Relative Accuracy of High precision Total Stations and DEMEC Gauges for Masonry Structures

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SUMMARY

The requirement for precise, sub-millimetric measurements is essential for structural deformation surveys. Whilst total stations offer internal calibration to mitigate the impact of atmospheric factors, residual systematic errors in the instrument persist. Typical total stations such as the Trimble S9 specify absolute accuracies of 1” for horizontal and vertical angles and ±(2mm + 2.0ppm) for reflectorless distance measurements. However, these nominal specifications often fail to represent actual performance under varying angles and distances. High-precision monitoring is essential for ensuring structural integrity, maintaining health and safety, and achieving legislative compliance. Therefore, this research aims to investigate the magnitude and behaviour of systematic error in total station observations as angular deviation increases.

For this study, an array of structural monitoring points were installed to a custom MDF board. A 200mm and 600mm DEMEC gauge, with a nominal resolution of ±0.001mm provided accurate point-to-point distance measurements, producing a baseline dataset. Each point was then observed with a Topcon MS05AX 0.5” accurate total station under controlled laboratory conditions. The instrument was positioned centrally to the target on an elevating tripod to minimise angular deviation, and all surveys were completed in a day.

All total station observations were converted from DMS into arbitrary Cartesian coordinates in Microsoft Excel, where relative distances were compared to the DEMEC baseline dataset. The data was divided into horizontal and vertical sections, where cumulative error was assessed comparing the 200mm and 600mm gauge measurements to the total station calculated distances. The X and Y plane were analysed separately to investigate the influence of orientation during measurement and potential effects at obtuse angles. Furthermore, both gauge sizes were checked independently to identify any discrepancies in the baseline data.

Results reveal that when comparing observations from the centre to the extent regions of the board, there was a 23% error increase as the horizontal angle increased. This indicates that total station accuracy decreases progressively as angular variation increases from perpendicular line of sight.

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1. INTRODUCTION

The scale of structural monitoring applications is increasing exponentially across the world in response to new infrastructure solutions. Manual monitoring with strain gauges, is becoming less suitable and efficient for large scale monitoring procedures. While standard surveys can specify an accuracy in structural monitoring of 2-4mm with a high-quality control network, there is an increasing demand for sub-millimetre surveys. Early and continual monitoring of structural performance can assess safety and serviceability, whilst providing early warnings for excessive strain, deflection, and settlement which may compromise structural integrity.

Extensive research on total station accuracy and its implications has already been conducted however, much corroborates manufacturers specifications where accuracy is known and required up to 2mm, as required in British Standards. Nonetheless, if sub-millimetre is required, credibility of the total station measurements arises. Monitoring in this way can provide insight to address structural deformations before visibility.

Through measurement of an array of DEMEC studs from a stationary position, this study aims to evaluate the suitability, accuracy, and precision of total stations for structural monitoring solutions. The paper provides best practice for engineers and surveyors by investigating sources of error from angle of incidence, proximity to target and material reflectivity. Environmental, geometric, and ergonomic errors from various DEMEC gauge sizes have also been assessed for future consideration.

This research provides a detailed analysis of total station relative accuracy when compared with manual monitoring methods, offering practical insights into their accuracy and practicality under laboratory conditions. Furthermore, the paper will explore the effect of the angle of incidence for sub-millimetre accurate surveys. This paper is organised as follows: Section 2 states the methodology, detailing board fabrication and data collection, Section 3 details processing and calculation methods, Section 4 explains the analysis of the results and Section 5 concludes with limitations, recommendations for future studies, and practical implications.

2. METHODOLOGY

A Topcon MS05AX was chosen for this investigation due to its precise angular measurements accurate to 0.5” and sub-millimetric EDM accurate to $1x10^{-5}$. The DEMEC gauge with an accuracy to $1x10^{3}$. Both instruments were tested on the same day. Distances from both instruments will be compared, to test their suitability for measuring over large distances.

