

Optimising baseline monitoring to understand the timing, magnitude, and direction of seasonal movement of assets – a review of recent experience from a major infrastructure project

Fiona Hughes, Peter Ingram
Arup Ground Engineering, United Kingdom, fiona.hughes@arup.com

Phil Allvey, Sarah Duckworth, Enric Cruzate
Skanska Costain Strabag JV, London, United Kingdom

Mark Lemmon
High Speed Two, London, United Kingdom

ABSTRACT: Underground construction works may cause movements of the ground, sub-surface, and adjacent infrastructure which need to be calculated, monitored, and managed during the design and construction process. Changes in temperature and moisture content of shallow strata related to natural seasonal or environmental processes can cause cyclical variations in movement that can be of similar magnitude to, or greater than, the calculated movement and specified trigger values for actions during construction activities. It is therefore important to understand the behaviour of the monitored asset prior to the impact of construction works so that appropriate responses can be made to monitored movement. Whilst the benefits of background monitoring prior to construction are well understood, codified rules for durations and type are not available, and it is left to the designer to specify something appropriate whilst often under external economic pressures to reduce the scope of monitoring. In this paper, the seasonal variations from monitoring of a range of different assets in London, UK are presented which show the timing, magnitude, and direction of seasonal movement. Knowledge gained from the pre-construction review of data and long-term monitoring of assets are detailed which will enable designers, contractors, and monitoring specialists to implement monitoring strategies on future projects which can better understand seasonal movement and facilitate a more efficient and effective review of monitoring data during construction. Recommendations with respect to the timing and duration of pre-construction background monitoring are also made based on experience of the difficulties in isolating construction movements for certain construction operations at specific times of the year.

KEYWORDS: Baseline, monitoring, tunnelling, settlement, risk management

1 INTRODUCTION

In order to properly control underground construction works, it is important to be able to understand the likely magnitudes of ground movements caused by their excavation. The impacts of these settlements on third party assets or other adjacent infrastructure can then be calculated and mitigated as appropriate. It is standard practice to specify and install instrumentation to facilitate monitoring of these movements during construction. Whilst procedures for calculating potential ground movements for construction of tunnels and excavations are generally well understood (e.g. CIRIA C760 (2017) for box excavations and error functions described by Attewell & Woodman (1982) for tunnel construction), the impact of seasonal movements on the monitoring points can be more challenging to estimate.

This paper presents case history data from the Northolt Tunnels West section of the High Speed Two project, to demonstrate the potential difficulties that are faced by those interpreting monitoring data to control impacts to third party assets. It also makes observations about the pattern of seasonal movements and the magnitudes that are routinely observed, in order to assist planning for those carrying out similar works.

2 BACKGROUND

2.1 *The project*

High Speed Two (HS2) is a UK national infrastructure north-south railway project, connecting London with Birmingham. The project comprises four new stations and a railway that will cross urban and rural areas via bridges, embankments, cuttings, and tunnels. The excavations required to build the stations, tunnels, and associated shafts and portals are large and have the potential to cause ground movement.

The HS2 project is built under the powers of the High Speed Rail Act, 2017. The Act incorporates Environmental Minimum Requirements (EMRs), which include commitments regarding the project's approach to assessing and reducing settlement from construction activities that have the potential to cause ground movement, including tunnel, shaft, portal, and station excavations. These requirements are set out in the HS2 Phase One Information Paper C3: Ground Settlement (High Speed Two, 2017). HS2 includes 44km of twin bore tunnels constructed using Tunnel Boring Machines (TBMs) and Sprayed Concrete Lining (SCL) plus a 7.2km Green Tunnel.

2.2 *Northolt Tunnels West*

This paper presents data from Northolt Tunnels West (NTW), which is one of the HS2 bored tunnel packages on the S1/S2 Contract. Northolt Tunnels West consists of twin 8km long, 9.84m diameter Earth Pressure Balance (EPB) TBM tunnels, driven from West Ruislip to Greenpark Way. There are two intermediate shafts at South Ruislip and Mandeville Road, and 20 cross passages constructed using a combination of ground treatment techniques which include ground freezing and dewatering. The TBM launch was completed using a thrust frame and blind rings from a cut and cover portal and the TBM arrivals were into shafts using shutter cans capable of holding the EPB pressure. The tunnels and cross passages were constructed within variable ground conditions. The TBMs were launched into London Clay and the Harwich Formation. For the first third of the drive the face consisted of Lower Mottled Clay with highly variable amounts of sand unit, then diving into the Ruislip Formation and Chalk with flints. For the middle third of the drive the face conditions were highly variable, consisting of cohesive Lower Mottled Clay and Lambeth Group sands. For the final third of the TBM drive London Clay was encountered

at the TBM crown with varying presence of Harwich Formation, Upper and Lower Mottled Clays, and Lambeth Group Sands.

