Advanced Surveying Techniques for High-Rise Construction: Enhancing Precision and Sustainability

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Key words: deformation monitoring, survey control, verticality, positioning, high-rise, tall buildings, GNSS, IoT, construction, automation, autonomy, sustainability, efficiency

SUMMARY

Urban construction is significantly shifting towards vertical development, with a focus on high-rise and super high-rise buildings. This trend is driven by the increasing need for efficient land use in densely populated cities with the goal of creating more sustainable and versatile environments.

Increased vertical developments make it more important than ever to effectively consider a range of impacts on high-rise buildings, including wind loading, live load from construction, and thermal expansion. This article explores the crucial roles of survey control and deformation monitoring during construction and throughout a building's lifetime, including discussing challenges and highlighting the importance of real-time data, which ensures accurate positioning, whilst validating structural integrity and stability. We compare the traditional survey control transfer process using an optical level, total station, and/or plummet to an active survey control alignment system for tall buildings. Active survey control is a real-time system, used for positioning, including GNSS and IoT geotechnical sensors, which automatically resolves positions to the high precision required for gridline stakeout process.

Additionally, we address the challenges of dynamic positioning of tall buildings, referencing case studies of notable high-rise buildings, such as the Central Park Tower and One World Trade Center in New York, 22 Bishopsgate in London, and the Burj Khalifa, which illustrate successful implementations of these techniques.

The article also discusses the workflow and solution developed by Leica Geosystems to aid high-rise buildings construction and emphasises the automated and autonomous aspects through data collection, transfer, processing, analysis and reporting.

Intelligent use of active survey control supported with automated deformation monitoring allows for higher accuracy, faster operations, and supports safety with sustainability through more efficient and lean construction.

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1. INTRODUCTION

The urban landscape is experiencing a profound transformation as cities increasingly embrace vertical development, focusing on high-rise and super high-rise buildings. This shift is driven by the demand for efficient land use in densely populated urban areas, aiming to create sustainable and versatile environments (Al-Kodmany, 2024). As cities grow, the pressure to optimise space while maintaining liveability has led to the construction of taller structures, exemplified by the Burj Khalifa in Dubai (van Cranenbroeck, Controlling Vertical Towers, 2010), the tallest building in the world at 828 meters (CTBUH, 2025).

High-rise buildings are more than just architectural feats; they are symbols of economic growth and urbanisation. As land values rise and the demand for central locations intensifies, skyscrapers become a practical solution to accommodate more people and businesses in limited spaces. These structures offer the potential for mixed-use developments that integrate residential, commercial, and recreational spaces, fostering vibrant communities within a compact urban footprint.

However, constructing tall buildings presents unique challenges, particularly concerning structural integrity and safety. Environmental forces such as wind loading and thermal expansion can significantly impact a building's stability. For instance, the Burj Khalifa's design had to account for wind forces, which dominate the structural behaviour of skyscrapers as they ascend to greater heights (Ali & Moon, 2007). Additionally, differential foundation settlement, differential concrete shortening, construction tolerances, sun radiation and live loads can lead to structural deformations if not properly managed.

To address these challenges, survey control and deformation monitoring have become critical components in the construction and maintenance of high-rise buildings. Traditional survey control transfer processes utilising optical levelling, total stations and/or plummet, may not provide the precision needed for modern skyscrapers, especially the ones approaching the kilometre-tall mark, such as Jeddah Tower (Wikipedia, 2025). This is where advanced technologies, like active survey control, augment existing methodologies. This system combines data from GNSS, a high-precision total station and tilt sensing to ensure precise positioning and vertical alignment throughout the building's construction process. The ability to use continuous, 24/7 measurements to monitor the position and deformations, not only enhances accuracy but also supports construction sustainability and efficiency, especially with the innovative slipform construction systems.

With the completion of the Burj Khalifa project in 2010 (van Cranenbroeck & Abusharks, 2011), numerous tall buildings, including One World Trade Center and 432 Park Avenue in New York, Millennium Tower in Boston, and 22 Bishopsgate and The Shard in London, continued the advancement and innovation of Leica Geosystems' surveying and monitoring technologies, establishing the company as a leader in this specialised field. The combination of Leica Geosystems precision total stations and GNSS, the versatility of the WiSenMeshWAN® system, cloud services and the Leica GeoMoS monitoring software can fulfil the construction and maintenance requirements of any modern tall building.

