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Field monitoring to support use of the observational method for retained excavations in overconsolidated clays

Surveillance sur le terrain pour soutenir l'utilisation de la méthode d'observation pour les fouilles retenues dans les argiles surconsolidées

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ABSTRACT: Field measurements are an essential part of nearly all construction projects. Field monitoring is the repeated measurement of a particular parameter over a period of time and is used to evaluate designs, assess the effectiveness of construction methods, control construction progress to avoid unwanted damage, provide warnings of unacceptable performance and prevent failures. The Observational Method is a strategic approach with the ability to bring about significant savings for a construction project. It requires accurate and reliable measurements coupled to real-time back-analysis of the monitoring data to support decisions that are made when the real behaviour of a structure and the ground is perhaps not as expected. This paper presents a range of measurement techniques that can be used for monitoring supported excavations (e.g. propped retaining walls) with particular reference to those constructed in overconsolidated clays.

RÉSUMÉ : Les mesures sur le terrain sont une partie essentielle de presque tous les projets de construction. La surveillance sur le terrain est la mesure répétée d'un paramètre particulier sur une période donnée et est utilisée pour évaluer les conceptions, évaluer l'efficacité des méthodes de construction, contrôler l'avancement de la construction pour éviter les dommages indésirables, fournir des avertissements de performances inacceptables et prévenir les défaillances. La méthode d'observation est une approche stratégique ayant la capacité de réaliser des économies significatives pour un projet de construction. Cela nécessite des mesures précises et fiables couplées à une rétro-analyse en temps réel des données de surveillance pour soutenir les décisions qui sont prises lorsque le comportement réel d'une structure et du sol n'est peut-être pas comme prévu. Cet article présente une gamme de techniques de mesure qui peuvent être utilisées pour surveiller les excavations supportées (par exemple les murs de soutènement étayés) avec une référence particulière à celles construites dans des argiles surconsolidées.

KEYWORDS: Inclinometers, Extensometers, Piezometers, Strain Gauges, Geotechnical Monitoring

1 INTRODUCTION

Field measurements are an essential part of nearly all construction projects. Field monitoring is the repeated measurement of a particular parameter over a period of time and is used to evaluate designs, assess the effectiveness of construction methods, control construction progress to avoid unwanted damage, provide warnings of unacceptable performance and prevent failures.

In his 1969 Rankine Lecture on The Observational Method, Professor Ralph Peck said that "far too much dependence is placed on reports of the successful performance of instruments…To a large extent this unfortunate situation arises because those who see the need for measurements and who plan the programme are not themselves personally experienced in installing, observing and maintaining various types of instruments under a variety of conditions for a number of years." Peck deliberately avoided discussing the methods used to obtain field measurements, but he did state that they "must be reliable" and that "whoever plans an installation of any complexity will need all the skills that can be developed only by years of experience in actually installing and observing field measuring equipment."

A supported excavation generally consists of a retaining wall, with the ground outside the excavation at a higher elevation than the ground inside the excavation. The part of the retaining wall that is above the formation level of the excavation is required to support the ground outside the excavation and to do so it might require temporary or sometimes permanent props (struts) to do so without potentially damaging bending moments developing within the retaining wall. If the excavation is in overconsolidated clay with a low permeability it is likely that the process of removing overburden will cause the pore water pressures to decrease in the short-term as the total stress reduces under undrained conditions and the pore water pressure may eventually reach a negative value. At the same time the ground at the bottom of the excavation will probably heave, and this can continue for many years as the pore pressures slowly increase, which can cause stresses and deflections to develop on the bottom slab and parts of the retaining wall that lie below the bottom slab. Appropriate considerations when monitoring a supported excavation are therefore the deflection of the retaining wall and any bending moments that are generated in the retaining structure during excavation, the pore water pressures and heave at the base of the excavation. All of these should be monitored throughout the excavation period so that any changes to the expected behaviour can be considered in the context of The Observational Method.