2.3 Asset Protection

In any tunnelling project the protection of third-party assets, potentially affected by settlement from the underground excavation, is a key consideration. Settlement can affect third party assets, such as buildings, infrastructure, and services in different ways – in extreme cases settlement damage could interrupt utility services or public infrastructure, or building damage could affect businesses or residents. As a result of extensive experience of ground movement behavior on other major UK tunnelling projects, advancement in tunnelling technology, and strict adherence to risk management processes, the impact of tunnelling on third party assets is generally small and goes unnoticed.

On HS2, in line with asset protection best practice, buildings or assets which may be affected by settlement are assessed using a three-phase Ground Movement Assessment (GMA) approach proposed by Mair et al. (1996) which is well publicised and not detailed here. The GMAs set some key parameters for monitoring the effects of settlement, namely:

- The Zone of Influence - the limit of the calculated 1mm settlement contour, which generally sets the extent of general ground and infrastructure monitoring.
- Protective works requirement, where the assessed settlement impact is unacceptable to the asset owner or exceeds a project damage criteria.
- Third party structure or asset specific monitoring requirements, where not covered by general background monitoring i.e. tunnel monitoring transects.
- Ground and structure monitoring frequencies, generally set to meet a specification requirement but subject to the Designer's recommendations, should enhanced baseline or long-term post construction monitoring be appropriate.

For Northolt Tunnels West, 1,203 third-party assets, including utilities, bridges, buildings, and rail infrastructure, were monitored to manage tunnelling-induced ground movements. Collaborative efforts between the project teams ensured that baseline conditions were established. Data were continuously assessed in cross-disciplinary meetings, allowing for prompt decision-making and transparent communication. This proactive approach ensured minimal disruption and protected asset integrity while facilitating efficient tunnelling progress, demonstrating the value of data-driven decisions and strong team coordination throughout the project.

3 ASSESSING THE CONTRIBUTION OF SEASONAL MOVEMENT

It is common practice for designers to specify a period of background monitoring to firstly demonstrate reliability of the instrumentation, and secondly to allow the estimation of background or seasonal movements that the third-party structure is already subjected to. It is worth noting that impact assessment procedures generally implicitly allow for these background movements, and therefore it is the additional construction induced movements that need to be controlled rather than sum of these and the background movements.

It is generally not economical to monitor at high frequency and for sufficient duration to identify the full seasonal (and potentially diurnal) profile for all impacted assets, and therefore shorter periods are usually specified. A period of 3 months is often chosen as an appropriate background monitoring period, as in theory this can capture the amplitude of the 'repeatable'

seasonal cycle. For larger projects such as HS2, this is often specified as a minimum period in technical standards.

The general pattern of seasonal movements is for settlement to occur through spring and summer, as the ground dries, with heave occurring through autumn and winter, as it is re-saturated. For stable ground, this cyclical pattern can be seen to be repeatable over several years. This cycling can be particularly evident in areas where vegetation is close by, as water demand from roots can amplify this effect. Observed seasonal movements can be larger than calculated movements due to construction, and this can create difficulties for Engineers responsible for assessing impacts from monitoring data in order to ensure that adjacent structures are protected.

Figure 1 shows 3 months of data from a monitoring point located above the NTW tunnelling works. The baseline monitoring was carried out during summer, as was the associated tunnelling works. As can be seen, a general pattern of settlement of the ground can be seen prior to tunnelling works, and it is difficult to determine the movements from the tunnel passing from the monitoring data, even though settlements of around 20mm were anticipated from conservative calculations.