2. CONSTRUCTING TALL BUILDINGS

The construction of tall buildings represents both an engineering marvel and a significant challenge. This chapter explores the inherent difficulties in their construction and highlights the critical role of engineering surveying in addressing these challenges.

2.1. The complexities of vertical construction

In contrast to a low-rise structure, the height of tall buildings introduces new, complex construction challenges. The rigidity of the structure is significantly altered when the relative geometry changes from a short, wide structure to a tall, narrow one. This geometry reduces resistance to deformation as the distance from the supporting base increases and as internal and external forces are applied. Each force must be measured, and its influence compensated for, creating a complex problem: determining the correct vertical alignment of the structure and positioning the top accurately, rather than where it is affected by loads. To ensure that the building remains true to its intended position during construction and meets verticality, position, and height design specifications, engineering surveying and monitoring measurement systems are essential. These systems detect and adjust for changes during construction.

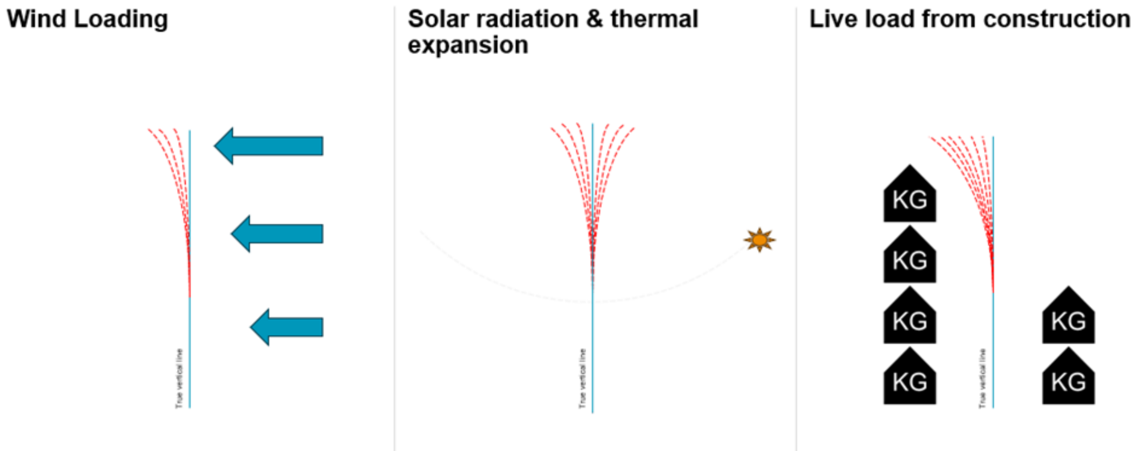

Figure 1 Environmental forces and live load impacting tall buildings

2.1.1. Environmental forces

Tall buildings can be significantly affected by wind load forces (**Figure 1**), which can cause the structure to deflect. This movement varies with the stiffness of different elements, the location on the structure, and the force applied. Furthermore, temperature changes and the heat effect of direct sunlight can cause one side of the building to heat and expand more than the other, resulting in the building leaning away from the sun.

2.1.2. Structural load, deflection and compression

During construction, as progress is made, the mass of the structure increases as materials are added. This increase in mass causes compression of previously constructed elements, which now serve as load-bearing materials at the lower levels (**Figure 2**). This loading can be uneven due to the construction progress, leading to additional vertical alignment issues. Vertical compression can result in differential settlement, where the structure experiences varying degrees of compression between elements or zones. Due to this compression, any vertical datum must be adjusted to account for axial shortening to ensure that the final required height is achieved, allowing for the compression.

