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Literature Study of Building Verticality Monitoring Analysis Using GNSS and Triaxial Tiltmeter Data Integration

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ABSTRACT

The vertical housing system is a solution for the urban population which continues to increase as time goes. By using high-rise buildings, the land used for housing will be more effective. However, high-rise buildings have their own problems, one of which is bending due to the load acting on the building. One of the loads that causes bending in buildings is wind load. Bending will cause a major problem for the building's endurance if the deviation exceeds the structural strength tolerance of the building, which will cause structural failure in the future. Therefore, it is necessary to periodically monitor the verticality of the building to detect this bending, both during and after constructions, to evaluate the performance and health of the building. The monitoring can be carried out using a variety of methods and equipment, one of which is particularly using the GNSS observation and triaxial tiltmeter measurement. GNSS measurement is used to detect the lateral displacement of the building, while the triaxial tiltmeter measurement is used to detect the deflection angle that is formed when the building is bending. To examine whether monitoring with GNSS and triaxial tiltmeter measurements can be used for practical purpose, this contribution delivers a simulation of wind load calculations to one high rise building in Bandung, Indonesia. This factor, in particular, is chosen to see the impact of bending on a building at high level floors. The wind load calculation refers to an Indonesian National Standard (SNI) 03-1727-2013, while the bending calculation will be carried out based on the beam deflection theory. Based on the simulation, it is found that the deflection that occurs at the highest level reaches 2.832 cm, and the largest deflection angle reaches 1.792". Hypothetically, it can be stated that these values can be detected by the survey standard GNSS observation and the triaxial tiltmeter measurement since the accuracy of those two monitoring tools is smaller than the simulation results. In turn, the health and safety of the buildings being monitored can be determined, which leads to issuing of the building functionality certificate for the building insurance purpose.

Keywords: high-rise building; bending; wind load;GNSS observation; triaxial tiltmeter measurement; Indonesian National Standard (SNI); deflection theory; building functionality certificate; building insurance

INTRODUCTION

End of the year 2019, the total urban population in Indonesia was 150.9 million people, or 55.8% of Indonesia's total population of 270.6 million (Worldometers, 2019). In the city of Bandung, it was noted that there were 2,507,808 people living in the city of Bandung (BPS Kota Bandung, 2020), and the number will definitely increase over time. These things prove that cities must start using a vertical housing system in the form of tall buildings.

In designing tall buildings, there is a structural strength design stage that serves as a guarantee of security for the structure as a whole. This is because tall buildings experience various problems, one of which is bending due to loads.

The higher the building, the greater the load. This is of course problematic if the bending that occurs exceeds the structural strength of the building (Park et al. 2004). To avoid this, it is necessary to monitor the bending.

With monitoring, the bending of the building can be observed continuously, then the existing data can be used to verify the results of the construction of a structure, as well as to provide information related to the safety of the structure that can affect the building performance evaluation, for the issuance of insurance for the building. Monitoring can be done using a variety of different tools and methods to detect the shear of the building. In this study, monitoring will be carried out using GNSS and Triaxial Tiltmeter measurements.

REVIEW ON DEFORMATION ON HIGH RISE BUILDING

A high-rise building is a building that is high enough to need a vertical transportation system such as an elevator. A building can be categorized as a high-rise building if it has a height of more than 23 meters or the equivalent of 7 floors (Hall 2013).

Rows of high-rise buildings were first constructed in America in the 1880s. This is the result of soaring land prices and a high population which causes the need for housing to also soar. Therefore, vertical housing is one of the solutions to this problem because it is more efficient in land use than horizontal housing. High-rise buildings became easier to make with steel and concrete frames until the mid-20th century high-rise buildings had become the standard for major cities around the world. Even so, every construction of high-rise buildings must pass a series of calculations and tests to prevent fatal damage to the building structure.

In Indonesia itself, vertical housing is being heavily promoted. This is a result of the increasing population of the city and the limited supply of land. This was taken as an opportunity by several property developers to build apartments in large cities. However, the taller the building, the more structural challenges that must be faced, one of which is the problem of disaster management, starting from the evacuation route, piping, and others. In addition, their mass will also be bigger than smaller buildings, this results in the loads that must be supported by the building. Moreover, Indonesia is known as an active seismic area, so that loads from outside also affect the loads that must be supported. In their original state, the working loads can provide a shift in a fraction of mm per level. Of course, it doesn't really matter if the building only has 5 levels, but what if the building has 100 floors, then the shift on the 100th floor can reach 1 meter (Angerik 2009).