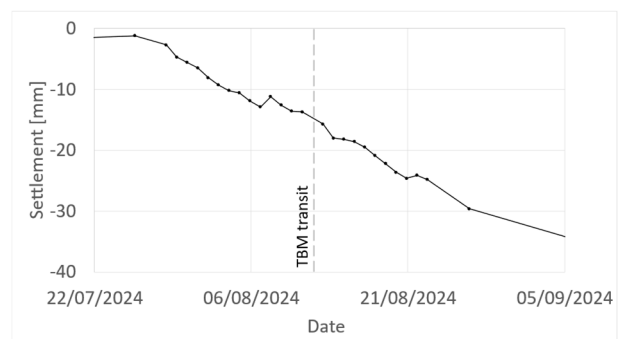


Figure 1. Monitoring data close to a tunnel crossing.

The above creates difficulties for Engineers on two fronts: firstly, if only very limited background monitoring had been carried out, settlements prior to tunnel excavation may have been attributed to survey error; and secondly it is difficult to separate the immediate settlement from tunnelling and any ongoing settlement (due to e.g. incorrect back grouting creating voids). Monitoring settlement triggers set to represent construction movements are easily exceeded in this scenario, and without proper understanding of the background movements, it is difficult to properly assess their cause until perhaps movements reverse as winter approaches. This can be a long time to wait to provide confidence in the recorded movements to reassure third parties.

Figure 2 shows the monitoring data following tunnel construction and for a period of several months after, demonstrating this seasonal reversal of movement. This reversal provides confidence that settlements observed following the tunnel crossing are principally seasonal, and considered in concert with data measured by the TBM, which provide detailed evidence that operations were carried out correctly, the potential for unexpected ongoing tunnel settlements (i.e. those not related to consolidation / re-equalisation of water pressures) can be effectively ruled out.

The following sections present monitoring data from a number of locations close to the NTW tunnelling operations, to further demonstrate the seasonal effects, and the influence of adjacent vegetation.

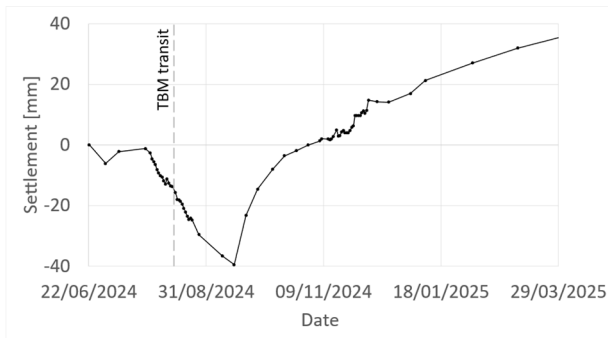


Figure 2. Monitoring data following tunnel crossing

4 CASE HISTORY DATA FROM BACKGROUND MONITORING

Monitoring data from 12 ground surface levelling points spaced along the 8km NTW alignment are shown in Figure 3. These points were identified to be presented in this paper as they show variations in settlement attributed to seasonal effects and not construction activities. There is typically 9-12 months of monitoring data for each levelling point, consisting of 3-month baseline, followed by approximately 2 months construction monitoring during the passage of the two TBMs, and then post-construction monitoring for a minimum of 4 months prior to decommissioning of the instrument. A longer duration of monitoring was undertaken for some instruments due to delays to construction or specific monitoring requirements for sensitive third-party assets. The frequency of monitoring was increased when the instruments were within the calculated Zone of Influence of the TBMs.

The monitoring data presented in Figure 3 show a sinusoidal pattern of settlement over a year period, with settlement during the spring and summer months (April to September), followed by heave in the autumn and winter months (October to March). Seasonal variations in settlement with an amplitude of up to 40mm were recorded, exceeding the calculated settlement due to tunnel construction. The data in Figure 3 show that the timing of the cycles are approximately the same for each of the instruments along the 8km tunnel drive, however the exact timing of the maxima and minima (and rates of change) vary each year, as shown in Table 1.