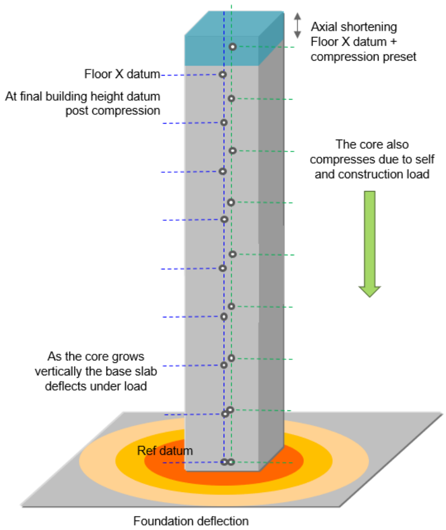

Figure 2 The effect of the load on tall buildings

2.2. Dimensional control reference frame(s)

Dimensional control is fundamental to the construction of tall buildings. Each floor requires precise survey control, both horizontally and vertically (**Figure 3**). This is crucial for positioning structural elements, cladding, and mechanical systems. It involves establishing precise references that define the alignment horizontally and vertically. Traditional survey methods, such as optical levelling, total stations, and optical/laser plummets, have long been utilised for this purpose. Base gridlines are established at low levels on stable ground, as construction progresses new references are established on the upper floors of the structure, using the same reference until the stage where this direct connection is no longer practicable due to construction progress or engineering limits. Uninterrupted vertical lines of sight are required to be maintained throughout the structure for this purpose, this can be prohibitive to progress, and costly to infill at later stages.

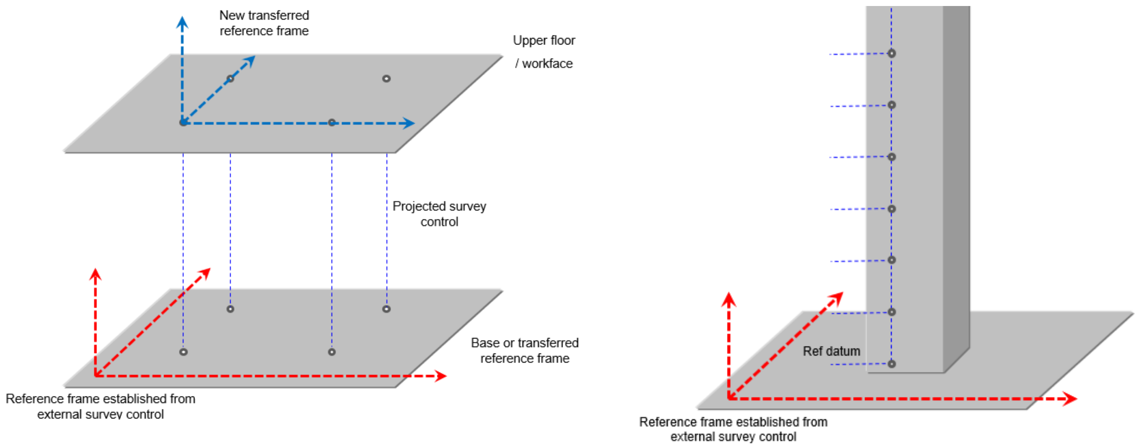

Figure 3 Transfer of the building's reference frame

2.3. Real-time monitoring systems

During construction, structural deformation monitoring data also allows engineers to validate design calculations and maintain construction within tolerances by adjusting construction parameters for alignments. Tall buildings can be equipped with real-time monitoring systems that track structural movement, the effect of stress and strain from loads implied and environmental changes. Meteorological sensors, inclinometers, accelerometers, load cells, strain gauges, distance meters and 3D measurement systems such as Global Navigation Satellite Systems (GNSS) and total stations, can provide this continuous data. The information allows engineers to assess the structural performance both for the current structure and future design models.

Structural deformation monitoring from these systems extends beyond the construction phase to the entire lifespan of the structure by tracking responses to environmental and structural changes, providing data to allow engineers to assess the structural performance both for the current structure and future design models.

2.4. Survey control and deformation monitoring

The advent of active survey control systems marks a significant advancement merging the domain expertise of structural deformation monitoring and positioning systems. Systems with interoperable connectivity between survey instrumentation and Internet of Things (IoT) sensors, combine to provide easy-to-use real-time data that ensures accurate positioning. Active survey control systems automatically resolve positions to the necessary precision, reducing human error and increasing efficiency.

These systems use GNSS and IoT sensors to continuously monitor and report positions, allowing for the compensation of dynamic structural deformation. This creates survey control points and a reference frame within specified tolerances. The integration of active survey control systems into construction also streamlines the engineering surveying processes, providing instant, reliable data rather than delaying operations while awaiting the transfer of control points, whose absolute certainty and relation to the base cannot be guaranteed.

Real-time system information is used to determine live axial shortening values for structural compression using multiple vertically installed IoT distance sensors, while the rotation component from the sensors is used to determine live structural tilt. Additionally, GNSS positioning data provides absolute XYZ locations at the upper working face of the structure for a complete integrated solution. By combining these data sets with the traditional monitoring of foundation deformation and environmental sensors, a comprehensive understanding is generated of where to place new elements at the upper workface, thus ensuring positional data is available and within tolerance when required.