The purpose of this paper is to set out some useful guidance for monitoring supported excavations in overconsolidated clays.

2 DEFORMATION MEASUREMENTS

There are two principal methods of measuring deformation in ground, inclinometers measure displacements across a line and extensometers measure displacements along a line. The accurate location of the line is unimportant, only the change in position of the measuring points on the line need to be measured. Inclinometers and extensometers can be orientated in any direction, but they are mostly orientated vertically or close to vertical and these are the cases that will be examined in this paper.

Inclinometers and extensometers can be divided into those that are read manually by an operator who visits the site, commonly known as probe instruments and those that are read automatically and stored on a datalogger for collection either by visiting the site or by transferring the data wirelessly to a remote location, commonly known as in-place instruments.

2.1 *Inclinometers*

Deflections of a retaining wall can be measured using a device known as an inclinometer. This consists of an access casing with two pairs of grooves aligned orthogonally. The access casing is normally installed into a reservation tube that is cast into the retaining wall and the space between the access casing and the reservation tube is filled with cement-bentonite grout. One pair of grooves is aligned perpendicular to the line of the wall (commonly referred to as the A direction) and the other pair of grooves is aligned along the line of the wall (commonly referred to as the B direction). The shape of the tube is measured using devices that contain tilt sensors known as probe inclinometers and in-place inclinometers. Figure 1 shows schematically the similarities and differences between the common types of inclinometer devices. The difference between the deformed shape of the inclinometer access casing and the original shape of the access casing represents the deflection at each discrete elevation.

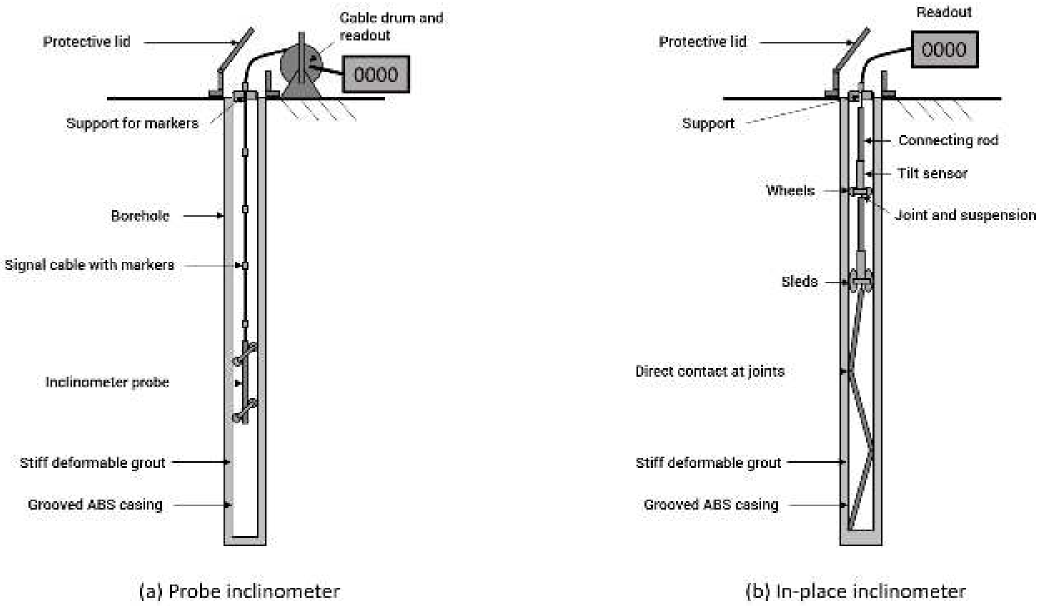

Figure 1. Similarities and differences between common types of inclinometer devices (after Ridley 2020)