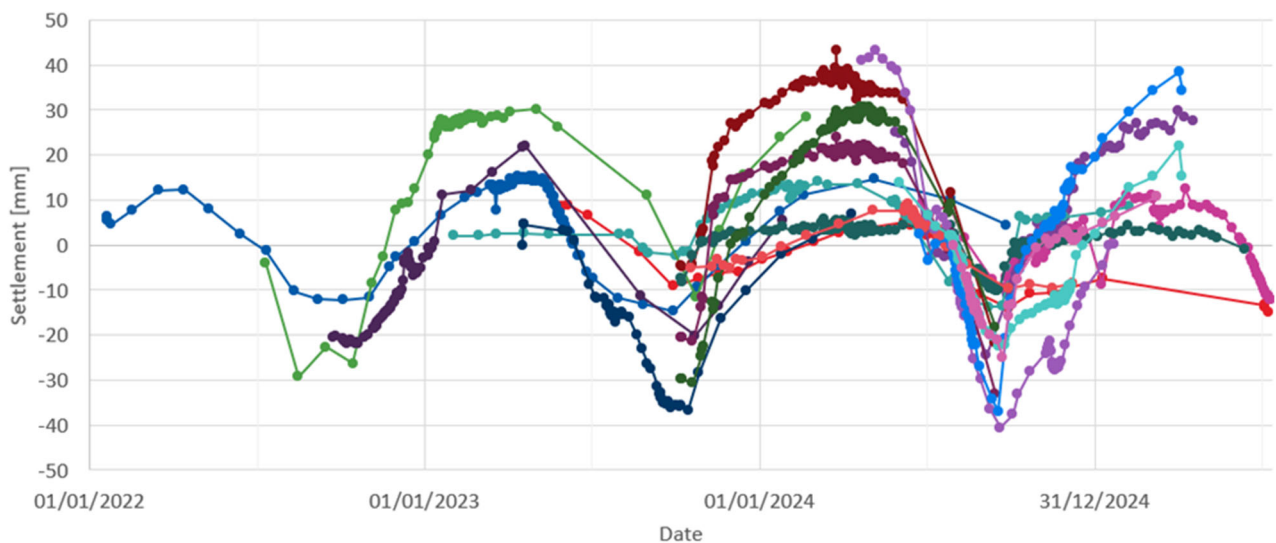


Figure 3. Settlement data from 12 ground surface levelling points along the tunnel alignment

Table 1. Average dates for apex and nadir in seasonal vertical movement

Year	Average date of apex	Average date of nadir
2022	13/04/2022	12/09/2022
2023	02/05/2023	11/10/2023
2024	21/04/2024	17/09/2024
2025	22/03/2025	

Weather data for London, downloaded from Visual Crossing Weather website, are shown in Figure 4. The average temperature profile follows a sinusoidal pattern over a period of one year, with minimum temperatures recorded at the start of the year (January/February) and peaks in the summer months (typically June/July). Precipitation data shown in Figure 4 show that autumn (September-November) is typically the wettest period, but that precipitation occurs throughout the year and the frequency and volume vary each year. Seasonal weather patterns are becoming more extreme and less predictable due to climate change.

The temperature and precipitation data plotted in Figure 4 explain the seasonal pattern seen in the ground surface monitoring data in Figure 3. During spring and summer months the ambient temperature increases and precipitation typically reduces. The water content of the ground decreases because of (1) reduced precipitation; (2) increased evaporation due to increases in temperature and intensity and duration of sunlight; (3) in vegetated areas, increased transpiration due to higher temperatures, increased intensity and duration of sunlight, and lower humidity. The reduction in water content of the ground causes shrinkage and results in settlement of monitoring points shown in Figure 4 which is exacerbated in vegetated areas. In mid-summer 2023 and 2024, the rate of settlement reduces, which correlates with periods of increased precipitation in Figure 4.

During autumn and winter months, the temperature decreases and precipitation increases (as shown in Figure 4), and the duration and intensity of sunlight decreases resulting in an increase in moisture content and swelling of the ground. The reversal of direction of movement of monitoring points from settlement to heave in September 2024 in Figure 3 correlates with a period of heavy rainfall and reductions in temperature in Figure 4.

