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Real-time monitoring and performance of retaining structures

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ABSTRACT: The advent of reliable real-time monitoring devices has changed the way we monitor the construction of geotechnical infrastructure. This paper presents a case study where Shaped Accel Arrays (SAA) were employed as part of the real-time monitoring regime for the construction of two retaining structures that utilised a combination of secant and sheet piles. To improve their structural rigidity, a capping beam and horizontal props were employed. The retaining structures were erected to facilitate the launching and retrieval of a Tunnel Boring Machine (TBM). The monitoring regime detected structural sway and toe movement of the sheet pile walls. Adjustment methods for these effects are discussed within this paper, along with a comparative study between manual and real-time monitoring. Adjusting for the effects of sway and toe movement can considerably change the maximum deflection from that registered by an SAA, therefore, it is important to account for these effects when employing SAAs to monitor the movement of a retaining structure. Furthermore, a cost comparison of using real-time monitoring in place of manual monitoring suggests that for a project of this nature where monitoring is required for more than 6 months, real-time monitoring becomes more cost effective.

KEY WORDS: Retaining structures, real time monitoring, shaped accel arrays.

1 INTRODUCTION

The Corrib Gas Field is located approximately 83km off the west coast of Ireland. It was originally discovered by Enterprise Energy in 1996, which was bought by Shell E&P Ireland Limited in 2002. Shell E&P Ireland Limited will operate the field on behalf of its Partners, Statoil and Vermilion. The field is one of only three gas fields discovered in Ireland and is classified as a medium-size gas field, estimated to yield approximately one trillion cubic feet of natural gas over an operating life of fifteen to twenty years. At peak production, Corrib will supply up to 60% of Ireland's natural gas needs.

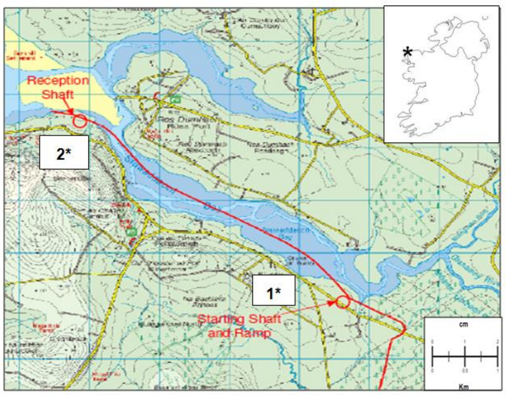
As part of the onshore pipeline link to the Bellanaboy Bridge Gas Terminal, a 4.9km long tunnel was constructed to allow the installation of the pipeline under Sruwaddacon Bay (Fig.1). To facilitate the installation and extraction of the TBM, a launch shaft was constructed to the east of the bay at Aughoose and a reception shaft to the west at Glengad. Each shaft was formed by constructing a secant pile wall, orthogonal to the longitudinal axis of the tunnel and sheet piles along the shaft boundaries (Fig.2). Inclinometers, Shaped Accel Arrays (SAAs), optical surveying equipment and piezometers were employed as part of the monitoring regime during and after construction.

Real-time monitoring of wall movements enabled by the SAAs is the focus of this paper. There is very limited experience of SAA use in Ireland, so the paper serves as a source of information on the devices. In addition, the SAA data attained is presented and interpreted. The launch shaft retaining structure experienced nominal toe movement and sway during its construction. Methods for incorporating these movements into the deflected shape of the retaining structure are discussed. The final section of this paper will serve as an aid to assist engineers in the appraisal of real time and manual monitoring options.

2 LAUNCH AND RECEPTION SHAFTS

2.1 General

The launch shaft consisted of two zones, a start pit and ramp section, measuring approximately 9.5m wide by 17.6m long and 6.2m wide by 74.2m long, respectively (Fig. 2). The overburden was retained on the west face (i.e. orthogonal direction to the longitudinal access of the tunnel) by a male-female secant pile wall with piles of 1.2m diameter which incorporated Glass Fibre Reinforcement (GFR) to create a “soft eye” through which the TBM was launched. The remaining walls were constructed of interlocking U-section sheet piles, with toe depth between approximately 9.0m and 14.0m below ground level (bgl). Constructed on the top of the start pit walls was a 1.4m wide by 1.0m deep reinforced concrete capping beam, to which horizontal steel props were fixed. The props and capping beam were installed prior to excavation of overburden within the start pit. To maximise the amount of unrestricted space in the ramp section, post-tensioned ground anchors and waler beams were placed 2m bgl.