Details of how inclinometer measurements are made and the errors that can exist in them are covered by Ridley (2020) and will not therefore be covered in detail again here. There is an increasing trend towards using in-place inclinometers with automatic data collection for monitoring retaining walls. This is particularly appropriate when The Observational Method is being used because the frequency of the measurements is important for the decision-making process. In addition, the design of retaining walls allows for smaller and smaller deflections so it is important to have instruments that can detect small deflections reliably. In-place inclinometers do not suffer from the same systematic errors that befall probe inclinometers. They do however provide the flexibility to change the gauge length (the linear distance between measuring points) and Ridley et. al (2020) has shown how longer gauge lengths (>1m) can cause measurement errors if the access casing is not straight. ISO 18674-3 (2017) recommends that the initial shape of the inclinometer access casing is measured with a probe inclinometer before selecting the gauge lengths and that the gauge lengths are never more than 2m.

As has already been described inclinometer devices measure the shape of the inclinometer casing and the absolute location of the casing is unknown. Therefore, the accuracy of displacements calculated using inclinometers is dependent on knowing the change in location of a point on the casing or having certainty that one point along the casing does not change its location (i.e. it is fixed in space). It is easiest if this reference point on the measuring line is at either end of the line. If the retaining wall is embedded far enough to be sure the wall will not translate during excavation it is acceptable to use the bottom of the inclinometer casing as the reference point. If, however the retaining wall is not embedded far enough to be sure that the wall will not translate during excavation, the top of the inclinometer casing can be used as the reference point and its location must be measured accurately using survey techniques throughout the monitoring programme. If this is done though it must be borne in mind that the accuracy of the survey will probably not be as good as the accuracy of the inclinometer measurements, particularly for a confined excavation. Alternative approaches are to extend the inclinometer casing below the bottom of the retaining wall, which will require drilling inside the reservation tube after the wall has been constructed or to place an inclinometer casing in the ground behind the retaining wall and outside the excavation, where it can easily be extended below the bottom of the retaining wall.

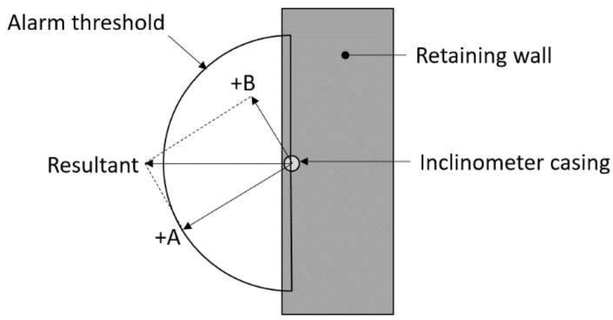

Figure 2. The importance of aligning an inclinometer casing correctly.

When installing an inclinometer access casing the specification will normally say that one set of grooves shall be aligned with the wall and the other set will thereby be aligned perpendicular to the wall. In practice this is extremely difficult to achieve accurately and there will nearly always be a small misalignment. This will probably result in the inclinometer device recording some small deflections in the B direction. In practice if this occurs the displacements at each elevation should be vectored and the resultant displacement can then be assumed to be in the direction perpendicular to the retaining wall (Figure 2). This problem is further compounded by the specification setting alarm thresholds against the deflections that occur in the A direction and these are not therefore triggered at the correct time. Alarm thresholds for retaining walls should therefore be set against the vectored displacement.

2.2 *Extensometers*

An extensometer consists of a linear array of measurement points (known as anchors) that are attached to the ground. Each anchor can move along the line connecting the anchors and its position can be measured relative to one end of the line (known as the reference point). Different types of extensometer exist but the most common are magnet extensometers (probe type) and rod extensometers (in-place type). Ridley (2020) discusses the main features of the different kinds of extensometer.

The most appropriate extensometer for use in supported excavations is the magnet extensometer because it can easily be installed before the excavation commences and can thereafter be cut down as the excavation proceeds, thereby maintaining continuity of the measurements before, during and after the excavation of ground. This cannot be easily done with a rod extensometer because the process of reducing the length of the rods is lengthy and can introduce significant errors into what is normally a very accurate instrument. Figure 3 shows the main features of a traditional magnet extensometer.

