Measurement 123 (2018) 115–124

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Real-time high-rise building monitoring system using global navigation satellite system technology

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ARTICLE INFO

Keywords:
Monitoring control
Local geodetic network
Gaussian analysis
Least squares adjustment
Satellite survey measurements
Torre Espacio

ABSTRACT

Continuous assessment of the displacement of a high-rise building enables verification that it meets the structural assumptions calculated in the project, and provides additional useful feedback for structural engineers. Unexpected structural responses during the phases of construction, or once the building is in use, can help detect current and future problems, as well as provide cost savings. Furthermore, it contributes to an improved risk management for natural phenomena and can be used to verify the stability of the structure, providing an additional safety layer for the building.

The technological improvement in global navigation satellite system (GNSS) techniques has allowed significant advancements of Gaussian methodologies applied to control the dynamics of building structures in real time, especially for calculating, controlling, and interpreting satellite survey measurements, based on Gaussian analysis and least squares adjustment.

The real-time monitoring system works by implementing a local geodetic network with GNSS technology on the structure to be monitored. Algorithms are then applied that improve the compensated network solution, and this is integrated into original software. The system allows us to achieve a high level of safety and effective risk management in real time, as a unique mathematical model that allows GNSS position errors to be reduced is designed for each building. In the case of Torre Espacio, the overall mathematical adjustment model reduces the maximum error by 40%. The system has been installed on a high-rise building, Torre Espacio, in Madrid, Spain, and is fully operational.

1. Introduction

The last decade has seen a notable rise in the demand for increasingly flexible structures and complex architectural forms, that can help solve the problem of rapid urbanisation. As of mid-2017, nearly 7.6 billion people inhabited the planet and, since 2016, more than 4.1 billion have been living in urban areas that cover barely 5% of the earth's surface [1]. It is increasingly evident that cities need to grow vertically in the form of high-rise buildings.

The control of structural positions using global navigation satellite system (GNSS) techniques is now a reality. Determining the exact position of structures (that vary owing to natural phenomena, such as wind and earthquakes) reduces the risk of failure, improves the level of safety of structures, and can also provide cost savings in the construction process.

The technological improvement in GNSS techniques and advances in computer data processing, combined with the development of the Internet and mobile telephony, have allowed us to upgrade and improve Gaussian methodologies applied to control the dynamics of building structures in real time.

The coordinates, obtained using real-time GNSS techniques, have a short-term accuracy of 0.2–3 cm. However, at times, projects may require greater accuracies. The proposed system enables instant quality control of precision, corrects GNSS coordinate errors using Gaussian algorithms, and determines the accuracy and reliability of the errors that could not be corrected.

By implementing a local geodetic network with GNSS antennae and receivers on the structure to be monitored, and by applying mathematical and statistical algorithms, it is possible to improve the compensated network solution. Software has been designed that implements all algorithms that are used in the real-time monitoring system. It is precisely this treatment of data, and adjustment and analysis of partial and final results, that allows us to achieve a high level of safety and effective risk management in real time.

Monitoring the dynamic deformation behaviour of civil engineering structures and building structures has been a subject for concern of

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https://doi.org/10.1016/j.measurement.2018.03.054
Received 26 July 2017; Received in revised form 19 March 2018; Accepted 20 March 2018
Available online 21 March 2018
0263-2241/

engineers for many years [2]. It is also becoming a research field of great academic interest [3,4], with an understanding that tolerance levels, sometimes to millimetre accuracy, are important details.

The advancement of technology and communications has allowed the development of methods that provide these positions with millimetre accuracy. In this sense, the adoption of GPS technology for the monitoring of civil and architectural structures has already been validated in other preliminary research, verifying its adoption as a standard technique for measuring structural vibrations. Examples of this include the Calgary Tower in Canada [5], the Central Business District in Singapore [6] and in the UK, the Humber suspension bridge [7], in Nottingham [8].

Later, owing to the evolution of GPS technology, an improved method using differential positioning real-time kinematic (RTK) was developed. Several studies have demonstrated the feasibility of RTK-GPS, such as the observed full-scale performance of three tall buildings in downtown Chicago (USA). The wind-induced responses of the buildings were measured and compared to wind tunnel tests, and finite element models, by installing force balance accelerometers and a GPS receiver [9,10]. Another study with the same aim used full-scale measurements to measure the displacement of a tower in Japan [11]. In Singapore, from 2001 to 2005, a GPS system was installed to monitor a high-rise building and test the capability of GPS to resolve the relatively small deflections expected. In addition, GPS technology has been able to detect and resolve dynamic responses to both wind and seismic effects. [12].