According to SNI 03-1727-2013 concerning minimum loading for the design of buildings and other structures, loads are classified based on their type into dead loads, live loads, flood loads, snow loads, rainwater loads, earthquake loads, special loads, and wind loads.

BEAM DEFLECTION THEORY

Deflection, refers to the movement of a block or other object, from its initial position due to the forces and loads exerted on it. Deflection can be caused by various kinds of external loads or loads in the structure. Deflection can occur in various structures such as beams, trusses, frames, and other structures (Hibbeler 2015).

As a result of the force acting on a certain length, it will create momentum in the structure which causes deflection to occur. To be able to calculate the amount of deflection in a simple structure, Elastic Beam Theory can be used, which will produce an equation below (Hibbeler 2015),

$$\frac{d^2v}{dx^2} = \frac{M}{EI} \tag{1}$$

with,

V : Deflection,

M : Internal momentum acting on the object (bending moment),

E : Material of the structure (elasticity and plasticity / Young's modulus),

I : moment of inertia of the sections in the structure.

This equation assuming the material of the structure is homogeneous, with an illustration in FIGURE 1.

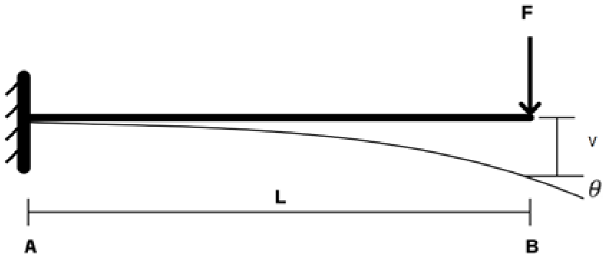

FIGURE 1. Deflection that occurs on a beam

Equation (1) is then integrated twice taking into consideration the supporting conditions and the load acting on the structure. In this study, two load distribution conditions are used, as illustrated in FIGURE 2, where the load is evenly distributed (uniform distributed load), and the load condition is triangular distributed load (Hibbeler, 2015).

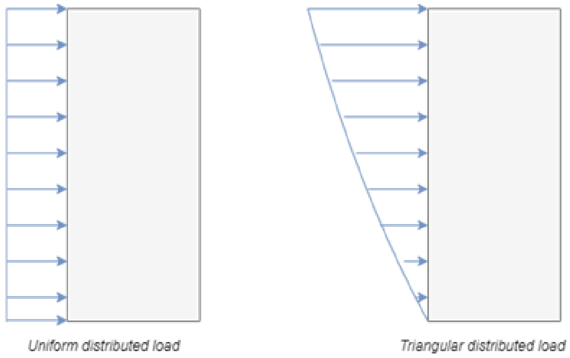

FIGURE 2. Two loads conditions

For uniform distributed load condition, equation (2) is used to find deflection at point x,

$$EI\ v = -\frac{Wx^4}{24} + \frac{WL^3x}{6} - \frac{WL^4}{8} \tag{2}$$

And equation (3) is used to find deflection angle at point x,

$$\theta EI = -\frac{Wx^3}{6} + \frac{WL^3}{6} \tag{3}$$

For triangular distributed load condition, equation (4) is used to find deflection at point x

$$EI\ v = -\frac{Wx^4}{24} + \frac{WL^3x}{6} - \frac{WL^4}{8}, \tag{4}$$

and equation (5) is used to find deflection angles at point x,

$$\theta EI = -\frac{Wx^3}{6} + \frac{WL^3}{6} \tag{5}$$

Where,

v : Deflection at point x
θ : Angle of deflection at point x (deg),
W : Wind load acting at a certain height (N/m),
x : Certain height point (m)
L : Total height (m) ,
E : Young material modulus (N/m^2),
I : Moment of inertia of the building section (m^4).