2.1 Board Fabrication

A control board was constructed from 2440 x 1220 x 25mm MDF (Medium Density Fibreboard). A 6 x 12 array of DEMEC studs was set out at 200mm centres to allow the comparison between the cumulative length of three consecutive 200mm DEMEC measurements and a single 600mm gauge measurement. With a gross weight of approximately 55kg and only use of manual handling available, the board size was limited. The dimensions represented a compromise, a span large enough to capture angular variability whilst compact enough to handle. The stud setting out plan was produced using Autodesk AutoCAD at 1:1 scale (Figure 1). The drawing was edited during conversion to PDF, removing margins and conserving the scale to minimise errors during printing. Due to small tolerances in the DEMEC gauge, perpendicularity between studs must be maintained.

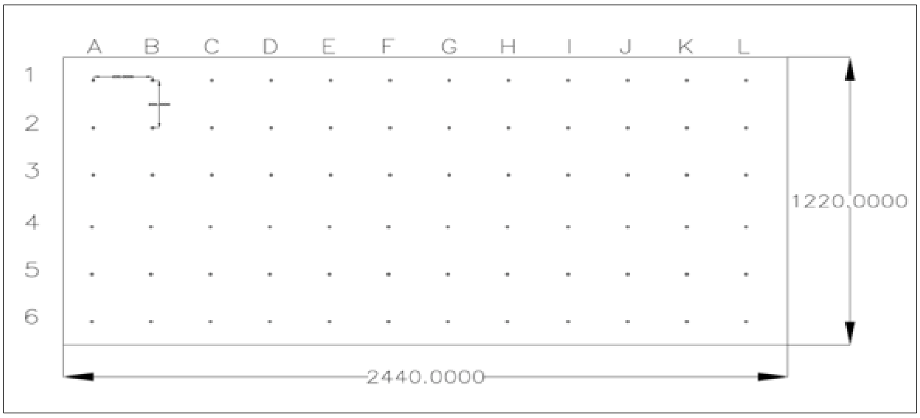

Figure 1: Control Board Setting Out Diagram

The drawing was printed to three A0 pages connected and fitted to the MDF board (Figure 2). The page size was used to minimise the number of paper connections reducing the probability for setting out errors. Indentations were made through the paper into the MDF at each stud location with two intermediate marks per interval to define grid line references. Grid centrelines were drawn with a 1m spirit level and fixed with an adhesive which became inert once cured. Using MDF as the base for the board created a uniform surface for the studs to bond to. The boards properties however can cause the material to be vulnerable to temperature and humidity. To mitigate the risk of deformation, all monitoring was completed in a day under laboratory-controlled conditions at a temperature of 19-20 °C.

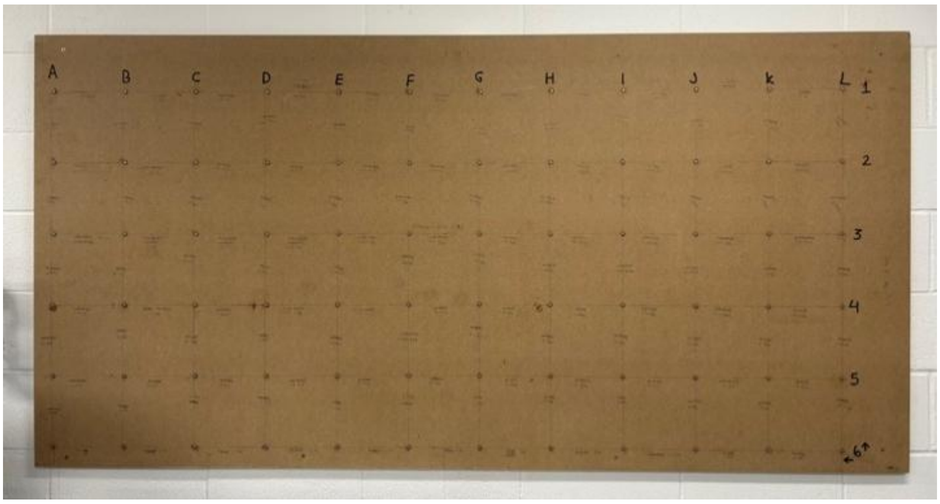

Figure 2: MDF Control Board

2.2 Data Collection

Using a tape measure and level, an arbitrary control point was positioned 3m centrally from the board. The central location and proximity to the target allowed for variance in angle of incidence across the control grid. To control the height of the instrument, an aluminium elevating tripod was selected, which was approximately 40% lighter than a traditional wooden tripod. Whilst this may affect the stability of the instrument in an outdoor environment, the legs are more than suitable for indoor applications and are further improved by a spider.