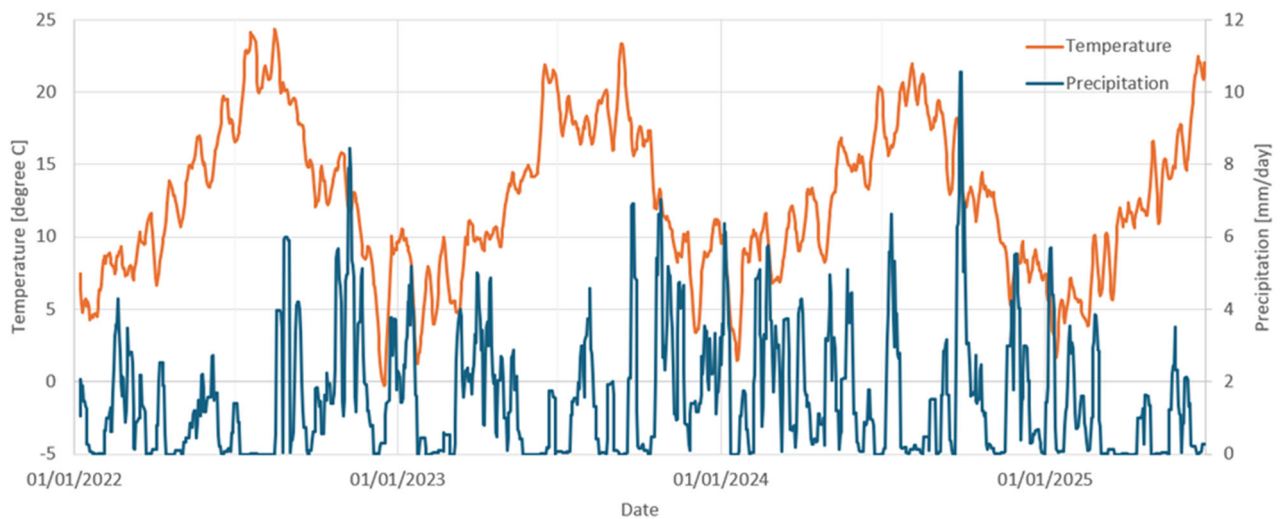


Figure 4. Temperature and rainfall data for London

The amplitude of the seasonal variation in heave and settlement will be dependent on the soil type and proximity to vegetation with different water demands. Figure 5 presents monitoring data from ground surface levelling points installed at 5m spacing in the curb of a pavement, which are located 1m, 4m, and 9m from a large beech tree. Monitoring data for a period of 32 months are presented.

The levelling points 1m and 4m from the beech tree show seasonal settlement and heave with an amplitude of approximately 15mm and 11mm respectively, which remains approximately the same over the period of monitoring. Cracks were visible in the pavement and curb prior to installation of these levelling points, which suggests that this seasonal movement has been ongoing for many years before the monitoring began. InSAR data are not available in this area to verify this, as the wavelengths used for InSAR monitoring are not able to penetrate through the vegetation present. The monitoring point 9m from the beech tree however shows no distinguishable seasonal cycle, which indicates that it is outside the lateral zone of influence of this tree. These data demonstrate how local the effects of vegetation on seasonal movement can be and highlight the importance of clearly documenting and understanding the installed location of instruments to facilitate review of the monitoring data by the project teams. Installation reports are useful for this purpose, and should be readily available when reviewing monitoring data during construction.

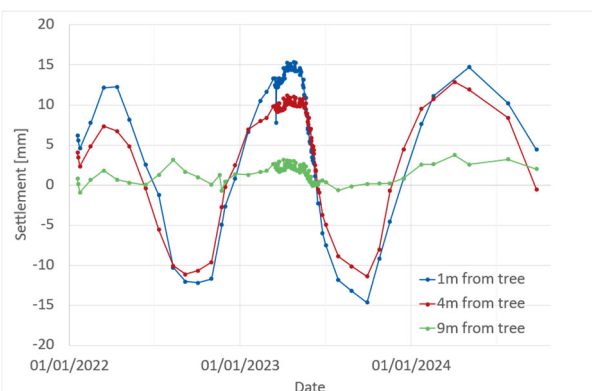


Figure 5. Comparison of settlement monitoring data close to a large beech tree

This observed lateral zone of influence is less than the 15m lateral zone of influence presented in the National House Building Council (NHBC) Standards (2024) for beech trees, assuming a mature height of 20m. The NHBC standard classified beech trees as a moderate water demand species and therefore a lateral zone of influence of 0.75x mature height would be appropriate. For comparison, the lateral zone of influence is stated as 0.5x mature height for low water demand species such as birch and 1.25x mature height for high water demand species such as oak, elm, and willow.

5 DISCUSSION ON BASELINING PERIODS

5.1 Baseline periods for major projects in the UK

In order to ensure that a sufficient understanding of seasonal movements is gained prior to construction works, it is typical for major infrastructure project technical requirements in the UK to mandate a minimum period of background monitoring. A 3-month minimum baselining period is often used, as in theory this allows for a quarter of the “sine wave” of seasonal movement to be understood, potentially allowing for a curve representing a full year’s seasonal movement to be constructed.

