Geospatial Monitoring: Advancements and Thresholds

Jordan K. Baldwin, Ph.D., P.E., M.ASCE[1]; and Isaac L. Howard, Ph.D., P.E., F.ASCE[2]

[1]Principal Engineer and Surveyor, Ridgeline Engineering, Stockton, CA. Email: jordan@rle.us
[2]Professor and Director, Richard A. Rula School of Civil and Environmental Engineering, Mississippi State Univ., Mississippi State, MS. Email: ilhoward@cee.msstate.edu

ABSTRACT

Continuous advancements have been made, particularly over the past three decades, in the monitoring of infrastructure. Effective use of instrumentation and sensors can aid in identifying safety hazards during construction. Geospatial monitoring, in particular, is an activity that measures relative displacements or deformations that may otherwise be unrecognizable early on when intervention is most crucial. A framework to define threshold values for geospatial monitoring using baseline statistics is presented and application of the approach is detailed using measurements obtained from a deep excavation project in Brooklyn, New York. A potential relationship with temperature was identified and used to increase the precision of the behavior model, and this framework would allow for a variety of measured independent variables. Monitoring results identified an abnormal permanent shift in the position of a shoring monitoring prism toward the area of excavation. Although the apparent movement stabilized after nearly 70 days into the monitoring period, the threshold exceedances would have alerted the abnormal trend around 25 days, demonstrating the utility of the approach. Such real-time feedback is imperative to ensure hazards are identified early on, prompting investigations and the implementation of safety measures as soon as a potential hazard is detected.

INTRODUCTION

Continuous advancements have been made, particularly over the past three decades, in monitoring infrastructure; they include effectiveness, technologies employed, and frequency of implementation. In general, monitoring is an activity that utilizes sensors to better understand behavior and identify inconsistencies or changes that may otherwise be unrecognizable. If deficiencies are appropriately identified, precautions may be implemented to protect surrounding infrastructure and any individuals in the project vicinity. The metrics derived from various sensors and instrumentation may be categorized as either *localized* or *geospatial*. *Localized* sensors and instrumentation, such as strain gauges, inclinometers, and accelerometers, provide metrics for a discrete location, whereas *geospatial* sensors and instrumentation, such as Global Navigation Satellite Systems (GNSS), total stations, and laser scanners, provide reference to positional relativity between measured locations. Implementation of sensors and instrumentation of varying types is often favorable so that redundancy and output validation is available.

Geospatial monitoring of has been identified as a useful and important activity in a variety of situations. Baldwin (2023) presents a state-of-the-art review of a variety of geospatial monitoring applications and organizes them into performance, in-service, and construction monitoring categories. Performance monitoring (PM) during and after construction provides valuable feedback to engineers, demonstrating if infrastructure is behaving as expected, because design model limitations or simplifications may lead to full-scale performance that differs from design (Baldwin, et al., 2023; Li et al, 2006). In-service monitoring (IM) of infrastructure, such as bridges and dams, may assist with identifying deficiencies that need attention. Of the more than 617,000 bridges that currently exist across the United States, 42% are at least 50 years old and 7.5% are considered structurally deficient while approximately 17% of the more than 91,000 dams nationwide have been labeled as having high-hazard-potential (ASCE 2021).

Construction monitoring (CM) can be especially crucial because new construction has the potential to unintentionally impact existing infrastructure, particularly in urban environments (Moss and Mathews, 1995). A Zone of Influence (ZOI) emerges when construction activity commences, and stresses are applied to the surrounding environment. The extent and magnitude of influence depends on the proximity of the proposed activity, the type of activity, local environmental and geological parameters, as well as the location and type of existing infrastructure. Each component of infrastructure may be affected differently within the ZOI and therefore needs to be individually evaluated. Whether the type of construction involves tunneling, excavating, pile driving, blasting, or some other influential activity, adjacent structures, roads, bridges, railways, slopes, pipelines, or other infrastructure may have serviceability or safety compromised. Examples of influence include ground loss and ground movements resulting from changes in the state of stress within the ground mass. Such construction induced disturbances may cause structures to settle and shift, roads and railways to misalign and deform, pipelines to bend, displace or rupture, or slopes to weaken and fail (Attewell et al., 1986; Boscardin et al., 1989).