Following the instrument positioning, atmospheric conditions were recorded from a weather station within the lab and inputted into the total station to allow self-adjustments from the EDM (Electronic Distance Measurement). Three sets of face left and rights were recorded for each stud and averaged due to line-of-sight error. The numerical values from the total station included horizontal/vertical angles and slope distances that were further averaged across the three sets. Anomalies were identified and removed based on consistency checks across repetitions.

DEMEC readings were taken with both 200mm and 600mm gauges across the grid, and the values inputted directly into a Microsoft Excel workbook. To reduce variability, a single operator performed all DEMEC readings, ensuring consistent contact pressure and perpendicular alignment. The gauges were handled carefully to avoid disturbances between readings. Recalibration with an invar reference bar was performed 1 in 5 readings, or sooner if accidental impact occurred. Spot checks were performed 1 in every 10 readings for both gauge sizes to check for variability.

2.3 Data Processing

All data collected from the total station and DEMEC gauge was manually entered into a Microsoft Excel workbook. This introduced the potential for human error during data logging, which was addressed through repetitive verification between measurer and data inputter. The total station output was provided in raw form (degrees, minutes and seconds), therefore manual input was unavoidable. All angles were converted from DMS to decimal degrees and then to radians for use in excel formulas. The results coupled with slope distances were used to calculate X, Y and Z values establishing an arbitrary coordinate system to calculate distances between points. The distances were then compared to the corresponding DEMEC reading to determine any deviations between the two data sets.

3. Analysis

The aim of this analysis is to identify the accuracy of a high precision total station when compared with a DEMEC gauge and what factors may impact the performance of both methods. Both the horizontal and vertical planes have been analysed independently followed by each gauge in comparison to their counterpart and the total station using the full data set.

3.1 Horizontal Plane Analysis

The horizontal measurements from the 200mm gauge were compared to the corresponding total station distance. The board was divided into four horizontal sections (Figure 3) to access the distribution of deviation. When comparing the central and extent regions of the board, columns J-L and G-I produced errors of 0.303mm and 0.246mm, respectively exhibiting a 23% increase of error. Similar errors were also present when comparing columns A-C and D-F demonstrating a clear pattern across the board. The data indicates that as the horizontal angle of incidence increases, the accuracy of the total station is reduced highlighting systematic errors in the instrument.

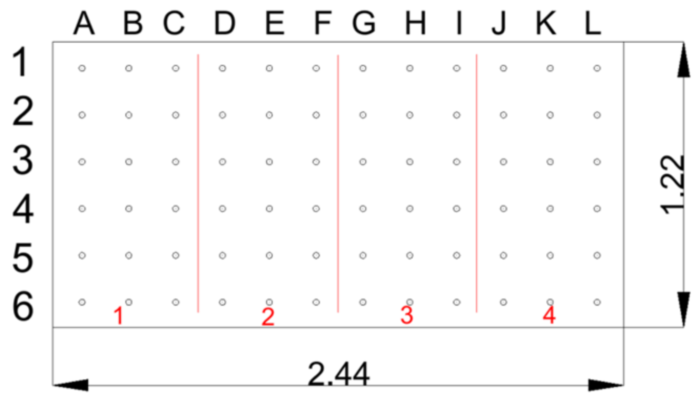

Figure 3: Control Board Sections

The reduced accuracy of the instrument can potentially be attributed to the contact of the LASER with the DEMEC stud. The MS05AX has the potential to be accurate to 0.1mm, with a 90% reflective surface (Topcon , 2011) however in the absence of direct contact, accuracy is significantly reduced. As the angle of incidence increases, the EDM's view of the stud's rear face (Figure 4) is limited resulting in offset measurements taken from the side wall. Although the stud measures 1mm in diameter, the 0.5 mm distance from the outer wall introduces the potential for overestimation when measuring to <1mm accuracy. By contrast, the DEMEC gauge maintains direct contact with the stud's rear surface removing this error.