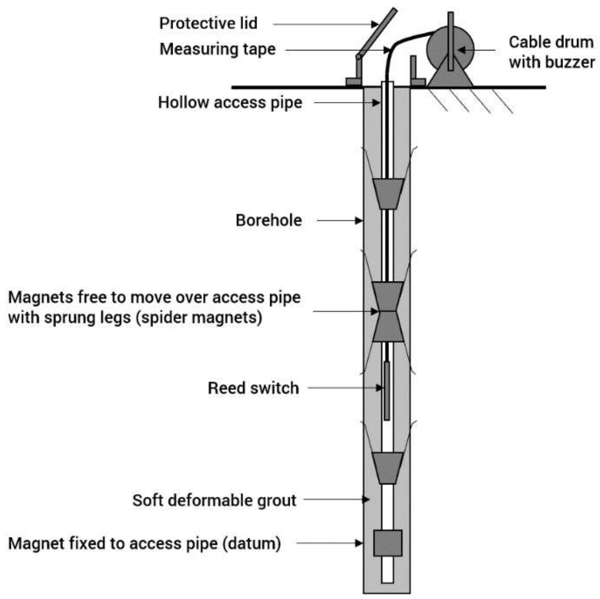

Figure 3. Key components of a magnet extensometer

In a magnet extensometer, each anchor contains magnets that generate a magnetic field. Anchors are inserted in the ground over a central (hollow) access pipe that is installed inside a borehole. The anchors also have sprung metal legs that are used to connect the anchor to the ground. The remaining space inside the borehole is filled with cement-bentonite grout and for this reason it is important that the anchors make good contact with the ground and that the grout does not restrict movements of the anchors. If for example the anchors do not penetrate the ground, but instead just rest on the side of the borehole and the grout is too stiff it might restrict the movement of the anchor. If however the anchor does penetrate the ground the relative stiffness between the grout and the ground becomes less of a concern and the grout can be quite soft in comparison to the ground, thereby allowing the anchor to move with the ground. Most systems rely on the sprung legs to penetrate the soil, which is unlikely in stiff overconsolidated clays and reliable measurements can be difficult to achieve for the reasons explained above. Figure 4 shows a magnet extensometer that allows the legs of each anchor to be forced into the ground and these will produce better results in stiff clays.