FUSION METHOD FOR DEFORMATION OBSERVATION

The position accuracy obtained by GNSS observations generally depends on the data accuracy factor, satellite geometry, positioning methods, and data processing strategies. In this case, it would be very natural that the positioning with GNSS could provide a fairly wide spectrum of positioning accuracy, ranging from very precise (millimeter) to mediocre (meter). Furthermore, the signal received from the satellite contains several errors and biases, such as orbital errors, ionosphere and troposphere biases, phase ambiguity, cycle slips, multipath, and clock errors. These errors and biases can be solved in various ways, both during measurement and reduction when processing data.

A tiltmeter, or inclinometer, is a device used to measure the angle formed by an object to a gravitational field. It senses the angle using an electronic chip which is often referred to as a Micro-Electro-Mechanical Systems (MEMS), in which there are several electrically charged plates (Posital 2018).

Simply put, when there is a rotation or tilt, the pieces that are inside the MEMS Accelerometer, will also move according to the slope that occurs. This causes a change in the electric potential in it which is then measured as a change in electrical capacitance, as illustrated in Figure 3 (Jewell Instruments 2018).

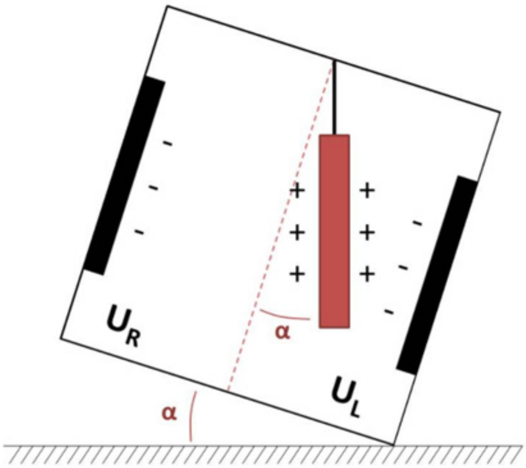

FIGURE 3. Electrically charged plate changes in MEMS (Jewell Instruments 2018)

The measurement accuracy produced by this MEMS tiltmeter can reach a resolution of 3.6 x 10-1”. If higher accuracy is required, a tiltmeter with an electrolytic system can be used, whose resolution can reach up to 3.6 x 10-4”. The choice of the type of tiltmeter depends on the intended use of the tiltmeter (Jewell Instruments, 2018). As an illustration, FIGURE 4 shows the resolutions of various MEMS tiltmeter sensors.

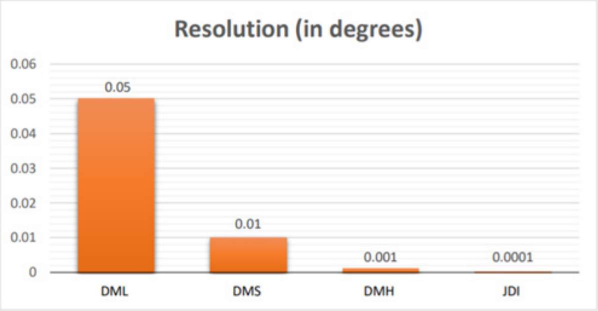

FIGURE 4. The resolution of some MEMS tiltmeter products (Jewell Instruments 2018)

Tiltmeter is usually connected to a controller, either using a cable or wirelessly, and producing output in the form of yaw, pitch, and roll angle data, plus temperature data during measurement.

BUILDING MONITORING PARAMETERS

BUILDING VERTICALITY

In monitoring the verticality of a building, there are several parameters used to identify deflection, including deflection, v, and deflection angle θ to the vertical axis of the building. To obtain these parameters, various methods can be used for monitoring, with a variety of different equipment. Among the methods and equipment used are measurements with GNSS, Electronic Total Station (ETS), and a combination of other equipment.

The method of monitoring with a total station is carried out by taking sample points at different building heights, with the assumption that these points are on the same vertical axis, so that deflection can be measured referring to the vertical axis. In the method used by Syahfitrianie et al. (2019), the principle is used that the column in a building can be declared upright if the base coordinates (x_0, y_0) at the bottom of the building column are the same as the top coordinates (x_n, y_n) at the top of the building column. This method is also used by Wang (2019), by using ETS to measure several points at different heights (1st floor, 10th floor, and 17th floor), to get the slope, then compare the results with the field regression obtained through calculations.