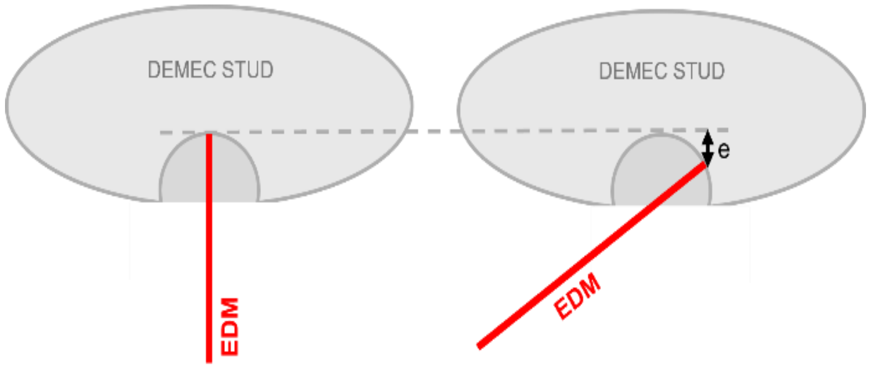

Figure 4: DEMEC Stud Sighting Error

The discrepancies in the horizontal plane could also be attributed to EDM reflection as the LASER contacts a curved, metallic surface. The signal reflects within the gauge hole of the DEMEC resulting in a weaker signal received by the instrument. Depending on the angle of incidence and reflected path of the beam, multipath error may also be present in this study. This requires multiple beam reflections within the gauge hole and a return signal in the direction of the instrument. The elongated path results in an overestimated distance measurement by the EDM. The likelihood of multipath is relatively low when compared to scattering but should still be considered as a potential source of error.

3.2 Vertical Plane Analysis

To analyse measurements in the vertical plane, the board was split into 6 rows along the Y axis to determine if the horizontal systematic errors were present. The horizontal total station measurements were compared to the 600mm gauge resulting in the greatest errors stemming from the centre of the board. Row 4 exhibited a mean error of 0.274mm whereas rows 1 and 6 produced 0.209mm and 0.146mm respectively indicating a 20-50% decrease in error at the vertical extents of the board. The vertical instrument measurements in rows 1-6 when compared to the 200mm gauge exhibited similar results. Rows 1-2 produced a mean error of 0.255mm whilst rows 3-4 realised a 32% increase with a mean error of 0.299mm. The data suggests there is additional systematic errors in the total station arising from a previously undiscussed source.

The error observed at the extents of the board in the horizontal plane was not present in the vertical plane. Due to the position of the instrument and the dimensions of the board, the maximum theoretical angle to the vertical and horizontal extents was 13° and 28° respectively. Therefore, when measuring in the vertical plane the range of the angle of incidence was reduced by >50% limiting the effect of an obscured DEMEC stud present in the horizontal plane.

The increase in error at the central region in the vertical plane potentially stems from the smaller field of view when closer to the target. Figure 5 shows an exaggerated diagram of how proximity can limit the surveyor's ability to align the EDM centrally with the target. The lack of reference points in the field of view increases the probability of crosshair misalignment with the stud and increases the angular range when sighting to the centre. As distance from the target increases, the outer edges can be used as references improving the surveyor's ability to sight to the centre and replicate the alignment. Although the errors in most cases will be negligible, this may significantly reduce accuracy when requiring <1mm precision.