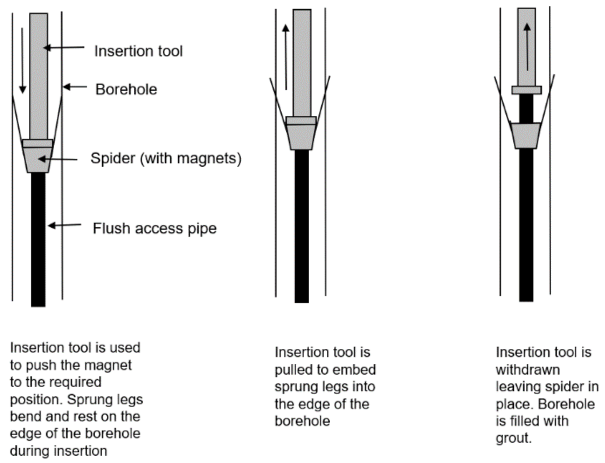

Figure 4. Modified magnet extensometer

Once installed, the anchors need to be free to move along the access pipe as the ground at the depth of the anchor also moves. It is good practice to glue at least one anchor (with no sprung legs) to the casing, normally at the bottom, so that it can be used to calibrate the measurements. Glued anchors (frequently referred to as datum magnets) also allow an operator to check their technique and will show up a systematic error in the measurement device. The datum magnets are often used as a reference but doing so inherently assumes that the access pipe isn't moving, which might be a reliable assumption if the bottom of the access pipe is founded in an incompressible layer and the ground is settling, so the access casing is subjected to compression. In an excavation in overconsolidated clay however, the ground will heave, and the access casing can be dragged up by the swelling ground. Greasing the pipe might help to isolate it from the grout but a more reliable approach is to attach an anchor to the bottom of the access pipe and to embed the anchor into ground that is unaffected by the removal of overburden, although in a deep excavation this might require the access pipe to be extended to a very great depth. An alternative therefore is to measure the heave of the casing by precise levelling the top of the access casing, which might be difficult inside the confines of a deep excavation, and to relate the measurements to the remote reference to which the precise levelling is done.

3 PORE PRESSURE MEASUREMENTS

When overburden is removed from inside an excavation the total stress is reduced and in low permeability overconsolidated clays the pore water pressures will reduce and can become negative if the clay remains undrained. The most popular instrument for measuring pore water pressures is a vibrating wire piezometer, but negative pore water pressure poses a significant problem for vibrating wire piezometers because tension in the water can cause air to form in the piezometer and if air is present the measured pressure is likely to be the pore air pressure and not the pore water pressure. All piezometer devices consist of a sensing element, a reservoir of liquid and a porous filter. In the case of a vibrating wire piezometer two types of porous filter exist, low air entry filters and high air entry filters. Low air entry filters have a large porous structure and a high permeability, so they allow air and water to move freely through the filter. They also allow air to form quite easily when the water is in tension. High air entry filters on the other hand have much smaller porous structures and whilst water can move easily through the filter, the passage of air and the formation of air inside the filter (i.e., the ability of the filter to remain saturated when the water is subjected to tension) is restricted. Piezometer devices are normally installed from the surface, inside a borehole and surrounded by a filter pack at the depth of the measurement. Filter packs normally consist of sand and are enclosed above and below by a low permeability material such as bentonite or cement-bentonite grout. Sand also has a relatively large porous structure and will therefore not restrict the formation or passage of air. Cement-bentonite grout on the other hand has a fine porous structure and like high air entry porous filters it can restrict the passage of air and the formation of air when the water is in tension. The temptation therefore is to use vibrating wire piezometers installed with high air entry porous filters and placed inside a fully grouted borehole. However, when the water inside a piezometer device is in tension air can easily form in the same way as it does inside the low air entry filter or the sand pack because the reservoir is in effect a large pore. If air forms, it cannot easily escape from the reservoir if the piezometer device has a high air entry filter and is surrounded by a cement-bentonite filter pack. To continue to operate properly the air must be removed and, in this case, the only way to remove it is to flush water into the reservoir. This can be done with a hydraulic piezometer. Traditional twin-tube hydraulic piezometers (often referred to as "Bishop" piezometers) have high air entry porous filters and tubes for flushing water into the reservoir but the pressure sensor (normally a Bourdon gauge) is at the surface and when the porous filter is installed in a borehole that means there is an elevation difference between where the measurement acts (at the filter) and where it is measured (at the gauge). Each metre of elevation separating the filter and the gauge reduces the measurement range by 10kPa in the negative scale. Therefore, the usefulness of Bishop hydraulic piezometers is very limited in deep excavations.

An alternative flushable piezometer is shown in figure 5.

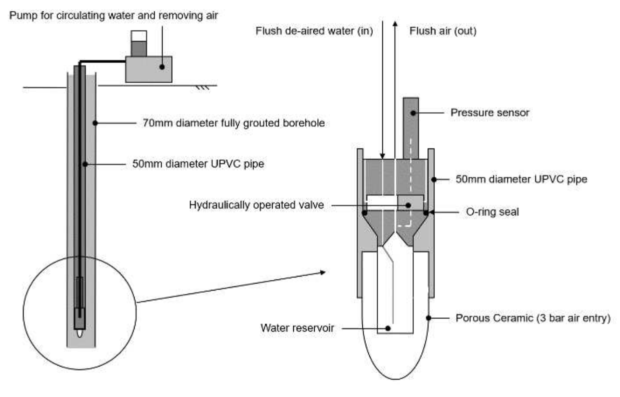

Figure 5. Flushable piezometer capable of measuring positive and negative pore water pressures (after Ridley 2015)