These points are measured in different time periods (during construction, and half a year after construction). In addition to the measurement of standing, the measurement is also carried out to compare the settlements that occurred in each time period. Settlement is a structural distortion that occurs due to uneven compression of the structure, shrinkage, and additional loads that occur during construction.

However, in reality, the value of the coordinates at the bottom of the column will not have the exact same value as the coordinate value of the top column, because of deflection due to different loads acting on the column. Therefore, the deflection tolerance in SNI 03-1729-2002 is used to determine whether the deflection is within the tolerable threshold.

In monitoring the verticality of a building, a piece of equipment is needed that can measure with accuracy the fraction of millimeter, because of the small changes that occur in the lower floors of the building. Therefore, ETS is usually used as equipment to measure the verticality of a building.

However, the problem occurs whenever the monitored building is very tall that it gives no possibility to measure using ETS, which means the limitation of using ETS. Therefore, another method is needed in monitoring the verticality. The upper level of a tall building usually experiences a much greater shift than the lower level of the building. Investigating to understand this behavior, many researchers have tried to monitor the standing of buildings using GNSS.

Xia et al. (2014) using a combination of GNSS, inclinometer, and strainmeter measurements. The object of his research is the Canton Tower in China and is one of the tallest buildings in the world. This building has a high (454 m) and complex structure. In its monitoring, one GNSS receiver was installed at a height of 10.2m acting as a reference station, and another one was located on the roof of the building at a height of 459.2 m, which purpose is to measure the shear that occurs on the roof of the building. An inclinometer was mounted at an altitude of 443.8 m measuring the deflection angle from the horizontal axis. The sampling rate used on the receiver and inclinometer was 1 Hz. The strainmeter was used to calculate the strain that occurs in critical building sections. From the strain data, the estimated lateral displacement that occurs in the building can be calculated. The results of the measurements and calculations are then compared and correlated with the wind speed around the building.

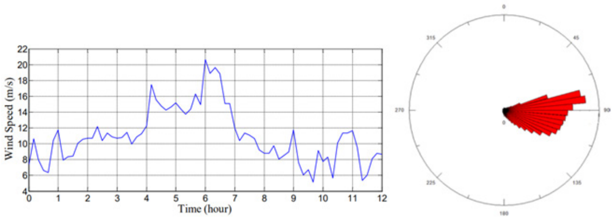

FIGURE 5. Wind direction and speed around the building (Xia et al. 2014)

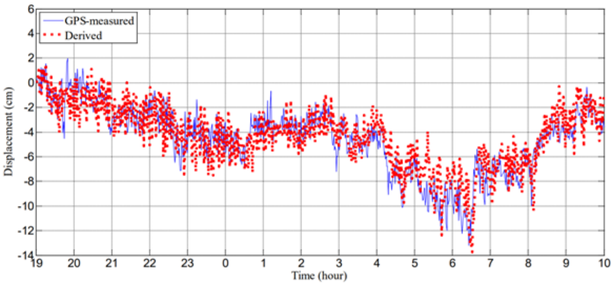

FIGURE 6. GNSS, and strainmeter measurement results (Xia et al. 2014)

The strain measurement data was also used as a comparison of the inclination angle measured from the inclinometer. FIGURE 7 showed the ratio of the angle between the calculation result and the measurement result at the height.

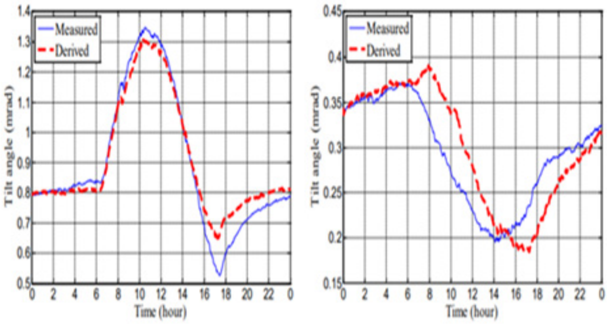

FIGURE 7. Inclinometer and strainmeter measurement results (Xia et al. 2014)