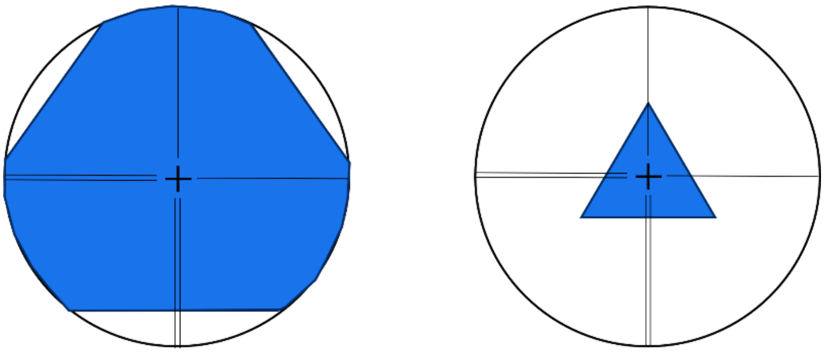

Figure 5: Proximity Alignment Error

3.3 600mm DEMEC and TS Analysis

When comparing the relative distance error between the 600mm DEMEC gauge and total station horizontally and vertically, the error was 0.056mm and 0.266mm respectively. As shown in Figure 6, the vertical data has a greater distribution from the mean, likely due to the ergonomics of the equipment. When taking vertical measurements with the 600mm gauge excessive weight can be exerted on the pivot joint. This potentially causing movement during measuring whereas horizontally the gauge can be held with ease. Due to this instability, the DEMEC gauge is predisposed to human error when taking vertical readings and should be assessed prior to use.

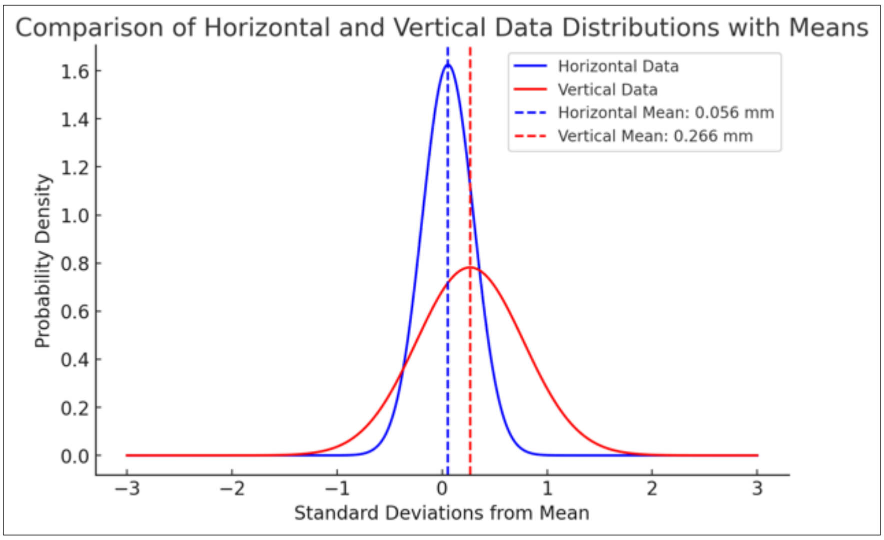

Figure 6: Horizontal and Vertical Normal Distributions (Shown Indicatively)

Mechanical errors can also be present in the DEMEC gauge, greater vertical inconsistencies could arise due to the unbalanced weight distribution. When measuring on a vertical face, there is potential for uneven pressure to be exerted on each tip of the DEMEC gauge, which can skew the internal mechanics when taking measurements, generating a source of error. There is also potential for individual error each time the gauge is calibrated on the invar stave, the operator must maintain perpendicularity during calibration and measurements. Therefore, it is unlikely for the calibrated orientation to be consistently replicated during readings.

3.4 200/600mm DEMEC Gauge Analysis

To assess the reliability of cumulative measurements over greater distances, a comparison was made of three consecutive 200mm gauge (Figure 7) measurements to the corresponding 600mm gauge measurement. The values for each axis were then comparatively analysed in both the vertical and horizontal planes. The sum of three 200mm gauge measurements exceeded the 600mm gauge correspondent, demonstrating that using this technique developed consistent overestimation from the short-range readings with a mean deviation of 0.48mm and horizontal range of 0.077mm (Figure 8). The consistent overestimation in both axis highlights the performance of the instrument with the error likely attributed to the setting out process.