Even when steps are taken to implement a CM program, it is critical to ensure that the system is designed and managed in such a way that it operates reliably and provides rapid and meaningful feedback. The importance of this process is emphasized by a fatal collapse that occurred during tunneling excavations in Singapore in 2004. Movements in the excavation had been detected two months before the collapse but authorities were unaware due to several problems. What contributed to the tragedy were inadequacies in the instrumentation and monitoring system, improper management of instrumentation data, a lack of competency in those performing the monitoring operations, supervisory personnel who were incapable of identifying adverse trends and implementing corrective measures, problems with communication were identified at virtually all levels, and a lack of clarity in the reporting and decision-making structure. As a result, a multitude of entities and individuals were prosecuted at every level of involvement (National Archives of Singapore [NAS], 2005).

Kenchington (2003) observed that automated and autonomous monitoring systems may incur higher upfront costs, but when implemented and managed appropriately, can produce large quantities of high accuracy data at low cost. For this reason, Automated Motorized Total Stations (AMTS) have been frequently deployed on a variety of construction monitoring projects (Roy and Gouvin, 2007; Kaalberg et al., 2003). AMTS instruments acquire measurements in the same fashion as their unautomated counterparts, except that they are permanently stationed and programed to repeatedly observe a list of targets. The target positions can be wirelessly transmitted and graphed in real-time, allowing for near-immediate deformation recognition.

Approaches to data evaluation, threshold definition, and the identification of abnormal results are not often defined. This paper presents a statistical approach to thresholds determination that is one of many approaches that may be incorporated. A layered approach that integrates other threshold defining criteria, whether by modeling, or known allowable movement related to the specific retaining systems or adjacent structures is encouraged.

Construction of a new building in Brooklyn, New York required AMTS monitoring of an adjacent 40-story building and associated shoring during deep excavation operations. The monitoring program was included as part of the construction bid and the contractor managed the system and interpreted the data acquired by the instrumentation team. Baldwin (2023) was part of the instrumentation team and reported on a post-construction review of the monitoring data to demonstrate how baseline statistics could have been used to define threshold values. The following section details this approach.

DEFINING MONITORING THRESHOLDS

The general purpose of construction monitoring is to identify changes in behavior that may eventually prove problematic. When modeled references do not exist, results are sometimes evaluated against arbitrarily defined threshold values that do not necessarily consider the distinctive and natural behavior of the structure or component. The approach presented herein considers how baseline data may be utilized to define unique and meaningful threshold values.

Figure 1 illustrates the general layout of the monitoring system. Two AMTS instruments were mounted at the top of the excavation on opposite sides and a total of six monitoring points (MPs) were installed on the adjacent building and excavation shoring, although only measurement results from MP-1A (one of the six monitoring points) will be highlighted. Reference points (RPs) were also installed to triangulate the instrument positions. Although the implementation of multiple RPs was planned, complications with installations resulted in only two per instrument being measured, notated as RP-1A, RP-1B, RP-2A, and RP-2B.