*1*Aughoose site, 2*Glengad site*
Figure 1. Sruwaddacon Bay, Mayo (Ireland)

Similarly, the reception shaft was constructed with a soft eye GFR secant pile wall to the east and the remaining retaining walls were constructed using interlocking U-section sheet piles. The reception shaft measured approximately 17.0m by 10.0m on plan with an average sheet pile toe depth of approximately 14.0m (Fig. 2). Horizontal props and a capping beam were also used in this shaft to enhance structural rigidity.

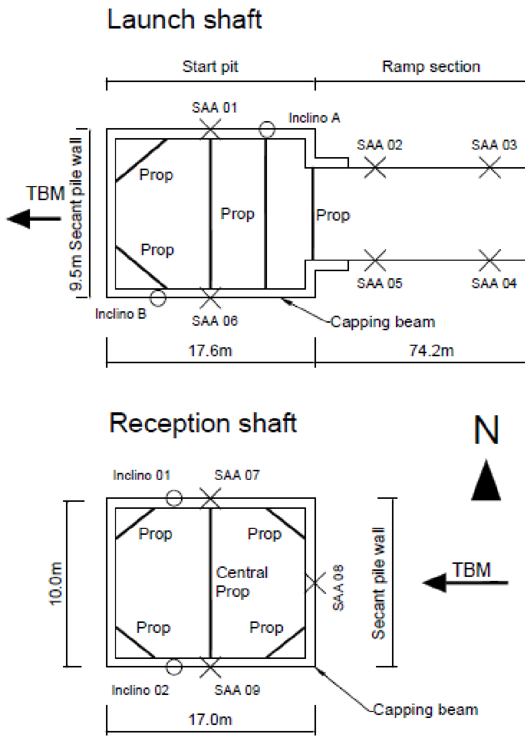


Figure 2. Plan views of launch and reception shafts, which are located at Aughoose and Glengad sites, respectively.

2.2 Ground conditions

The soil profile at the Aughoose site consisted of peat, silty sands and gravels overlying bedrock (Table 1). The peat layer was excavated and replaced with Clause 804 aggregate prior to construction of the shaft. The ground water table within the Aughoose site varied in depth from 0.8m to 2.8m bgl. Falling head permeability tests found the overburden layer had an average permeability of 6.35×10^{-6} m/s and well pumping tests established the bedrock had a permeability ranging between 3.0×10^{-6}m/s to 5×10^{-5} m/s. A number of Standard Penetration Tests (SPT) were conducted on the site, with the SPT N value of the sand layer ranging from 10 to >50. Shear box tests results indicated that the sand layer had an angle of internal friction in the range 36^0 to 41^0.

The soil profile at Glengad site consisted of sandy topsoil, silty sands and gravels overlying bedrock (Table 2). The average SPT N of the gravel layer was 46 with a range from 21 to >50 blows. The ground water table varied from 0.84m to 1.47m bgl, with an average bedrock permeability of 6.5x10-6 m/s, which was calculated from a well pumping test. During the construction stage of the shafts, well pumping was employed to reduce the ground water levels.

Table 1. Aughoose soil profile

Depth (m bgl)	Soil Profile
0-4.6	PEAT (*replaced with Clause 804 aggregate)*
4.6-6.5	Silty very gravelly SAND & sandyGRAVEL
6.5-7.5	Highly weathered, weak to moderately strong MICA SCHIST
> 7.5	Moderately weathered, strong to very strong PSAMMITE

Table 2. Glengad soil profile

Depth (m bgl)	Soil Profile
0-0.2	Sandy topsoil
0.2-3.5	Silty gravelly SAND/sandy GRAVEL with cobbles
>3.5	Moderately weathered, moderately strong to very strong PSAMMITE