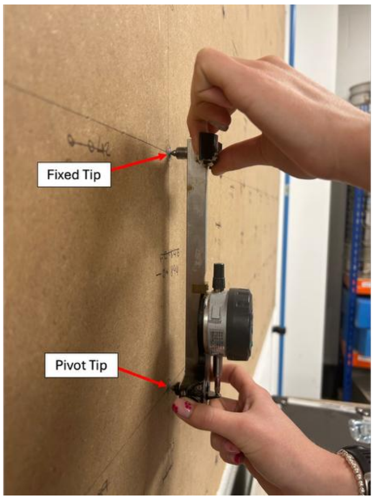

Figure 7: 200mm DEMEC Gauge

A setting out rod was used to create the 200x200mm grid, which theoretically would result in linear measurements between each of the studs. Figure 8 however shows how a setting out error can create a two-dimensional increasing the distance between each of the studs. Based on the 0.48mm deviation, and range of 0.077mm, measuring cumulatively can overestimate by >1mm, which is unsuitable when requiring sub-millimetre accuracy.

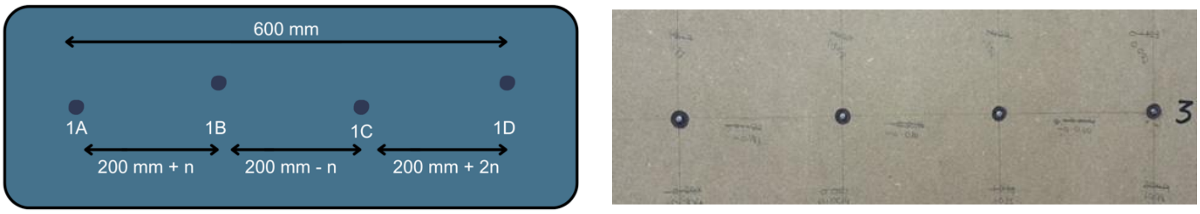

Figure 8: Potential Horizontal Setting Out Error

Further comparisons were performed by comparing three consecutive 200mm total station measurements to the equivalent 600mm gauge reading. The range of this horizontal dataset compared to the cumulative 200mm was 0.077mm to 1.721mm respectively. (Figure 9). Furthermore, when comparing the total station to the 600mm gauge, the range was $1x10^3$ times greater than the equivalent cumulative versus 600mm comparison. The horizontal values have a higher range but lower variance than the verticals, suggesting the horizontal values are clustered more closely together, but its most extreme outlier is greater than the corresponding vertical value.