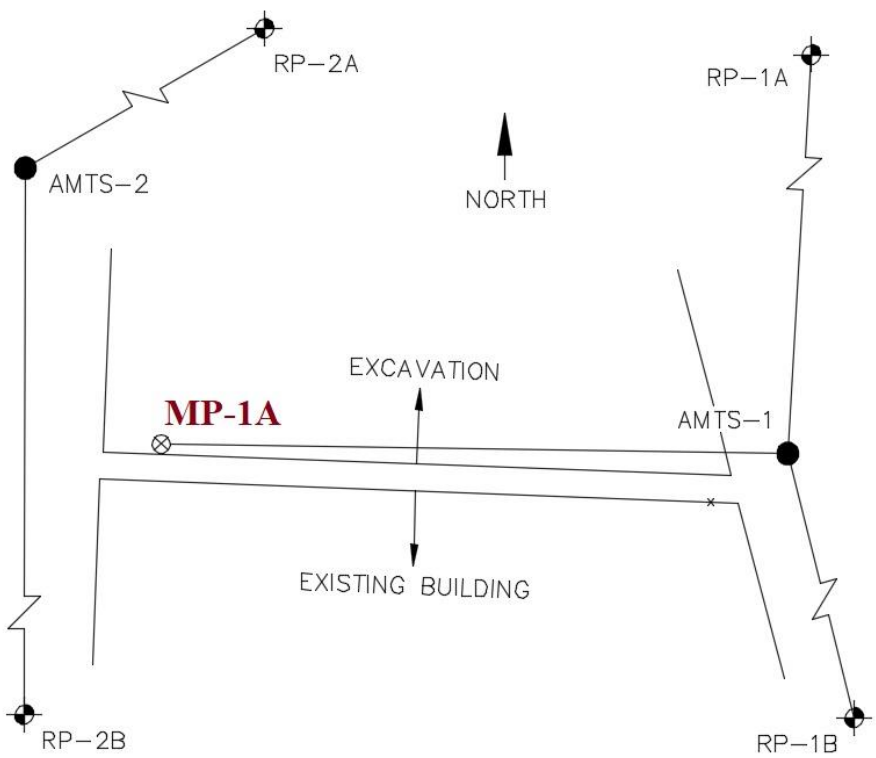

Figure 1. Project layout illustration

Atmospheric Corrections. The two instruments observed their respective reference and monitoring prisms at a one-hour frequency. An approximate four-week baseline period was initially established, and the raw slope distance and temperature readings were reviewed. The measurements from AMTS-1 to RP-1A indicated a possible inverse relationship between slope distance and temperature (Figure 2). To investigate this further, the relationship between slope distance readings and temperature were evaluated for each reference point measurement and coefficients of determination (R^2) were found to be 0.71, 0.75, 0.54, and 0.77 for RP-1A, RP-1B, RP-2A, and RP-2B, respectively.

Slope distance adjustments were applied based on the refractivity index approximation originally derived by Barrell and Sears (1939) and still used in present day by total station manufactures (Leica Geosystems, 2013). The adjustment takes into account ambient temperature, atmospheric pressure, and relative humidity. Since only temperature readings were acquired, average regional atmospheric pressure and relative humidity values were used in the adjustment computations. It was determined that the combined effects of atmospheric pressure and relative humidity fluctuations would only result in approximately 3 parts per million of measurement error as opposed to approximately 16 parts per million associated with temperature. Coefficients of determination between adjusted values of slope distance and temperature were reduced to 0.08, 0.42, 0.01, and 0.17 for RP-1A, RP-1B, RP-2A, and RP-2B, respectively. Any remaining apparent correlations may be associated with environmental variations along the measurement path or thermally induced movement of the structures supporting the instrument and reference prisms.