HS2, in common with previous large infrastructure projects, required a minimum baselining period for monitoring of 3 months in the technical standard for monitoring. This has been used in the NTW section of HS2 as a minimum, although clearly, from the case history data already presented, significantly longer baseline monitoring periods have been used in many locations.

This section of the paper discusses recent experience of using these minimum baselining periods and presents recommendations for future projects.

5.2 Observations from experience of asset projection

This section principally deals with vertical settlements related to TBM tunnelling, but the same principles can be applied to movements in other planes, and due to other construction operations.

A typical pattern of seasonal movement is shown in Figure 6 below. This shows shrink/swell movements, with settlement occurring as the ground dries out through the warmer, drier months, and heave occurring as the ground becomes re-wetted through autumn into winter. Observations from NTW suggest that the apex and nadir of the seasonal movements curve occur in approximately April and October respectively.

In order for a baseline period to be effective, it needs to properly identify one quarter of the cycle, and experience during construction of NTW has shown that the timing of the start of the monitoring period can influence the ability of the baselining measurements to properly identify the magnitude of the likely background movements.

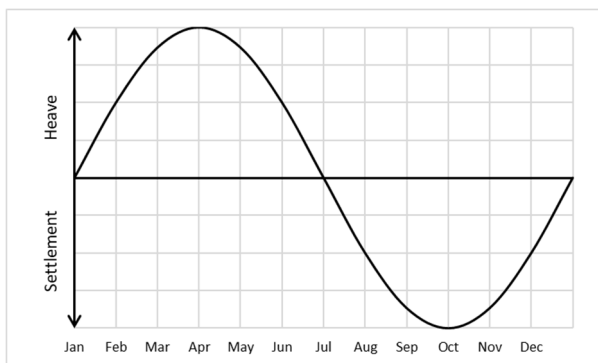


Figure 6. Typical pattern of seasonal settlement

Consider a 3-month period in the above figure, (Figure 6) commencing in mid-February, with tunnelling works commencing in mid-May. If a monthly monitoring frequency was chosen, then the fluctuation could be attributed to survey error, instrumentation accuracy etc. and a zero fluctuation could be assumed prior to tunnelling (see Figure 7). Following tunnelling, large settlements would be experienced until October, with a long intervening period where uncertainty as to the cause existing. Even if a monitoring frequency was appropriately chosen to identify that this was cycling behaviour (Figure 8), the baselining period would have completely failed to identify the potential magnitude of summer settlements, and a similar period of uncertainty would follow. This uncertainty can make project decisions around possibility of these movements being related to tunnelling, and assurance conversations with third parties, challenging.

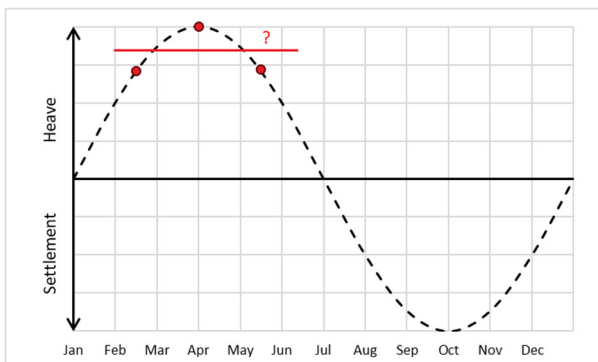


Figure 7. Typical pattern of seasonal settlement – reduced baselining period with infrequent monitoring.

With consideration of the above, it is more important that the monitoring baselining period correctly identifies an appropriate amount of the seasonal movement curve. For the above situation of tunnelling in mid-May, commencement of monitoring in January, even at limited frequency, but with an understanding that there would be likely a fluctuation of the pattern observed in the case history data in Section 4 above, would have provided considerably more helpful information about the expected amplitude of seasonal settlement that might be experienced following tunnelling. In contrast to the above, it could be possible to specify shorter baselining periods where the seasonal movement occurring during the works is in the opposite direction to the expected movements, allowing unexpected settlements to be more easily isolated. In other

words, if the ground overlying tunnelling works is heaving, then it is easier to identify settlement as being directly attributable to the transit of the TBMs.