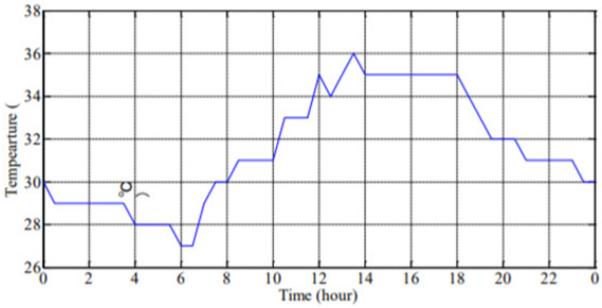

FIGURE 8. Air temperature around the building (Xia et al. 2014)

The research conducted by Xia et al. (2014) concluded that in addition to the wind, temperature in FIGURE 8 and sunlight also affect building deflection. As well as the verticality of the building can be measured using GPS and inclinometer measurements and has a similar result as the results of calculations using strain data.

WIND LOAD

Wind load calculations can be done using an algorithm developed in Angerik (2009), which uses the calculation of wind pressure generated with the parameters of the building shape coefficient and the maximum wind speed. These calculations are based on the theory and formula proposed by Schueller (1977),

$$p=0.002558\, C_D\, V^2 \qquad (6)$$

Where

p : Pressure on of the building (psf),

CD : Coefficient of shape,

V : Maximum speed (mph).

This formula is used with a different maximum wind speed at each altitude (Angerik, 2009). Then the pressure generated on each floor is multiplied by the height of the floor, to produce the wind load on each floor. The wind load for each floor is then added up to determine the total wind load.

BENDING

Apart from measurement, a method is developed by calculating the bending of the building using the beam deflection theory, as done by Angerik (2009). This method can be performed if the bending moment data of the building is available. The bending moment can be obtained by knowing the load acting on the building, and the dimensions of the building structure. In addition to the bending moment, it is also necessary to know the inertia of the cross-section of the building and the modulus of elasticity of the building.

In this study, the calculation to simulate the bending of the building will be carried out using beam deflection theory with two different load conditions: the uniform distributed load and the triangular distributed load. Unfortunately, direct measurements were not able to deliver since the local administration restrained public mobility due to the outbreak of a COVID-19 pandemic.

RESULTS AND DISCUSSION

In this contribution, as it is shown in FIGURE 9, the simulation object has an area of about 15 x 15 meters with 21 @ 3.66 m, with a total height of 76.86 m. The structure is supported by a core wall covering an area of 5 x 5 m with a concrete wall that has 50 cm of thickness.

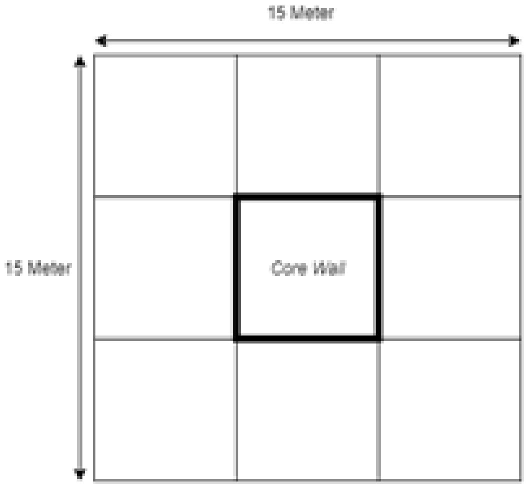

FIGURE 9. Building structure

WIND LOAD CALCULATION

The wind load calculation is carried out to find how much wind load is working on the building so that later it can be used to calculate bending that occurs on the building. In the calculation of this wind load, it is assumed that there are no obstructions blocking the wind from hitting the building. Wind speed is downloaded from the National Meteorology and Geophysics Agency (BMKG) website (https://www.bmkg.go.id/). It shows the highest wind speed at that time was 7 m/s, with the average wind heading in the southeast direction. Thus, this study used the given numerical value and direction.

By following SNI 03-1727-2013 guidelines, wind load can be determined with the result as shown by Figure 10, and the total of the wind load working on the building is 401917 N.