3. LEICA GEOSYSTEMS' SOLUTION FOR TALL BUILDINGS

Leica Geosystems, part of Hexagon, has pioneered a workflow that integrates cutting-edge technologies using advanced surveying and monitoring solutions to provide positional information for the construction of tall structures. The solution emphasises automation and autonomy throughout the entire workflow—from data collection to processing, analysis, and reporting. This chapter explores the Leica Geosystems solution, highlighting its technological advancements, commercial benefits, and contributions to sustainability and efficiency in the construction industry.

3.1. Core Wall Control System (CWCS)

CWCS is a solution specifically developed for tall structure construction. At the core of this solution is the use of highly accurate sensors, which work in combination to provide continuous, real-time data crucial for maintaining survey control and monitoring deformation.

3.1.1. Core components of CWCS

The core components of CWCS are (**Figure 4**):

- **GNSS**: Strategically placed on the uppermost floor to provide continuous, real-time positional data. The system eliminates reliance on low-level structure-based reference points, which become less practical as the building's height increases.
- **Total Stations and prisms**: Used to establish and verify survey control using positional information provided by the system. Total stations provide independent verification of GNSS data, ensuring accuracy in the positioning of structural elements.

- **Computation & collaboration software:** Cloud sharing enables instant processing and synchronisation of results to all stakeholders with automatic updates as construction progresses. Using integrations with Leica Geosystems desktop, cloud and on-instrument solutions.

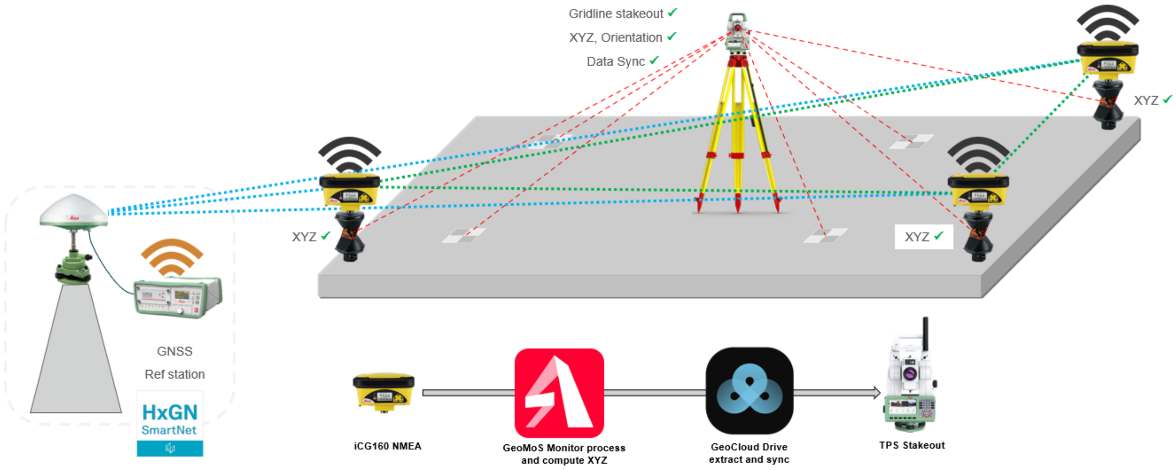

Figure 4 Core components of the Leica Geosystems' CWCS solution

Additionally, **inclinometers & distance metres** installed at various levels (**Figure 5**) will deliver displacement information with high accuracy. This is essential for predicting and adjusting for the effects of construction activities and environmental forces, such as wind and temperature variations and the vertical compression for axial shortening.

3.1.2. Horizontal positioning via RTK GNSS

GNSS receivers require a clear sky view to operate and receive the radio signals from the satellite constellations to compute positions. For accurate locations they require a correction service to compute accurate positions, this can either be from a known base and reference receiver transmitting corrections or a network correction via an internet service such as HxGN SmartNet. With the GNSS correction service data, the GNSS sensors mounted for dynamic tracking of the structure can attain real-time kinematic (RTK) data. The intelligence in the GNSS sensor from the Leica Geosystems iCON range can simultaneously read in the correction service, compute a fixed GNSS solution and output a final computed position as an NMEA GGA string. The advanced GNSS sensor from Leica Geosystems can filter bad GNSS data onboard and issue computed positions at defined epoch intervals. Using the data from this NMEA stream the logged and longer average positions are computed from the RTK data. Statistical analysis of the data confirms the stability of the calculated position and its deviation characteristics. These positions are then reported using a site-specific calibration of the coordinate system for the GNSS to align the native WGS84 coordinate system to the site and avoid issues with alignments of gravity vertical and ellipsoidal vertical. Additionally, should it be required, the entire system can also be used offline with manual file transfer and processing to achieve the same results.