3 SHAPED ACCEL ARRAY

3.1 Shaped accel array configuration

A SAA is an articulate chain of sensors installed inside a water-tight casing, which includes a microprocessor and temperature sensor every 8 segments. The rigid segments are either 305mm or 500mm in length and contain a tri-axial Micro Electro Mechanical System (MEMS) accelerometer. The MEMS accelerometer measures the static tilt of each segment relative to gravity and adjusts for temperature [1]. A composite joint connects the rigid sections together. This joint permits two degrees of freedom between segments, while preventing torsion. The MEMS also permits the measurement of vibrations up to ± 2g [1]. SAAs can measure either the 2D or 3D deflected shape of a structure, depending on how they are installed. Installing an SAA vertically permits 3D monitoring, while horizontal installation only permits 2D monitoring. They have an accuracy of ± 1.5mm non-grouted and ± 0.5mm grouted over a length of 32m and can operate within a temperature range of -45^0C to 85^0C with a maximum length of 100m [1], [2]. Unlike their predecessors (i.e. analog sensors), SAAs only require one cable per instrument, which significantly reduces the installation cost in large scale projects [3]. The SAA is factory-calibrated and completely sealed; therefore, no field calibration is required. However, careful consideration must be given to the required length of SAA, as no field adjustments are possible on the instrument. SAA installation and data acquisition can adopt a number of different formats.

3.2 SAA installation and data acquisition

An SAA can either be connected to a computer or a data acquisition system for remote monitoring, rendering them an ideal instrument for real time monitoring. SAAs have been successfully employed to monitor slope stability/movements, settlement, structural stability of deep excavations, mines, quarry faces and have become an important part of structural health monitoring regimes globally. At the planning stage of the project, careful consideration should be given to the installation of deflection monitoring equipment. For example, when installing an inclinometer or SAA to monitor the cumulative deflection of a retaining structure, a decision is required as to whether the base of the instrument should be anchored into a stationary soil layer beneath the proposed structure or fixed at the toe depth of the proposed structure. Fixing the base of the instrument into a stationary soil layer beneath the proposed structure requires installation within a dedicated borehole to ensure cumulative displacement is measured. However, if the base of the instrument is not firmly anchored into the soil layer, then alternative means are required to measure the cumulative displacement of the instrument. Adjustment to the deflected shape can be made by measuring displacement at the top of the instrument using optical surveying equipment [2].

SAAs are typically installed inside a special plastic conduit of 27mm internal diameter, which reduces the tendency of the instrument to try to twist and to facilitate installation or extraction of the instrument. This conduit is typically grouted into place, prior to installing the device. In the case of the sheet pile retaining structures at the Corrib Tunnel site, the conduits were grouted into hollow steel sections, which were pre-welded to the back of a sheet pile prior to its installation. An alternative to this method of installation is to grout the plastic conduit into a borehole, drilled adjacent to the retaining structure before inserting the instrument.

4 MONITORING REGIME

4.1 Overview

The monitoring regime for the construction of the launch and reception shafts at the Corrib Tunnel site consisted of piezometers, conventional inclinometers and SAAs and the use of optical surveying equipment. Eight SAAs were employed at the Aughoose site and three at the Glengad site, one of which was placed into the GRF secant pile wall (Fig.2). All SAAs were placed into plastic conduits, which were grouted in place, thereby improving the accuracy of the results produced. The inclinometers (at Glengad) were regularly monitored manually (up to twice daily), by an inclinometer probe, whereas the SAAs and their data acquisition systems recorded the deflected shape of the retaining structures every 30 minutes. In addition to the SAAs employed as part of the real time monitoring regime for the construction of the launch and reception shafts (the subject of this paper), SAA’s have been successfully used elsewhere on the Corrib project to monitor the construction of the onshore pipeline.

4.2 Data acquisition

Data acquisition systems installed at both shafts allowed for the continuous monitoring of the retaining structures, during and after their construction. This information was available to the relevant personnel via an internet portal. Deflection (magnitude and rate) thresholds were set by the designers, based upon predictions from finite element models. Should these thresholds be exceeded, appropriate contingency measures (such as halting excavation, opening of the weep holes and ceasing well pumping within the shaft) could be considered.

