifically on such a wide scale. InSAR potentially improves the performance and cost efficiency of the monitoring program.

SAR images are being acquired regularly over most strategic places on earth since the early 90's. In this casem it is possible to perform a retro-active analysis of the ground deformation and settlement of structures from previous years, even without ground monitoring in place at that time. This is a powerful tool to get extensive, reliable, and accurate baselines before new construction begins.

2.3.3 Limitations

InSAR for monitoring relies on the presence of natural PS on the ground. Although it is possible to add artificial reflectors on the ground, there are areas where InSAR will be inefficient due to the lack of natural PS, or due to the fast evolution of ground coverage. For example, roads with dense traffic or docks with containers are places where InSAR does not perform well.

InSAR is not meant to measure fast movements, with high magnitudes. When displacement rates exceed certain limits (which depends on the wave length of the radar signal used), InSAR algorithms may fail to capture the proper deformation of the ground prior to the collection of additional data.

Revisiting times are improving. However, InSAR will never be a (near) real-time solution and as such, cannot supersede ground instrumentation. Instrumentation remains essential for early warnings and automated alarms.

InSAR measures the displacement of surfaces corresponding roughly to the footprint of one pixel in the SAR image. Specifically, it is capturing an average behavior of the ground and structures located within this area. It is not always possible to compare the InSAR results within one pixel and the settlement data collected for a survey point on the ground. The survey point may measure the settlement of a building lying on deep foundations while the InSAR data represents the overall ground deformation. They may not be the same.

Finally, InSAR is presented herein as a technique monitoring vertical movements. Under very specific conditions, and by acquiring images in ascending orbit and descending orbit, it may be possible to breakdown displacement along the line of sight into a vertical and horizontal component. This is subject to many conditions, including, among others, the orientation of the structure monitored. Since images need to be acquired in ascending (S to N orbit) mode and descending mode (N to S orbit), the price for the acquisition of the SAR data doubles.

2.3.4 Applications

InSAR was recently specified in the RFP for two major urban construction programs in Europe: "Crossrail" in London, United Kingdom and "Le Grand Paris Express" in Paris, France. It is interesting to note that InSAR is now becoming a standard within the industry. For the Crossrail project, the fact that an InSAR baseline was available, and that InSAR monitoring data was continuously acquired and processed during the construction, considerably reduced the insurance costs for the project.

InSAR baseline and monitoring have also been provided for the Alaskan Way tunnel project in Seattle, WA from 2012 to 2017. InSAR was not specified in the RFP but both the owner and the contractor acknowledged before the start of construction that InSAR could be beneficial for the project. They decided to implement an InSAR monitoring program, financed equally by the owner and by the contractor. During the tunneling phase of the project, a settlement event occurred (for reasons still to be determined – not necessarily linked to this project), and affected both the influence zone of the project, but also areas beyond the zone of influence, including areas where references prisms for AMTS were installed and benchmarks for manual surveys were installed. Monitoring of its progression has been limited to InSAR methods showing the extent and the magnitude of this unexpected settlement. InSAR data has also been used to reset the positions of the reference prisms affected by this unanticipated movement and to maintain the continuity of the AMTS monitoring from start to end of the project.

2.4 4D Tomography

It is also possible to reduce the nuisances related to the use of underground instrumentation. Borehole extensometers (MPBX, SPBX), borehole inclinometers, piezometers, etc. often require traffic control during their installation, maintenance, and collection of readings if they are not automated. They cannot be eliminated from the IMP, but it is eventually possible to optimize their number and locations using the information provided by 4D tomography.

2.4.1 Description

In the last decade, ambient seismic noise interferometry has been used to monitor the time-dependent underground behaviors in various environments. This method essentially uses ambient seismic vibrations (caused by traffic, TBM, trains, metro, etc.) to create virtual seismic sources. This method can detect very small changes in the seismic velocity within stratigraphy (Olivier et al., 2017).

The data is collected continuously by a mesh of uniaxial and/or triaxial geophones buried in the subgrade (approximately 40 cm deep) to shield them from wind and rain. The spacing between the geophones depends on the site conditions and on the objectives of the monitoring program. The maximum depth monitored corresponds to approximately one third of the longest spacing between two geophones within the mesh.