3.1.3. Vertical alignment compensation via tilt sensors

In addition to the live GNSS location, to determine the structural deformation from true vertical alignment tilt sensors are installed within the structure at regular vertical intervals. The tilt in the X and Y axes are uniformly aligned to the structure so that movement in the X direction is the same on every sensor. The inclination sensors' locations are measured in XYZ so that the exact separations in 3D are known, and they are read simultaneously and repeatedly over time to determine the building's verticality range and motion. This data then can be used analytically to determine the deformation from the true vertical alignment of the structure. Initially, these sensors were the Leica Nivel wired sensors, however with recent advances in IoT geotechnical sensors new WiSenMeshWAN® sensors now offer the same solution with a cable-free and self-powered sensor with easier installation and less maintenance.

3.1.4. Vertical positioning via axial shortening measurement

Traditional methods of measuring axial shortening included precise levelling vertically throughout the structure, with steel measuring bands tensioned and temperature compensated, or using EDM observing vertically. However, all of these are manual processes and will only provide information at the time of data collection, typically due to the rate of change in the structure, the axial shortening is measured monthly. Using WiSenMeshWAN® IoT sensors (**Figure 5**) measurements can be obtained automatically in real time, hourly, daily or on any user-defined schedule. Thus data of the compression of the structure for axial shortening is always fully known and not just over the surveyed length of the measuring sensor such as per 20 floors with EDM, but per sensor installed bay in catenary due to the sensors being installed to the lift core or vertical riser open space. This dynamic availability of data and the ability to know where in the structure compression is occurring in which magnitude offers much more data to the structural engineers who assess the condition and deformation of the structure.

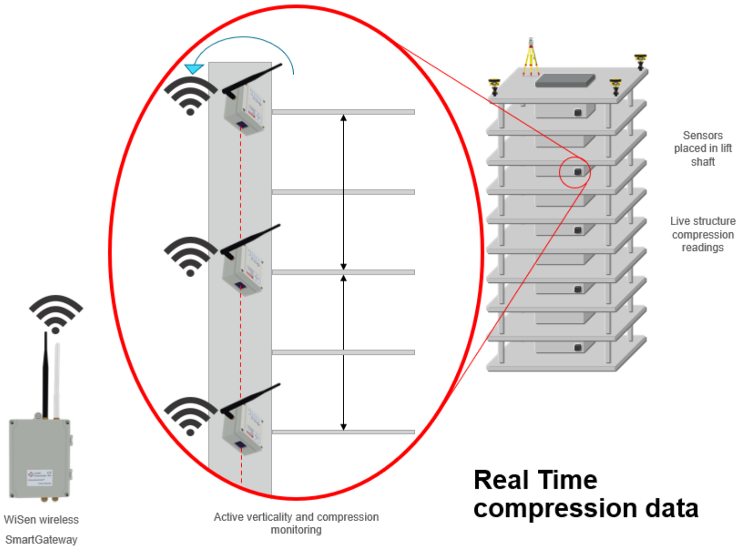

Figure 5 WiSenMeshWAN® solution for real-time compression readings

3.1.5. Integration and automation

All of the Leica Geosystems' solutions are designed to integrate seamlessly with construction workflows. The system's modular nature allows for customisation based on specific project needs, and its automation capabilities reduce the need for manual intervention, speeding up the process. Automation of data processing with quality control validation provides a reliable result for the positioning data with minimal effort post-installation and configuration. Automatically sharing the result with relevant stakeholders through secure, cloud-based platforms further safeguards data transposition errors and enhances collaboration among project teams.

3.2. Computation stability and data assurance

By using the combination of sensors and measurements in the Leica Geosystems' CWCS solution, it is possible not only to determine the real-time corrected position of the structure but also to measure the live deformation state. This enables users to understand the per-floor deformation and identify when the building is in an inert state due to external environmental forces.