The SAAs at either shaft were not anchored into the bedrock beneath the retaining structures. Therefore, as alluded to in Section 3, a total of 16 benchmarks were needed to monitor the movement at the top of the structures. Thus, 8 were placed on the capping beam of the launch shaft and a further 8 were placed on the capping beam of the reception shaft. The benchmarks were surveyed on a regular basis using optical surveying equipment, which had an accuracy of ± 3mm. Results of the optical surveying and SAA monitoring regime were amalgamated to calculate the cumulative deflection of the retaining structures.

5 RESULTS AND DISCUSSION

This discussion focuses primarily on how to adjust the deflected shape produced by an SAA to incorporate the sway and toe movement of a retaining structure. This adjustment could equally be applied to the inclinometer results. Furthermore, the results from an inclinometer and SAA, located in close proximity, are compared.

5.1 Unadjusted deflection

The unadjusted deflected shape of SAA 01 is presented in Figure 3, as a function of the excavation depth. As outlined in Section 2, the capping beam and horizontal props were installed prior to the excavation of the overburden from within the shafts. Therefore, it is assumed that once the props were installed, the distance between opposite walls of the retaining structure at the capping beam level remained relatively unchanged. The base of the SAA was not anchored into the subsoil strata beneath the retaining structure. Hence, it is reasonable to assume that as the overburden was excavated from within the retaining structure, the toe of the sheet pile wall rotated into the excavation, bringing with it the base of the SAA; this has been observed by other studies [2]. Two adjustments to the deflected shape of the SAA 01 are necessary when in the above configuration. These adjustments are:

(i) Adjustment of the deflected shape of the SAA for the movement of its base.

(ii) The retaining structure as a unit may sway because of unequal earth and/or hydrostatic pressures on opposite walls. Sway will also affect the deflected shape of the SAA.

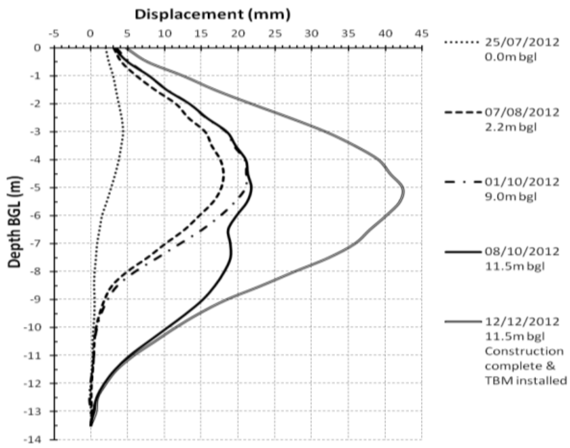


Figure 3. SAA 01 unadjusted deflected shape

5.2 Adjustment for base movement

To remove the error generated by the movement of the SAA's base, it is sufficient to consider the top of the SAA as stationary and all displacements are relative to the top rather than the base of the instrument. The adjusted-for-base-movement deflected shape of the SAA 01 is presented in Figure 4. It can be seen from this graph that the toe of the sheet pile moves away from the excavation, rather than into the excavation. Temporary horizontal props were placed within the start pit during its construction and may account for the outward movement of the sheet pile toes. Excess toe movement of the retaining wall can be a precursor to the onset of failure of the structure and warrants monitoring. For example, during the construction of the Tottenham Court Road Station (London), excess inward toe movement of a retaining wall during the excavation phase prompted the early installation of a floor slab section [2].

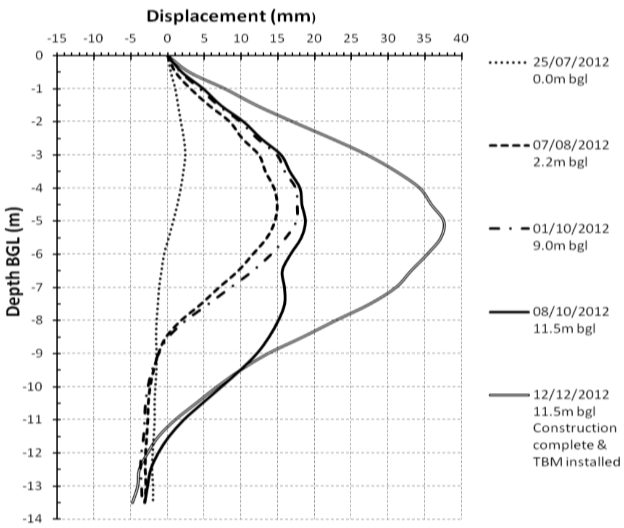


Figure 4. SAA 01 Adjusted-for-base-movement

5.3 Adjustment for sway

The sway effect may be monitored through the regular surveying of the capping beam benchmarks, and then accounted for by adjusting the deflected shape. Regular optical surveying of the capping beam found that, at the end of the construction phase, the launch shaft's north side retaining wall had swayed approximately 10mm (± 3mm) to the north. To remove the effect of sway from the deflected shape of the SAA, a correction (C) was applied as follows (C>0 represents inward sway, i.e. toward the excavation):