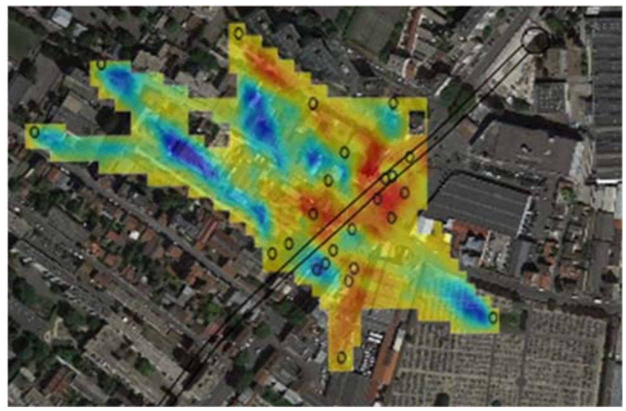

Figure 7. Example of mesh of geophones used to process a tomographic image (S Wave velocity values in a given time) on "Le Grand Paris Express", Paris, France.

The 4D tomography highlights areas in the ground where ground conditions were potentially improved or deteriorated. This may be the result of a sinkhole slowly raising to the surface, a decompression in the ground or caused by ground improvement (grouting, compaction, stones columns, etc.).

2.4.2 Advantages

The geophones used to collect data are buried in the subgrade. Their installation is much easier, faster and less intrusive than the installation of any borehole instrument installed via drill rig. They are trenchless as they are powered with batteries. The deployment of a geophone mesh thus generates negligible disturbance to the public during the installation phase.

The 4D tomography constitutes a very efficient and reliable time sensitive method to detect a phenomenon slowly coming up to surface. Moreover, the 3D model obtained is continuous, and detects events not necessarily occurring at the location of the geophones, in opposition to MPBX which only reacts if the ground compresses or expands exactly at the location of the instrument anchors.

2.4.3 Limitations

The huge volume of data recorded by the geophones makes real-time transfer of data to the central server very challenging with the current technologies. The geophones can be wired (ethernet, optical fiber, etc.) but require trenches to run data and power cables. This seems to defeat the purpose of a light non-intrusive method. In some cases, trenches cannot be dug (i.e. across highways) and this influences the design of the geophone mesh. The results obtained from a mesh with an irregular geometry are less reliable and will probably consist of shadow areas with no data.

Although this technology has the advantage of providing an early warning, it does not clearly describe the nature of the event, nor its magnitude. It is only when the phenomenon reaches the surface that it can be quantified and qualified. This technology should be used as a decision tool at an early stage to identify areas where the focus of the ground instrumentation shall be in priority.

2.4.4 Applications

4D tomography has been used on “Le Grand Paris Express” project for two purposes. The first was to monitor the degradation of the soil during tunneling. The method revealed changes in the stiffness of the ground in a section where the ground was known to be susceptible, which quickly resulted in ground settlement measured by AMTS units at the surface. It helped during tunneling by prompt indication that a ground movement was to be expected, which enabled adjustment of the boring strategy and optimization of the monitoring at the surface. It also showed that nothing out of the ordinary was happening in other sections of the tunnel.

The second application was to measure the positive effect of the ground improvement work performed prior to tunneling by injection grouting. By determining a 6 week baseline, an average soil condition was established. The 4D tomography measured a deterioration of the soil conditions during grouting, followed by a gradual improvement in the stiffness of the soil as the grout cured in the following weeks. The result displayed a much stiffer ground.

3 CONCLUSION

The technologies presented herein are innovative, cutting edge and have been adopted by the construction industry. They have been implemented for production in various projects. They reduce the nuisance and intrusion in public spaces for urban projects and reduce the hazards for workers. They also improve the performance of the monitoring program (spatial resolution, frequency of readings, accuracy, redundancy, extent of the area covered). In the long term, these methods result in cost savings when compared to conventional methods.

However, each of these methods has some limitations and cannot be taken to be a solitary solution superseding all other techniques. They are complementary to each other and to conventional optical, geotechnical and structural instrumentation. An IMP shall be designed, considering the points listed in this paper to select the proper solution suitable to each case. It is important to involve experts and experienced monitoring specialists to fully understand the possibilities, the advantages, and the technical limitations for each solution.

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