Figure 6 shows a structure over 24 hours, where the live RTK positions of GNSS track the structure in real time to an accuracy of around ± 3cm. However, by averaging this data over a period of one hour or longer, significantly higher accuracy data is achieved. Typical averaged RTK data over 6 hours for a structure reveals the actual slow movement of the structure when influenced by environmental conditions, displaying a cyclic pattern that moves with the sun and wind. During this period, if data is averaged, an overall accuracy of ±5mm is reached, with typical repeatability of ±2~3mm within 1~2 hours. Thus, tracking of the structure is possible, and aligning this data with tilt information and environmental sensors enables seeing the daily rotation patterns of the structure and how each element affects the position of the GNSS sensors at the top. Hence, once modelled, the corrected locations can be reported at any time.

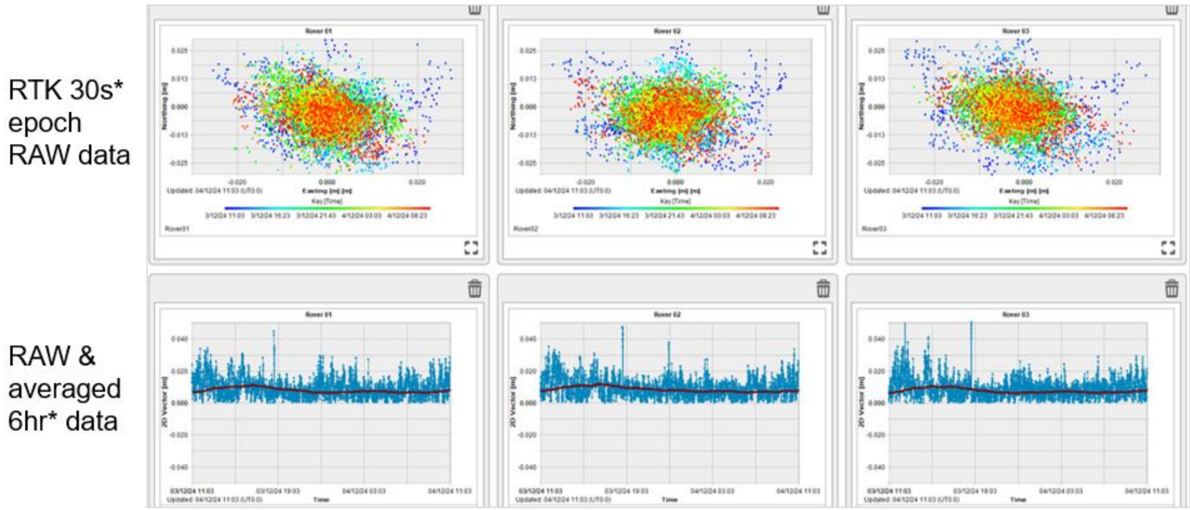

Figure 6 Raw and averaged RTK GNSS positioning data

3.3. The balance between passive and active survey control

Constructing tall structures in densely populated urban environments causes technical geometric issues for the engineering surveyors who establish and maintain the positional alignment. At lower levels, the structures are stable without the dynamic deformation effects, so the traditional, passive survey methods (e.g. plumb line) can be applied and achieve greater accuracy than GNSS due to the multipath and urban canyon effects with reduced sky view. At higher levels, the situation is inversed, i.e. the active survey control with GNSS is the more suitable solution, as the plumb lines experience quality and continuity issues with line of sight within the structure and catenary measurements. A shift in the accuracy of methods occurs between 100m and 200m elevation from the ground level (Figure 7).