C = ± Total sway x (1-depth considered/total depth) (1)

Corrected deflection = deflection at point considered + C (2)

The adjusted-for-sway and adjusted-for-base-movement deflected shape of SAA 01 is presented in Figure 5, from which it can be seen the maximum recorded deflected is reduced by approximately 5mm. Sway adjustment can have a significant effect on the deflected shape of a SAA. The adjusted deflected shapes of SAA 06 are presented in Figure 6. A survey of the benchmarks closest to the SAA 06 indicated that this wall of structure had swayed approximately 13mm (± 3mm) to the north during its construction. Applying the sway correction to the already adjusted-for-base-movement deflected shape of SAA 06 increased the maximum deflection by approximately 9mm. In some circumstances adjusting for sway may cause the deflected shape of the retaining structure to approach or exceed the threshold limits imposed within the monitoring regime [2]. Therefore, when using an unanchored SAA to monitor the construction of a retaining structure, the effect of sway and instrument movement should be incorporated into the deflected shape of the SAA, to produce a more rigorous monitoring regime.

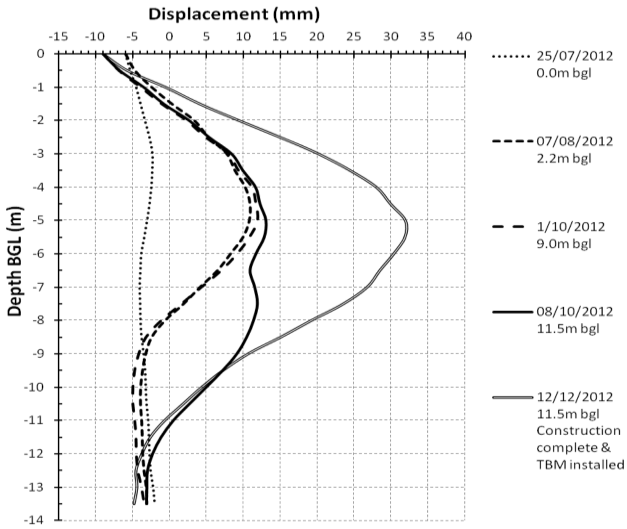


Figure 5. SAA01 adjusted-for-sway and base-movement

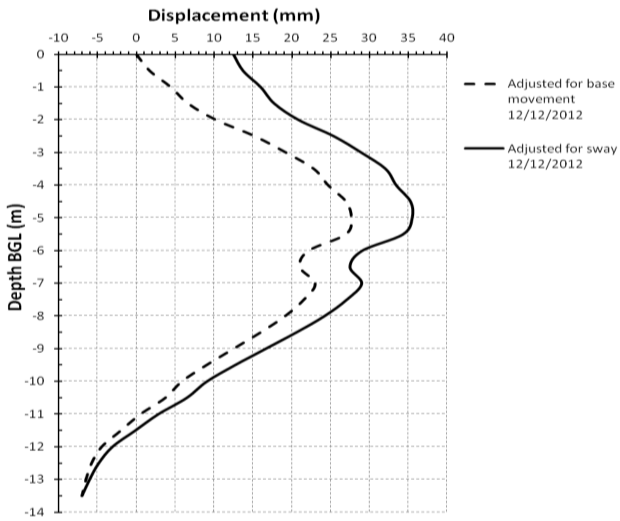


Figure 6. SAA 06 adjusted-for-sway and base-movement

5.4 Inclinometer/SAA comparison

The movement profiles measured by devices SAA 07 and inclinometer 01, located 1.25m apart in the reception shaft, are compared in Fig. 7. As can be seen from this plot, there are slight differences between the deflected shapes, which may be due to the difference in position of the instruments along the capping beam (Fig. 2); SAA 07 is located closer to the central prop. The additional stiffness provided by the central prop at capping beam level may be reducing the extent of deflection in this region. Notwithstanding this, the deflected shapes of both instruments are in good agreement.