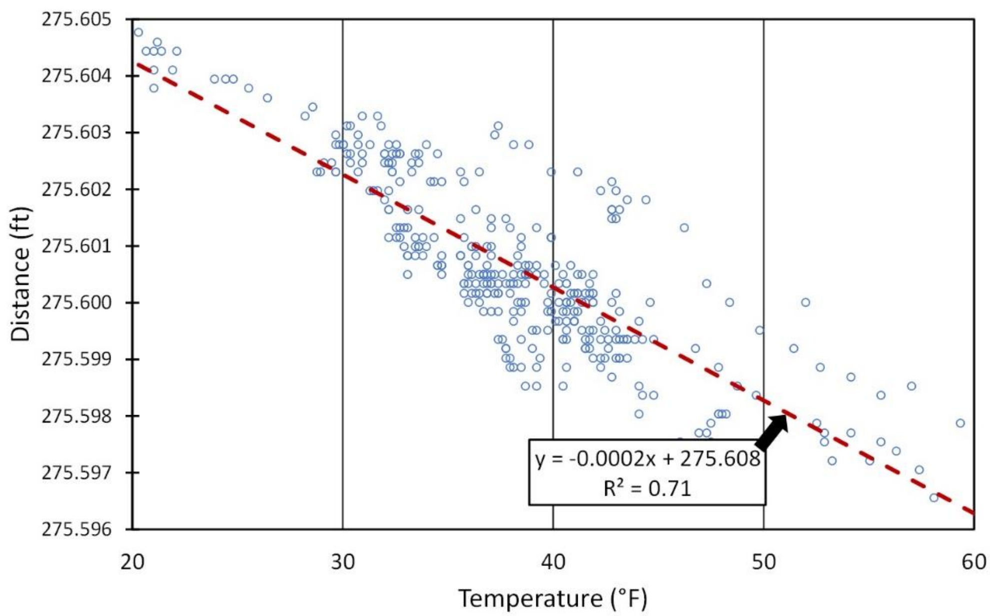

Figure 2. RP-1A: Baseline period distance measurements

Instrumentation Triangulation. The positions of the AMTS instruments were computed for each hourly cycle of measurements through a triangulation process where the reference point coordinates are held constant and the instrument's coordinates are trigonometrically computed using observed angles and distances. The associated changes in the northing, easting, and elevation components for each instrument position were then plotted. Figure 3 illustrates the results for the easting and elevation components of AMTS-1. The large fluctuations observed in the easting component is likely due to the poor geometric orientation of the reference points related to the instrument and the lack of additional reference points necessary to more accurately compute the instrument's position. RP-1A and RP-1B are nearly directly north and south of the instrument, resulting in a high level of variability in the easterly/westerly positional solution.

Baseline Behavior Analysis. The Baseline Behavior Analysis (BBA) method is a general framework that establishes a project specific baseline mean from which to measure displacements, evaluates displacement deviations to define unique threshold values, and if needed, incorporates an adjustment to compensate for external influences. Adjustments are necessary when precisions within the baseline dataset are low. The general form of the baseline behavior model, μ, is defined as the sum of the mean coordinate value, $\bar{y}$, and the adjustment value, $\hat{y}$. Displacements, D, for each measurement can be found by computing the difference between each individual coordinate value, y, and the model.

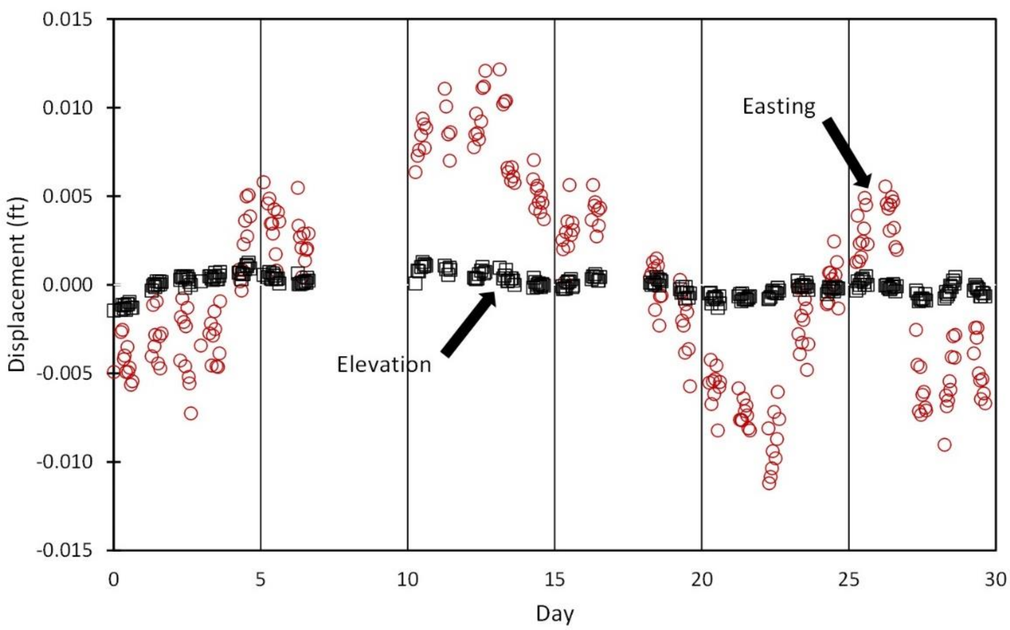

Figure 3. AMTS-1: Change in computed coordinates.