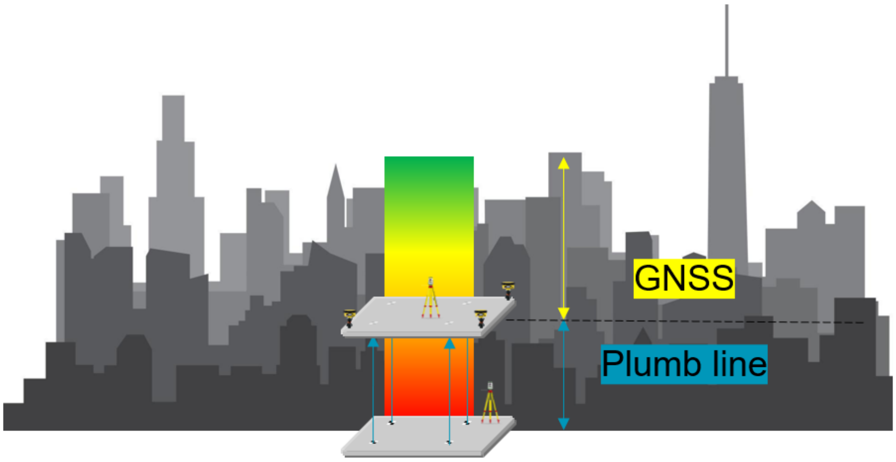

Figure 7 Positioning solutions for lower and higher levels

3.4. Repeatability and verification of accuracy

The accuracies of survey control are crucial due to construction tolerances, which specify the allowable error in the positional accuracy of each element at any stage of construction, both in absolute and relative terms. The specifications detail the positional tolerance for the accuracy of the base of the structure, followed by the allowable deviations in verticality and rate of change. For example, a specification might allow for ±10 mm positioning at the base, then a vertical tolerance of 1:500 up to a maximum deviation of ±25 mm, with no individual storey changing by more than ±5 mm. These tolerances can vary from region to region and are typically found in construction standards or specified by the engineering designer of the structure.

Using GNSS to position a structure can present significant issues due to the inherent noise in the GNSS signal and the coordinate system transformation used at height. Therefore, in many projects, a relative verification process is applied to even out the noise over the uppermost levels of the structure. This is achieved by using survey instrumentation to measure the floor-to-floor relationships and relative accuracy, ensuring that no bias from the GNSS or dynamic deformation causes an alignment issue. During initial construction, a tolerance of ±10 mm may not be problematic, so ±5 mm for GNSS accuracy is acceptable. However, in the later stages of mechanical and electrical operations or structural cladding, tolerances of ±2 mm floor-to-floor are required. Therefore, "tightening up" survey control is recommended to remove outliers and create a homogeneously aligned structure. Using this process, floor-to-floor survey control is typically aligned to ±2 mm, with ±5 mm to the base.

4. CASE STUDIES AND REAL-WORLD APPLICATIONS

The construction of tall buildings presents unique challenges that require innovative solutions for precise positioning and monitoring. Leica Geosystems has been at the forefront of developing state-of-the-art technologies to address these challenges, ensuring that tall buildings are constructed with the highest standards of accuracy, efficiency and safety. This chapter explores three case studies showcasing the application of Leica Geosystems equipment in the construction of tall buildings: 432 Park Avenue in New York City, 22 Bishopsgate in London, and Central Park Tower in New York City (**Figure 8**).

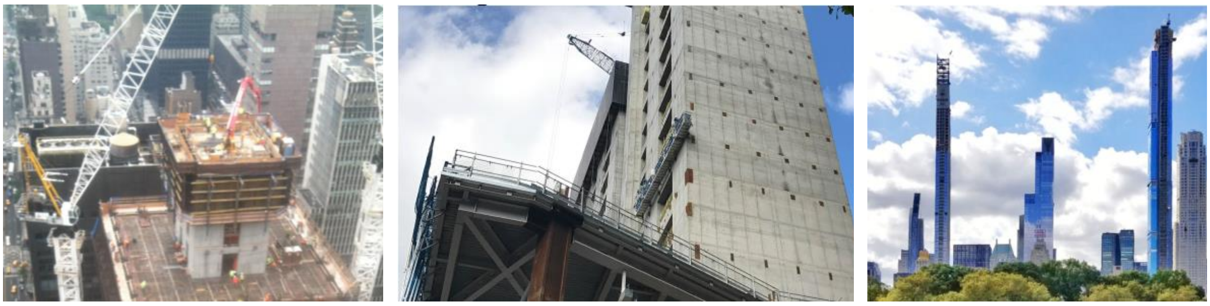

Figure 8 432 Park Avenue, 22 Bishopsgate & The Central Park Tower

4.1. 432 Park Avenue, New York (2015)

432 Park Avenue in New York City is a marvel of modern engineering and architecture. Standing at 426 meters, it is one of the tallest residential buildings in the Western Hemisphere. Its super-slim design, with a footprint of just 28.5 meters per side, posed unique challenges in maintaining vertical alignment throughout construction (Leica Geosystems, Innovative Vertical Alignment Systems Keeps 432 Park Ave Plumb, 2025).

The primary challenge in constructing 432 Park Avenue was maintaining its vertical alignment despite its slender design and significant height. Factors such as thermal expansion, wind pressure, and crane loading introduced dynamic changes that could affect the building's plumbness. Traditional surveying methods were inadequate due to the building's height and the need for rapid, accurate measurements.