Other preliminary studies in line with this paper were conducted in Slovakia, Singapore, and Korea. In the first example, in Slovakia, a 24-storey building [13] was monitored by applying electronic distance measurement technology and GNSS techniques, using network Slovak GNSS permanent stations (SKPOS). Similarly, in Republic Square in the central business district of Singapore [14], the implementation of a reliable and robust monitoring system of high-rise buildings was studied. This used the Singapore satellite positioning reference network (SIReNT), and incorporated VRS-RTK methodology. Finally, in order to verify the feasibility of a GPS method for monitoring high-rise buildings, an investigation was carried out to compare acceleration measurement from GPS and accelerometers in a 66-storey high-rise building in Korea [15].

In Hong Kong, China, wind engineering studies on the effect of typhoons on tall buildings was conducted by full-scale monitoring with accelerometers, anemometers, and pressure sensors [16]. There were further preliminary studies undertaken about the technical feasibility of GNSS observations by Kijewski-Correa et al. [17], Li et al. [18], and Li et al. [19].

The authors Yi et al. [20] presented an interesting review of current research and development activities in the field of high-rise structure health monitoring using the Global Positioning System (GPS).

What makes our system different from others, is the calculation method used, and the interpretation and the control of the results, using original software designed specifically to control high-rise buildings. This system has been operating in the 236 m high building, Torre Espacio (Fig. 1), located on Paseo de la Castellana in Madrid, Spain.

The real-time monitoring system software obtains robust results for the instantaneous position of high-rise buildings. A specific constraint, that defines the inner constraints required, is incorporated in the mathematical model. For each structure to be monitored, we add a unique condition equation to the mathematical model of the observation equations. The system can be adapted to other structures by changing the specific conditioning and inner constraints of the mathematical model.

2. Methodology

The proposed real-time monitoring system comprises of a local geodetic network with four GNSS antennae and receivers positioned on the rooftop of the structure to be monitored, in this case the Torre Espacio high-rise building. In general terms, the system accurately determines the position of a local geodetic network observed with VRS-RTK techniques [21].

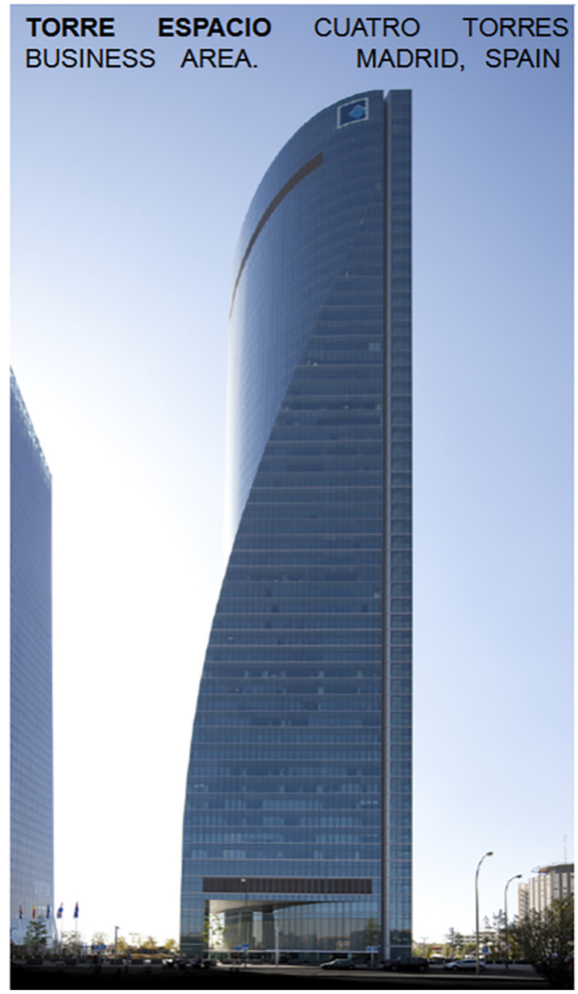

Fig. 1. Torre Espacio, Madrid.

The physical location of the four permanent GNSS antennae is shown in Fig. 2. In principle, it would be sufficient to utilise a line defined by two GNSS antennae [13,22] in order to define the torsional and translation response of the rooftop, but the more secure option is constituted by a quadrangle that keeps its shape.

Based on previous studies and the project background, it is essential to have detailed structural information about any structure to be monitored in order to provide a reliable assessment of its dynamic response. In this case, we know from previous reports that the tower can move approximately 20 cm in 5 min, with wind speeds close to or exceeding 90 km/h. Therefore, in order to detect Torre Espacio's wind-induced response, we used kinematic GNSS observations, with measurement intervals of 5 s although higher rates could have been used. The International GNSS Service (IGS) advises that observations should be at 30 s intervals to guarantee independence between them, as long as the receiver does not move and remains static. In general, the precision of displacement results of any structure will be directly proportional to the GNSS observation period.

In this way, we can determine the position of the building every 25 s, as require by the client, by means of least squares adjustment of 5 GNSS observations, as will be discussed later.

In this study, we distinguish between 'observation interval', and 'intervals of determination of the position of the structure' to be