It also has a high air entry filter and can be installed in a fully grouted borehole. However, the pressure sensor is located close to the porous filter and a hydraulically operated valve can isolate the reservoir and the pressure sensor from the hydraulic tubes that are used to circulate water from the surface and remove any air that is inside the reservoir. This piezometer can measure positive pore water pressures and to -90kPa regardless of the depth to which it is buried. It also has the advantage that it can be temporarily removed from its protective access tube so that the tube can be cut down as the excavation proceeds.

4 PROP (STRUT) LOADS

Structural loads can be measured using load cells or inferred from strain measurements. The shape of props and the end details can make positioning a load cell difficult. Moreover, end effects can make load measurements that are made too close to the point where the prop is fixed to the retaining wall unreliable (Batten, 1999). It is therefore frequently easier to fix strain gauges to a prop and infer the load by using the equation:

$$\text{Load} = E.\varepsilon.A$$

where E = Young's Modulus (kN/m^2), ε = microstrain and A = cross-sectional area (m^2)

Consequently, it is very important to recognise that the accuracy of load measurements made in this way is dependent on the accuracy of the Young's Modulus and the cross-sectional area.

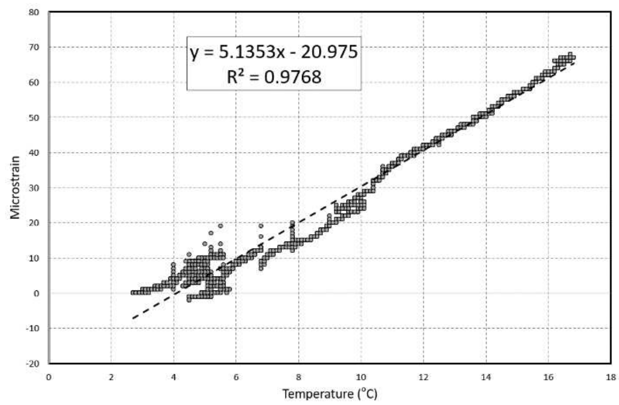

Figure 6. Typical relationship between microstrain and temperature.

Measurements of load in steel props are also highly susceptible to variation in temperature and therefore it is essential that temperature measurements are made and compared with the strain measurements. Batten et al (1999) showed that the temperature of a prop can be significantly higher than the temperature of the gauges and that painting the props white helps to reduce this difference. Nevertheless, the measured strain can vary with temperature and this can result in considerable uncertainty. Analysis of the measurements can help. This can be in the form of relationships between microstrain and temperature, which can be quite well conditioned (Figure 6) but sometimes are not and whilst they can be used to identify that temperature is affecting the measurements they should not be used as a means of adjusting the measurements to remove the apparent effect of temperature. Frequently the variations caused by the temperature fluctuations can be large enough to trigger multiple alarms as the apparent load fluctuates above and below the thresholds each day. This means that measurements of loads in props (struts) requires careful management. For example, systems can be programmed to average the measured loads over the cycle of variation so that the alarms are not triggered so frequently.

Another important aspect of measuring load in props is selecting where to place the strain gauges. Strain in a prop is made up of that due to axial loads and that due to bending, which originates from the self-weight of the prop. If the requirement is to measure axial load it should ideally be measured close to the neutral axes of the prop to minimize the effect of bending. In a circular section this is at the centre of the circle and it is not possible to place a gauge there, so the gauges are typically placed on the outside (or inside) surface of the section, diametrically opposite one another in pairs and then the average strain is used. Placing the gauges at 3, 6, 9 and 12 o'clock makes them quite vulnerable to damage and better protection is provided when they are placed as shown in figure 7.