Using measured horizontal angles, zenith angles, and slope distances, the coordinates of MP-1A, a monitoring prism mounted on the shoring system supporting the excavation, were computed for each hourly cycle of baseline measurements based on the triangulated position of AMTS-1. Standard deviations for the northing, easting, and elevation component displacements were computed as ± 0.0028 feet (0.85 mm), ± 0.0053 feet (1.62 mm), and ± 0.0018 feet (0.55 mm), respectively. To ensure real movement is identified, it is suggested that a minimum displacement of 0.020 feet (6.0 mm) be detectible, meaning the level of precision of the baseline behavior model should be less than ± 0.010 feet (3.0 mm) when evaluated at a 95% confidence level. Likely due to fluctuating movement of the instrument indicated in Figure 3, deviation in the easting component slightly exceeds this limit, requiring an adjustment to the model. Model errors may be reduced by compensating for potential influences on the monitoring measurements. For instance, the structure the instrument or monitoring prism is mounted on may experience expansions and contractions caused by changes in ambient temperature. Since temperature was measured during the baseline period, a relationship could be investigated. A linear regression analysis was performed to evaluate the relationship between model displacements in the easting component with changes in temperature, and a p-value near zero was accepted as an indication that a relationship was likely. This analysis produced an adjustment value, $\hat{y}$, which is equivalent to a model constant, $\hat{\beta}_0$, minus the constant associated with the independent variable temperature, $\hat{\beta}_1$, multiplied by temperature, T (Mendenhall and Sincich, 2012). Figure 4 illustrates the difference between the unadjusted and adjusted models.

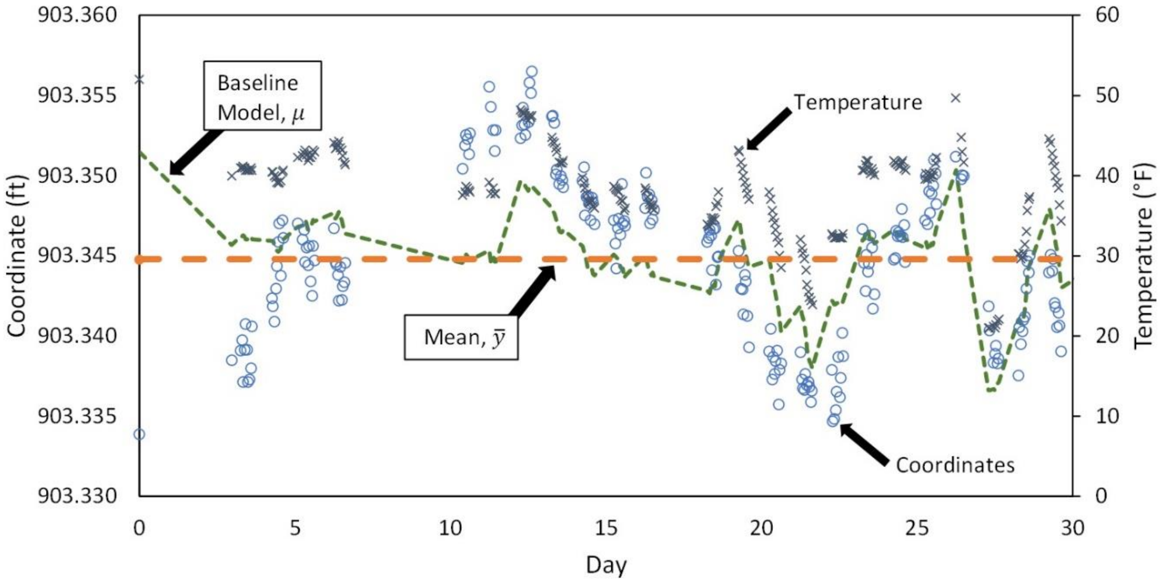

Figure 4. MP-1A: Baseline easting coordinates and model.

After computing displacements from the adjusted baseline behavior model, the easting component standard deviation was reduced by approximately 20% to ± 0.0043 feet (1.31 mm), meeting the suggested precision requirements. It should be noted that the modeled temperature range was between approximately 20 and 50 degrees Fahrenheit (-7 and 10 degrees Celsius). The model adjustment may need to be revised for any temperatures experienced outside of this range.