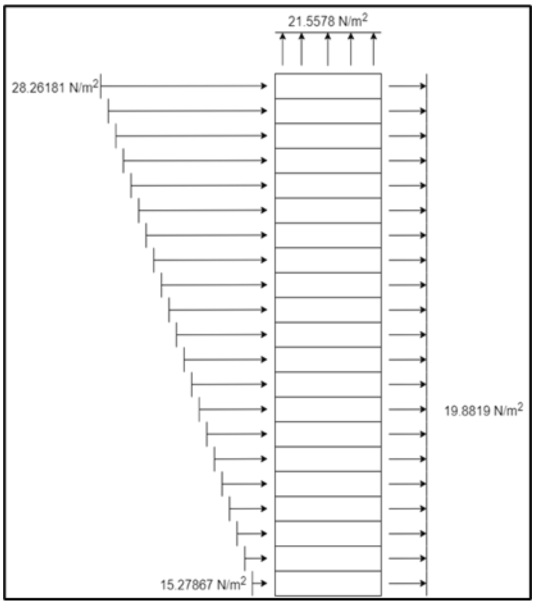

FIGURE 10. Wind load acting on each floor

BUILDING DEFLECTION CALCULATION

After knowing the value of the wind load acting on the building, the deflections that occur on each floor can be calculated and then put together to see the overall bending. In this case, 2 types of load distribution; uniform distributed load, and triangular distributed load, by transforming the wind scheme in Figure 10, into Figure 11.

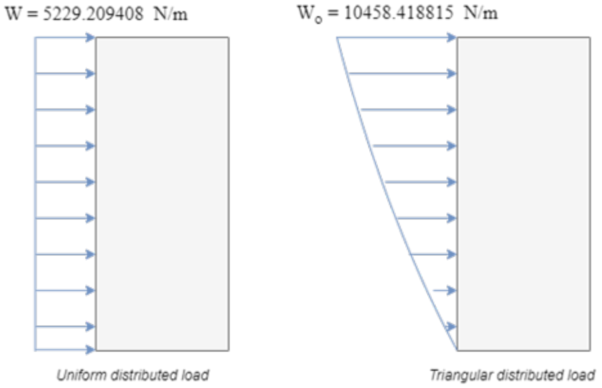

FIGURE 11. Wind load with 2 load distribution conditions

With parameters, such as building height L = 76.86 m, the modulus of elasticity E = 2.780557 × 1010 N/m2, and the moment of inertia of the cross-section is I = 35.72396 m4. With these values, we can use equations 2, 3, 4, and 5 to calculate the deflection that occurs on each floor with the results shown in Figure 12.

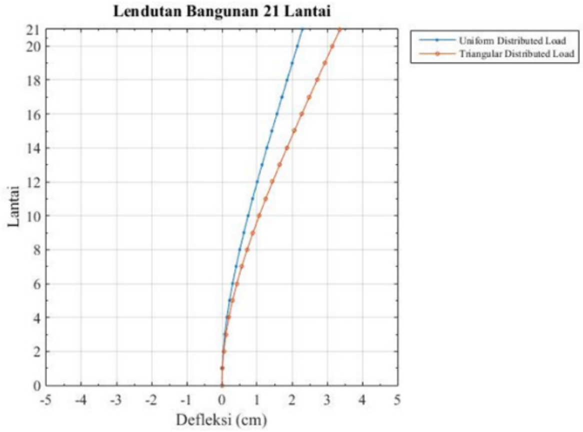

FIGURE 12. Wind load calculation result with 2 load distribution conditions

If the results of the calculation from the two methods are averaged producing the results as it is shown in Figure 13.