Leica Geosystems provided a sophisticated Vertical Alignment System for 432 Park Avenue. This system integrated GNSS positional data from Leica receivers placed at the building's corners, continuously monitored optical data from total station measurements on 360º prisms, and dual-axis inclinometers to measure displacement. The GNSS receivers monitored GPS and GLONASS signals, offering precise real-time data. The system's inclinometers and optical data provided feedback on the building's frame, ensuring accurate vertical alignment. The integration of a weather station allowed for real-time adjustments based on wind and temperature data. This comprehensive approach enabled surveyors to maintain precise control over the building's verticality, ensuring it remained plumb throughout construction.

4.2. 22 Bishopsgate, London (2020)

22 Bishopsgate, London's second tallest building, was designed to be the city's first "vertical village," integrating residential, commercial, and recreational spaces within a single structure. The construction of this 287-meter skyscraper required innovative positioning solutions to ensure accuracy and efficiency (Leica Geosystems, Precise positioning in London's sky, 2025).

The use of a self-erecting jump form system to construct the building's core presented challenges in maintaining accurate positioning without visible ground control points. As the structure rose, traditional surveying methods were insufficient to provide the necessary accuracy.

Leica Geosystems developed a tailor-made GNSS-based monitoring solution for 22 Bishopsgate. This system included seven Leica GM30 GNSS receivers, AR10 antennae, and Leica GeoMoS Monitor software, which provided reliable coordinates for the building's core. The integration of tiltmeters ensured accurate verticality, while the HxGN SmartNet reference station network provided reference coordinates. This automated system delivered precise coordinates continuously, enabling the construction team to maintain accuracy without relying on ground controls. The successful implementation of this solution demonstrated its effectiveness in high-rise construction.

4.3. The Central Park Tower, New York (2020)

Central Park Tower, one of New York City's tallest residential buildings, required precise positioning to ensure its structural integrity and alignment. This project highlighted the need for advanced monitoring solutions in urban environments. (Leica Geosystems, Locating the floors of America's tallest residential building, 2025)

Constructing Central Park Tower posed challenges related to maintaining accurate positioning amidst the dense urban landscape of New York City. The need for reliable data was critical to ensure the building's verticality and safety.

Leica Geosystems' GNSS system, coupled with Leica Viva TS15 Total Station, provided the necessary precision for Central Park Tower. The system utilized GNSS sensors as reference points, allowing surveyors to perform accurate measurements of the core wall with robotic total stations. The integration of Leica Spider Software and GeoMoS Now! facilitated real-time data access, ensuring high accuracy and reliability. This comprehensive solution enabled the construction team to maintain precise control over the building's alignment, even in the challenging environment of New York City.

5. CONCLUSION

The construction of tall buildings demands innovative solutions to address the complex challenges of accurate positioning and deformation monitoring. As urban environments become denser, the need for precise survey control and data in real-time becomes paramount to construction programmes are maintained and ensure structural integrity and safety. These solutions mitigate the limitations of traditional surveying methods, which often fall short in the face of modern high-rise buildings demands.

The higher the building, the more challenges arise, such as wind loading, thermal expansion, and live loads, together with all the structural deformations due to its unfavourable geometry of a thin and tall object on a small and narrow foundation. The traditional and passive survey techniques and instrumentation, such as optical level, total station, and/or plummet deliver satisfactory results until a certain elevation from the ground level, until their implementation becomes impractical, and the accuracy levels cannot be reached.

Since the construction of the Burj Khalifa in 2000's and the first implementation of the Core Wall Control System, Leica Geosystems has further developed its solution for positioning and deformation monitoring of tall buildings through experience gained on many iconic buildings such as One World Trade Center and 432 Park Avenue in New York, Millennium Tower in Boston, and 22 Bishopsgate and The Shard in London. The latest developments of the CWCS system include active survey control workflow utilised with GNSS RTK technology, precision robotic total stations and prisms, computation and collaboration software and enhanced with real-time deformation information from the IoT inclinometers and distance metres. The integration of these technologies enables understanding the movement behaviour of the building better than ever, as well as identifying its inert state.

Ultimately, the intelligent use of active survey control and automated monitoring not only enhances precision but also supports sustainability and efficiency in construction. By reducing manual intervention and enabling faster operations, these systems contribute to safer and more sustainable building practices. This shows a smart integrated informed future of high-rise construction and pushing the limits of positioning higher than ever, whilst maintaining accuracy and enhancing workflows.

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BIOGRAPHICAL NOTES

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