Finally, *log*, *review*, and *suspend* alert thresholds were established at two, three, and four standard deviations from each baseline behavior model, respectively. Statistically speaking, threshold exceedances would be expected at a rate of 1 in 22, 1 in 370, and 1 in 16,000, for each respective level when observing 'normal' behavior. A *log* alert would require that the magnitude, location, and time of the exceedance be reported and reviewed during the next regular monitoring system assessment; a *review* alert would require immediate notification of the exceedance to monitoring staff; and a *suspend* alert would require immediate notification to construction personnel to suspend operations in the vicinity of exceedance until monitoring personnel provide a thorough review. Figure 5 illustrates the baseline period displacements with alert thresholds overlaid for the easting and elevation components of MP-1A.

Monitoring Data Evaluation. The monitoring period extended approximately 130 days beyond the baseline period. Trends indicating a drop in elevation and a slight shift to the northeast were identified in the MP-1A measurements. Figure 6 shows monitoring period displacements with a 7-day moving average line overlaid to illustrate movement trends. The shift appears to roughly stabilize during the final 50 days of the monitoring period, indicating an apparent shift of approximately 0.01 feet in the easterly direction and a drop of approximately 0.01 feet in elevation. An apparent shift in the northerly direction of approximately 0.01 feet was similarly observed. The trends are consistent with movement toward the area of excavation. First indications of a downward trend would have been triggered by consistent exceedance of the *review* threshold around day 55 (25 days into the monitoring period). Displacements continue to exceed the *review* threshold until about day 100 (70 days into the monitoring period), at which point the *suspend* threshold is continuously exceeded throughout the remainder of the monitoring period.