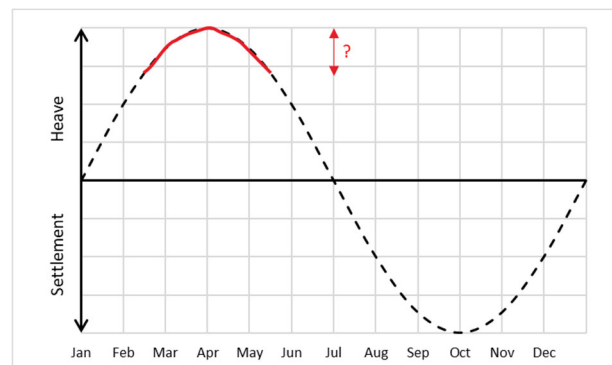


Figure 8. Typical pattern of seasonal settlement – reduced baselining period with frequent monitoring

6 DISCUSSION

6.1 Instrumentation and monitoring methods

Instrumentation and monitoring methods were selected based on required parameters to be measured, monitoring period, reading frequency, and access constraints. Traditional survey methods were the preferred option, and other methods were also used as required. Methods used include, but were not limited to: precise levelling; manual 3D monitoring with total station; automatic 3D monitoring with robotic total station; tilt meters; shape arrays; InSAR; and shallow datums.

Monitoring of streets and buildings was conducted via traditional survey methods, survey teams with precise levels or total stations taking manual readings on precise levelling points or 3D targets. On restricted access assets, automated systems were selected. Network Rail tracks were monitored with a combination of tilt meters and Automated Total Stations, while Shape Accelerometer Arrays were used in culverts.

InSAR data was available and used by the project teams, primarily to monitor buildings. As discussed earlier in this paper, InSAR was found not to be useful for understanding seasonal movement in vegetated areas during the baseline monitoring period as the wavelength of the electromagnetic waves used are unable to penetrate through leaves and vegetation to reach a reflective point on the ground or structure. Installation of InSAR reflector points (which provide a reliable reflector for the satellite, rather than relying on measurement points with good natural reflectance) was not undertaken on this project but could be considered on future projects.

The construction teams, in cooperation with the I&M Subcontractor, endeavored to provide quality data throughout the project during all phases of monitoring, and considered baseline data as important as the potential construction impact period data. The personnel, equipment, and methodology used were consistent throughout. All control networks were linked together by the survey team, were regularly reviewed, and all the data were treated as construction period data. The monitoring data were reviewed daily following the first set of readings. Frequencies of monitoring were increased if unexpected movements were identified and regular checks on the control networks were undertaken. As presented in this paper, the baseline data provided valuable information on seasonal movements that could otherwise have been attributed to the construction works. Data measured facilitated agreement and issue of Letters of Consent with Third Parties and enabled engineering judgement during the construction of the NTW tunnels.

6.2 Trigger values

Ground movement impact assessment procedures generally implicitly allow for seasonal and background movements, therefore it is the additional construction induced movements that need to be controlled rather than sum of these and the seasonal and background movements. Trigger values, which are pre-determined values of a measured parameter which “triggers” a response or management action, applied during construction therefore need to consider the magnitude and timing of seasonal movement.

During construction works on NTW, “virtual points” were used to isolate movement due to TBM construction activities. Monitoring data for instruments which had been identified as experiencing seasonal movement of a similar order of magnitude to calculated movement due to construction were duplicated and “virtual points” were created with the datum reset to zero prior to transit of the TBM. Trigger values based on calculated movements were applied to the “virtual points”. The short duration of the tunnel activities in comparison to the seasonal movement allowed the movement due to the construction works to be isolated and managed appropriately. This approach would not have been suitable for longer duration construction activities, such as shaft excavation, which normally occur over a period of months.

6.3 Background monitoring

Generally, baseline monitoring periods are specified to provide a reasonably practicable set of data at a frequency that allows the Engineer to understand the natural movement of the ground, an asset, or a structure prior to any external effects (such as underground excavation). The experience shared in this paper shows that for some areas, these reasonably practicable periods may be insufficient and that a longer period of monitoring in advance of an asset being affected by tunnelling would have been highly valuable to the Project. It would have allowed the Engineer to decipher seasonal effects well in advance and ensure suitable expectations were set with third parties and appropriate triggers based around those seasonal effects.