Other research which compared the results of inclinometers and SAAs during the construction of Tottenham Court Road Station (London) also found slight differences between SAAs and inclinometer deflected shapes [2]. The authors of that research suggested that the difference may have been due to the inclinometer probe, which was not fully stabilised during its reading.

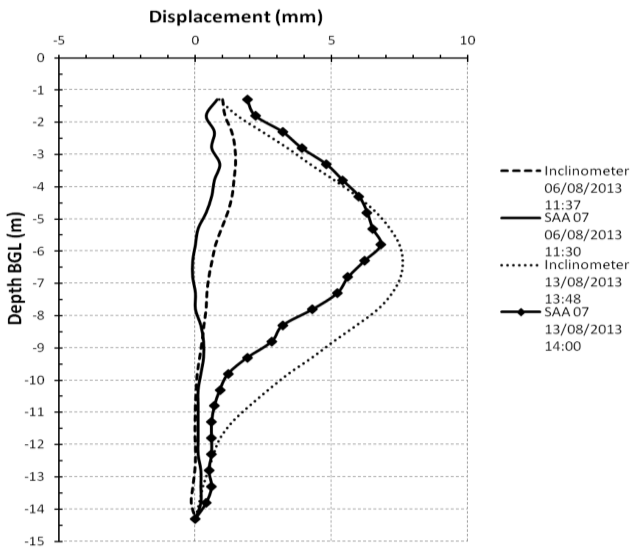


Figure 7. Inclinometer 01 and SAA 07 deflected shapes

6 COST ANALYSES AND COMPARATIVE STUDY

A cost analysis study comparing SAAs and manual inclinometer monitoring is presented in this section. Also outlined are some of the monitoring and practical considerations, which may assist when choosing between these monitoring regimes.

6.1 Cost analyses assumptions

The cost analyses study was based on using either 3 inclinometers or 3 SAAs, each measuring 10m in length, to monitor the movement of a retaining structure during construction. The assumptions of the study are as follows:

(i) Instrument costs for the inclinometers consisted of the 30m of inclinometer casing. The instrument costs for the SAAs consisted of the 3 SAAs plus a data logger necessary for remote monitoring. The cost of powering the data logger was not included in the study.
(ii) Installing the SAAs was deemed to take an extra day's labour, compared to the inclinometers, because of the additional time required to connect and program the data logger. Both methods require similar consumables for installation (such as grout). It is worth noting that when toe fixity is required, costs associated for boreholes are common to both methods, therefore, they are excluded from the comparison.
(iii) The inclinometer monitoring cost was calculated using the following assumptions; the monitoring regime was 7 days a week and 1 hour was required to read the 3 inclinometers. The time required to report the findings of the inclinometer monitoring were not included. The rental cost of the inclinometer probe was included within the monitoring cost. The maximum monitoring frequency was limited to 4 times a day.
(iv) The SAA monitoring cost consisted of a monthly subscription fee to access the monitoring data via a secure website, where the information is readily available to download in graphical format. This subscription fee does not change irrespective of the frequency of the monitoring.

6.2 Cost analyses

Table 3 compares the instrument and installation cost of both methods; the results are normalised relative to the cost of the inclinometer casing.

Table 3. Cost comparison of real-time monitoring relative to manual monitoring

Category	Inclinometer	SAA
(i) Instrument cost	1	26
(ii) Installation cost	3.3	5.7

The findings of this cost analyses are:

(i) The instrument and installation costs associated with 3 SAAs is approximately 7.5 times that of 3 standard manual inclinometers (excluding the inclinometer probe)
(ii) As the monitoring frequency and duration of the project increase, the real time monitoring becomes more economically advantageous relative to the manual monitoring (Fig. 8).

Therefore, careful consideration should be given to the duration of the project and the monitoring frequency required during its construction. Moreover, if the retaining structure is of a permanent nature, where the construction monitoring regime instrumentation can be incorporated into the structural health monitoring regime.