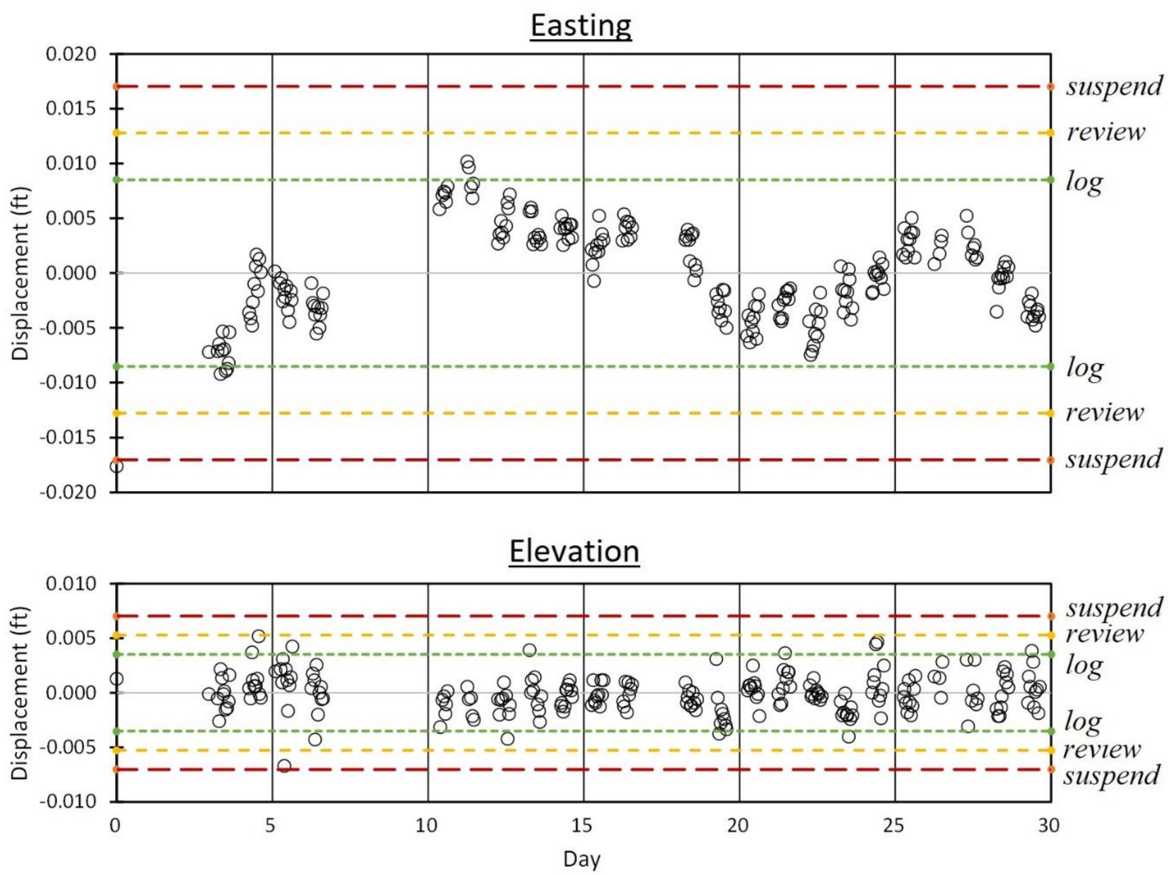

Figure 5. MP-1A: Baseline displacements & alert thresholds.

SUMMARY

Use of the Baseline Behavior Analysis (BBA) method to develop unique project specific thresholds (dashed lines illustrated in Figures 5 & 6) and evaluate monitoring results was demonstrated by incorporating construction monitoring data acquired during a deep excavation project in Brooklyn, New York. A potential relationship with temperature was identified and used to increase the precision of the behavior model, and this framework would allow for a variety of measured independent variables to be explored and applied individually or in combination on future projects. Monitoring results identified an abnormal permanent shift in the position of a shoring monitoring prism toward the area of excavation. Although the apparent movement stabilized after nearly 70 days into the monitoring period, the BBA method threshold exceedances would have alerted the abnormal trend around 25 days, demonstrating the utility of the approach. Such real-time feedback is imperative to ensure hazards are identified early on,

prompting investigations and the implementation of safety measures as soon as a potential hazard is detected. As mentioned earlier, a layered approach that integrates other threshold determination methods is encouraged.