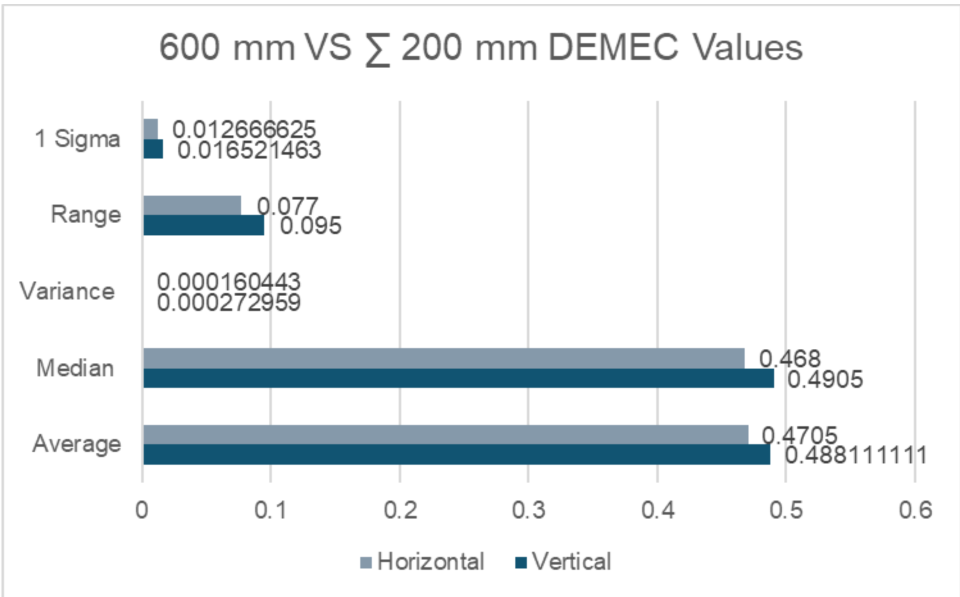

Figure 9: 600mm and Cumulative 200mm DEMEC Gauge Analysis

A potential source for this error could be introduced from the Z plane. The MDFs uniformity was checked with a 1m level prior to commencement however, sub-millimetric deformations would not have been detected. These discrepancies would be detectable when measuring between studs with the DEMEC gauge. A theoretical elevation model (Figure 10) would place each DEMEC stud a precise, constant Z coordinate. The boards surface would cause the actual elevation to occur, with each DEMEC stud being marginally offset from the last, thereby lengthening the overall three-dimensional distance.

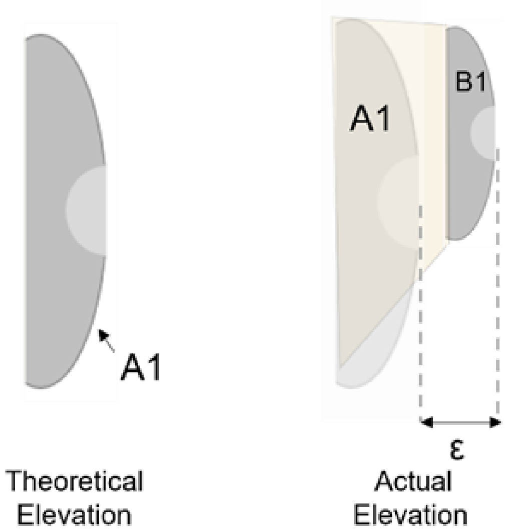

Figure 10: Stud Z Plane Discrepancies

One vertical 200mm gauge measurement between F3 to F4 resulted in 202.493mm, which is the greatest derivative from 200mm in this data set. This anomaly may have occurred during calibration, as the gauge is manually held in position and ‘set’. To replicate the same conditions used for each measurement would be challenging therefore there is potential for human error. Operator pressure can also impact the accuracy of the DEMEC gauge, if inconsistent pressure is used on the pivot and fixed joint or across multiple readings, this may have affected the results.

4. CONCLUSIONS

The results show that measurement error is systematic and orientation dependent. Across the board, the total station had an achievable accuracy of 0.5mm, and the DEMEC gauge had $1x10^{-3}$mm at various angles. There is a clear correlation between the angle of incidence and the relative accuracy of the EDM. Furthermore, a reduced field of view created by proximity to the target reduced accuracy. Shorter DEMEC measurements can be more accurate across uneven surfaces however, 600mm measurements are more suitable for flat surfaces that require long-span measurements. Despite the total being less accurate, it would still be suitable for high-precision structural monitoring applications.

This study has several limitations that should be addressed in future research. The test board could not be guaranteed to be perfectly planar, and small deviations in the Z plane could introduce errors into the dataset. Although the maximum sighting angle and its implications are discussed, additional variability may exist in real world applications beyond the laboratory conditions. The station distance from the target was also not varied, and different distances may impact accuracy.

The instrument position restricted the maximum achievable angle, and only one dataset was collected, limiting the assessment of repeatability or other external factors. Control conditions meant external influences such as atmospherics and vibration were not represented. A future study should therefore be conducted under site conditions, including a wider range of angles, several sighting distances, and a prism.

Overall, this research paper demonstrates that remote sensing can achieve sub-millimetre accuracy with minimal compromises. The achievable accuracy compares similarly to manual inspection methods, whilst providing a safer methodology. Furthermore, researchers and surveyors can have confidence in total stations for high-precision structural monitoring applications.

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