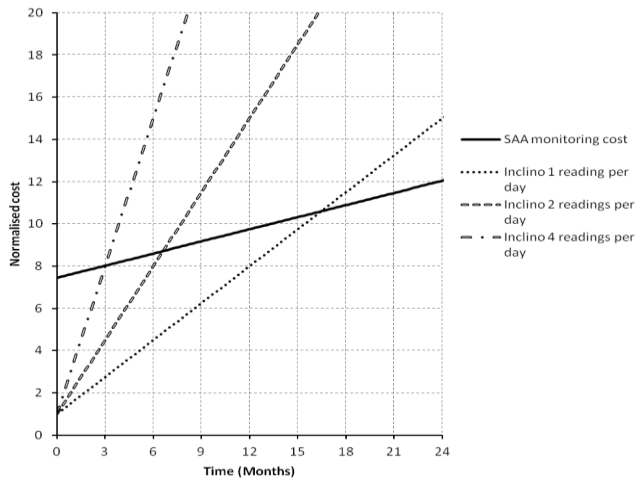


Figure 8. Monitoring comparison graph

6.3 Monitoring considerations

Apart from the monetary cost of the monitoring regime other considerations are presented in Table 4. This table is based on the authors' experiences, where high represents either a higher level of consideration, outputs or suitability.

Table 4. Comparison of real-time and manual monitoring

Category	Real time	Manual
(i) Design consideration	High	Low
(ii) Accuracy/reliability	High	High
(iii) Monitoring frequency	Very high	Low
(iv) Speed of alert	High	Low
(v) Remote location	High	Low

(i) At the design stage, real time monitoring requires more consideration: issues such as communications coverage, power supply (solar panels and batteries or mains), length of the SAA and data logger location must all be considered. Whereas, the major design consideration for manual inclinometers are length of the casing and location of the instrument, for ease of access during the construction stage.

(ii) Both instruments are highly reliable. The real time monitoring system requires a power supply and data logging system, unlike the inclinometer, thereby, making them more susceptible to power failures and surges etc. However, a back-up battery can be employed.

(iii) SAAs can monitor and log an average of a 1000 readings every 10 seconds and can measure vibrations of ±2g. This renders them particularly suitable for monitoring urban development adjacent to sensitive structures. Inclinometer readings are generally taken twice daily unless the rate of excavation warrants more monitoring.

(iv) The time taken to issue an alert can be a crucial consideration when selecting a monitoring system. Typically, the delay between the data-logger recording the information and its availability on the web portal depends on the frequency at which this information is uploaded from the data-logger. In isolated locations, to preserve battery life and reduce satellite connection costs, the monitoring system is typically configured to store a number of hours of monitoring data before uploading. In the aforementioned configuration the system can no longer be considered as real-time monitoring. SAA monitoring coupled with ground water monitoring can be used to provide important information for value engineering, for example in the Tottenham Court Road Station development, the use of SAA monitoring permitted the propping layout to be modified and reduced by one level of props, which subsequently reduced the schedule by 26 days [2].

(v) The use of real time monitoring is particularly suited to monitoring landslide prone zones, seismic zones or remote locations, where access can prove difficult or hazardous [5]. They reduce the requirement for physical presence on site, therefore improving health and safety and negate the need for lone working.

7 CONCLUSION

(i) Where the base of the SAA (and inclinometer) is not anchored and horizontal props are used at the top of the structure, then additional monitoring must be put in place to track the sway movement of the retaining structure. The results of which should be incorporated into the deflected shape of the SAA as soon as available, to provided a more holistic view of the deflection profile

(ii) It has been shown (in this instance) that SAA instrument and installation costs are typically more expensive. However, as the life span of the projects increases this cost reduces in comparison to manual monitoring.

(iii) Real time monitoring is particularly suited to monitoring remote structures or locations, where instant feedback is essential and can reduce the number of personnel required on site during construction. Their usage is likely to play an ever increasing role in efficient management of geotechnical risk.

On the Corrib project, a total of 11 SAAs were successfully employed as part of the real time monitoring regime, which monitored the construction of two retaining structures (shafts). Despite the value added for this project, they should not be seen as the panacea for all projects, sometime the time span and cost constraints of a project render them unsuitable as a monitoring solution.

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