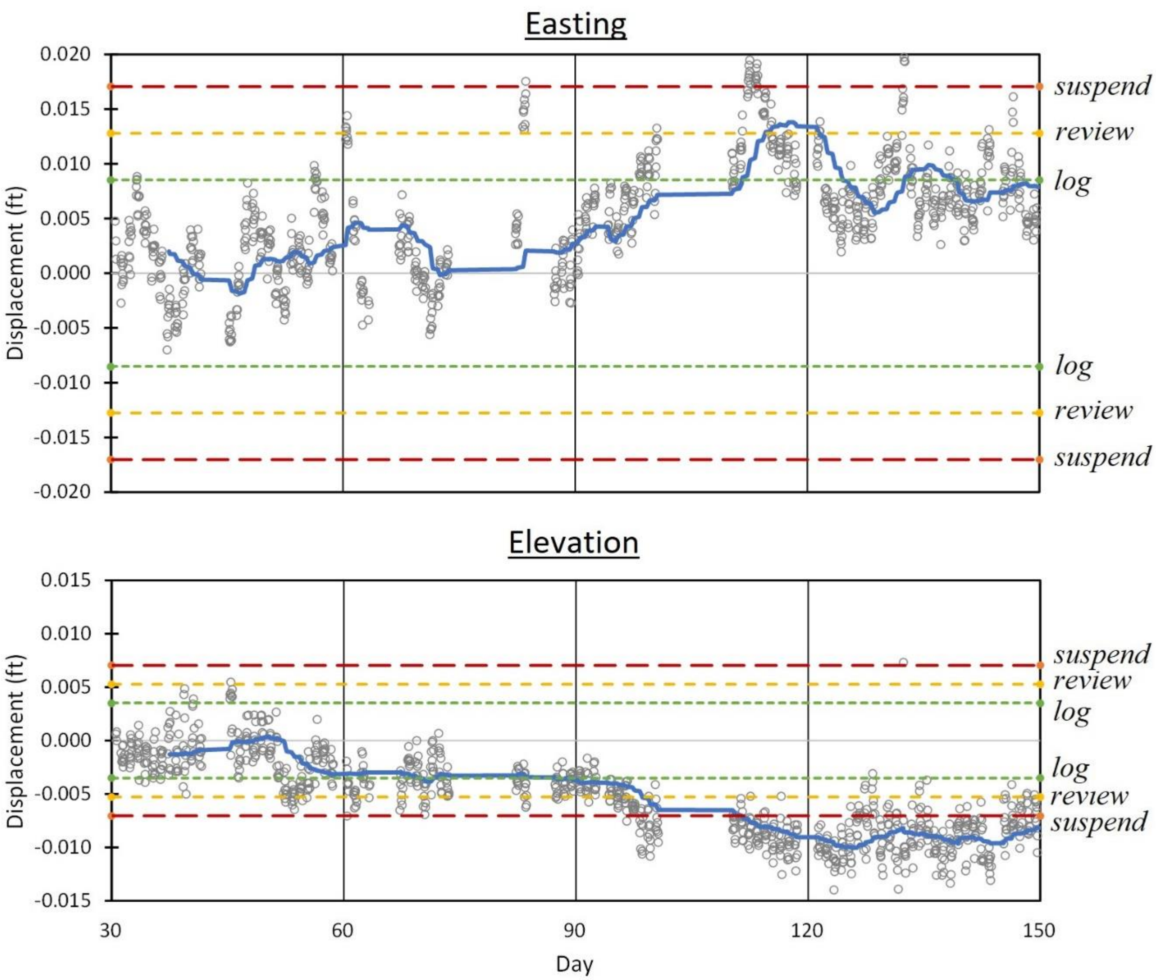

Figure 6. MP-1A: Monitoring displacements & alert thresholds.

REFERENCES

ASCE. (2021). ASCE's 2021 infrastructure report card. Washington D.C. 2021. http://www.infrastructurereportcard.org/. Accessed September 2022.

Attewell, P. B., Yeates, J., and Selby, A. R. (1986). *Soil movements induced by tunnelling and their effects on pipelines and structures*. Chapman and Hall. ISBN 0216918766.

Baldwin, J. K., Gullett, P. M., and Howard, I. L. (2023). Strain-based elevation monitoring during construction of the Salesforce Tower. *Engineering Structures*, 297, 116957.

Baldwin, J. K. (2023). *Advancements in geospatial monitoring of structures*, Ph.D. Dissertation, Mississippi State University, MS#6751.

Barrell, H., and Sears, J. E. (1939). The refraction and dispersion of air and dispersion of air for the visible spectrum. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 238(786), 1-64.

Boscardin, M. D., and Cording, E. J. (1989). Building response to excavation-induced settlement. *Journal of Geotechnical Engineering*, 115(1), 1-21.
Kaalberg, F. J., Braakman, S., and Cook, D. K. (2003). Amsterdam Noord/Zuidlijn: one of the largest settlement monitoring projects in Europe. *Proceedings of the Sixth International Symposium on Field Measurements in Geomechanics*, 15-18 September, 2003, 769-774.
Kenchington, A. (2003). *Monitoring building structures: automatic and autonomous monitoring*, 96-137. Springer. ISBN 0-203-16886-0.
Leica Geosystems. (2013). Leica MS50/TS50/TM50–User Manual. https://web.archive.org/web/20221028091618/http://docs.onepointsurvey.com/pdf/Leica-MS50-TS50-TM50-user-manual.pdf.
Li, X., Ge, L., Ambikairajah, E., Rizos, C., Tamura, Y., and Yoshida, A. (2006). Full-scale structural monitoring using an integrated GPS and accelerometer system. *GPS Solutions*, 10(4), 233-247.
Moss, R. M., and Matthews, S. L. (1995). In-service structural monitoring. a state-of-the-art review. *Structural Engineer*, 73(2), 23-31.
NAS (National Archives of Singapore). (2005). http://www.nas.gov.sg/archivesonline/data/pdfdoc/20050513987.pdf.
Roy, D. S., and Gouvin, P. (2007). Applications and limitations of automated motorized total stations. *Proceedings of the 7th FMGM 2007: Field Measurements in Geomechanics*, 24-27 September, 2007, 1-12.