Historically, background monitoring to identify seasonal effects has been specified but at a low frequency (e.g. monthly) and typically using manual survey methods, with results adding little value. Based on this HS2 project experience, an alternative approach is proposed using remote sparsely spaced (in comparison to baseline/construction monitoring) background monitoring installed at least 12 months prior to any expected settlement effects. The remote system, such as InSAR, could utilise historical data to complement the background monitoring period in urban areas but would likely need to be supplemented by InSAR reflector points installed in less built up or rural areas. The sparse spacing would allow a cost-effective scope of instrumentation often required during the early project stages. It is the authors’ view that the typical frequency of a remote automated system, such as InSAR, would be sufficient to identify any seasonal cyclical patterns. It is proposed that the Engineer assessing the settlement could identify locations for this monitoring that may be at risk of high seasonal variation, for example, older earthworks structures, areas with high vegetation influence, as well as ‘standard’ monitoring locations for comparison purposes.

A further recommendation, to supplement this background monitoring, would be to include shallow sub-surface datum points, with anchor points at least 3m deep, adjacent to the instruments specified to identify seasonal effects. These points could demonstrate depth of influence of the seasonal effects, which would be useful to allow the Engineer to separate surface fluctuations with the tunnel excavation effects.

6.4 Climate change

Seasonal weather patterns vary and are becoming more extreme and less predictable. Figure 4 shows that London experienced a long dry spring in 2025 compared to the preceding 3 years. Unpredictable seasonal weather patterns will likely pose a further challenge when assessing seasonal settlement cycles.

7 CONCLUSION

In conclusion, the authors believe that a blanket minimum 3-month baselining period may not be suitable for all projects, as an appropriate minimum will depend on the timing of the works related to the seasonal cycle, and the potential amplitude of that cycle. The baselining period for a particular asset should be considered along with the construction program (with appropriate flexibility to account for changes) to determine an appropriate duration. It is noted that whilst a full year cycle is obviously optimum in terms of understanding the full range of expected seasonal movements, time and economical considerations mean that this is often not possible or desirable.

Proximity to trees and vegetation should be considered when determining the exact locations to install instrumentation. Site visits, or use of remote systems such as Google street view, may be useful for this purpose. Installation reports should document the proximity to different species of vegetation and details of any existing evidence of seasonal movement, such as cracks in paving slabs. These reports should be readily available when reviewing monitoring data during construction.

Instrumentation and monitoring has been, and will continue to be, a team effort. Technical review groups were established during the NTW works and the cooperative approach led to a better understanding of environmental impacts, achieved agreement on recorded displacements unrelated to construction works but not fitting in the monitoring requirements, allowed optimisation of available resources and reuse of equipment to bring efficiencies to the project.

Sharing of case history data showing the magnitude, timing, and location of seasonal movement would be beneficial to the construction industry to inform monitoring regimes on future projects and enable data-driven decisions to be made. Collating and sharing baseline and background monitoring in an accessible database would be useful for this purpose.

8 ACKNOWLEDGEMENTS

The authors wish to acknowledge the many teams involved in the successful implementation of instrumentation and monitoring on Northolt Tunnels West. This project is a great example of collaboration between Contractors, Designers, Client organisations, and Third Party asset owners.

9 REFERENCES

- Attewell, P.B. and Woodman, J.P. 1982. Predicting the dynamics of ground settlement and its derivatives caused by tunnelling in soil. *Ground Engineering* 15(8), 13-36.
- CIRIA, 2017. C760 – Guidance on embedded retaining wall design.
- High Speed Two, 2017. Information Paper C3: Ground Settlement Available at <https://www.hs2.org.uk/documents/collections/hs2-phase-one-information-papers/> [Accessed 7th August 2025]
- Mair, R. J., Taylor, R. N. and Burland, J. B. 1996. Prediction of ground movements and assessment of risk of building damage due to bored tunnelling. *Proc. Of the Int. Symp. On Geotech. Aspects of Underground Construction in Soft Ground*, Rotterdam, 713 – 718.
- National House Building Council 2024. NHBC Standards 2024 – Chapter 4.2: Building near trees. NHBC.
- Visual Crossing Weather [Online] Available at <https://www.visualcrossing.com/weather-query-builder/> [Accessed 22nd July 2025]