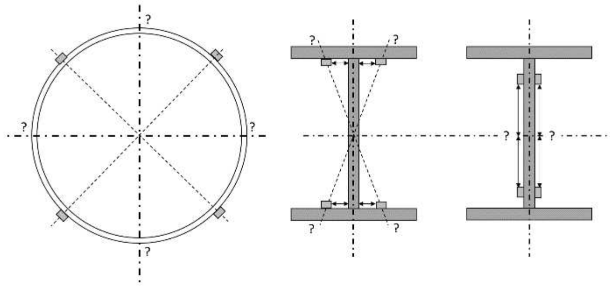

Figure 7. Possible locations for strain gauges on props (struts)

For an I or H section the strain gauges can be placed on the web or on the flanges, again in pairs and opposite each other. Placing them on the outside of the flanges makes them quite vulnerable so inside the flanges or on the web are the preferred options, taking care that all gauges have the same eccentricity relative to the neutral axes. For both sections, four gauges is preferred, and the results are averaged to provide the strain used in the calculation. This also provides some redundancy should a gauge be damaged although this requires some data management because the averaging will require adjusting if a gauge or gauges are damaged. For an I or H section it is also possible to place the gauges on the neutral axis and placing two gauges either side of the web on the neutral axis as well as four gauges as shown allows the bending and axial components to be assessed. As previously mentioned, consideration also needs to be given to where along the prop to place the gauges. Analyses by Batten et al. (1999) showed that the gauges should be no closer than three diameters (circular props) to the support point.

5 DATA COLLECTION AND PRESENTATION

The essence of the Observational Method is real-time back-analysis of monitoring data to support design decisions. Never has this been more possible than now because technological developments including wireless data transmission over long distances and web-based software, allow engineers to visualise the data shortly after it has been acquired. To be of real value though it must be possible to analyse and interpret the data in near real-time too, so the person viewing the data must also be able to manipulate the data without affecting the raw data, which might still be required to trigger alarms. Engineers frequently do their analyses by downloading data from the real-time monitoring software and manipulating it using spreadsheets for comparison with their designs. Being able to do these manipulations within the real-time monitoring software without affecting the raw data and then export the manipulated data into whatever software has been used to design the scheme will likely bring about more confidence in The Observational Method.

A key part of interpreting monitoring data is knowing what construction activity was happening at each stage of the measurement. How often do we hear the phrase “the instrument isn’t working” only to find out that the instrument was working perfectly and identified something that was not supposed to happen (e.g., the ground was excavated too quickly, or the prop wasn’t placed quickly enough)? To be of value the real-time monitoring software must also allow the real-time input of construction events and although the main contractor should gather that information it is probably the monitoring contractor that is best placed to do so, especially if they are reading the instruments manually. Monitoring technicians have the best instruments for recording this information, their eyes, and the development of smart phones means it is now easy to transfer what a monitoring technician is seeing directly into real-time monitoring software instantly so the engineer that is interpreting the data can see the site conditions at exactly the time that the measurements are taken. Fixed cameras and webcams can be used if the measurements are being collected automatically.

6 CONCLUSIONS

The Observational Method is a powerful tool with the ability to bring about significant savings for a construction project. It requires accurate and reliable measurements coupled to real-time back-analysis of the monitoring data to support decisions that are made when the real behaviour of a structure and the ground is perhaps not as expected. This might be because the design process confined the engineering team to use parameters that were too conservative or because the construction process was forced to follow a path that was not as expected. Either way good field measurements probably represent the real behaviour of the ground and structures and afford the engineering team a way of adapting their design along the way to bring about a solution that is often cheaper and perhaps safer than the original design. To paraphrase Peck choosing the correct instruments and a monitoring sub-contractor with the experience and importantly a keen interest in the problem will also help get the most from The Observational Method.

7 ACKNOWLEDGEMENTS

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