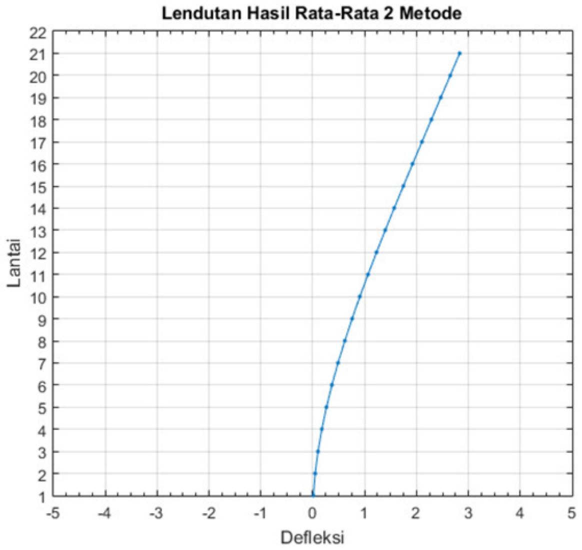

FIGURE 13. Wind load calculation with 2 load distribution conditions averaged

VERTICALITY MONITORING

Then, from the calculated deflection results, it is known that on the 21st floor, evenly distributed loads produce a deflection of 2.296 cm, while those with a triangular distribution produce a deflection of 3.368 cm. In reality, the loads that work on buildings are not only wind loads, but a lot of loads such as earthquake loads, dead loads, live loads, and other loads that can affect deflection or lateral displacement. It can be said that in the real world, the deflection that occurs will be greater than what has been calculated. In order to measure the deflection that occurs in the real world, in this study, GNSS measurement should be used. For civil engineering survey applications, the positioning with GNSS has accuracy between 1-5 cm. In addition, nowadays with multi-constellation GNSS, solving phase ambiguity should not be a problem, and can produce much better accuracy. Quesada-olmo et al. (2018), in their research using GNSS observations, the RTK method itself obtained observations with accuracy reaching the order of millimeters.

The receivers were installed at the top of the building (76.86 m) and at the base around the building as a reference, which are paralleled to the tiltmeter, and then carry out continuous measurements. For the processing itself, the differential method with post-processing, or RTK can be used.

The GNSS measurement was chosen because of the height of the building because the top of the building could not be seen using ETS which stands at the ground level of the building. Existed objects can potentially obstruct the ETS shot because the measurement area is a fairly narrow urban area.

Whereas for the resulting deflection angle, the load is evenly distributed, ranging between 0.195” on the 1st floor, and 1.434” on the 21st floor. While for the triangular distributed load, the deflection angle ranges from 0.263” on the 1st floor, and 2.151” on the 21st floor. Based on Figure 14, regarding the resolution of the tiltmeter measurement, it is known that the best resolution of the deflection angle that can be recorded by the high-precision tiltmeter (JDI) is 0.36”.

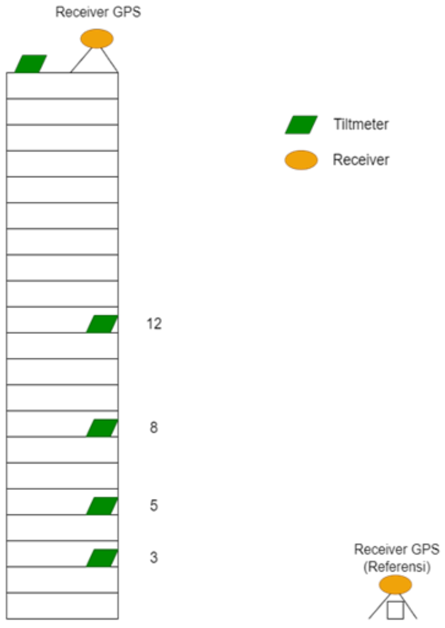

FIGURE 14. Building verticality monitoring scheme

The high precision tiltmeter (JDI) can be installed on floors 3, 5, 8, and 12, because the increase in the deflection angle exceeds the resolution of the tiltmeter. However, after it is installed on the 12th floor, it is better not to install it on floors 13 to 20, because the increase in the deflection angle is quite small, which does not become significant when measured by a tiltmeter with a resolution of 0.36 seconds.

Building verticality monitoring can be useful in evaluating building performance, both during and after construction. Monitoring can provide information about the real aspects of building safety and can be compared to the building’s initial design. The survey result is expected as a reference for issuing the Building Functionality Certificate (SLF) for Buildings in Bandung, which is submitted through the Bandung City Investment and One-Stop Integrated Service (DPMPTSP).

If the simulation results that have been carried out are used to find the deflection tolerance, it will produce a tolerance of 0.384 meters. Of the calculations with two different load distributions that have been carried out, both are still within the specified tolerance, even though the triangular distributed load is quite close to the tolerance limit, with 0.2296 meters at the load evenly distributed, and 0.3368 meters for the triangular distributed load. Thus, the building that is used as the object of the simulation can still be said to be safe to function, if we only see the aspect of the wind load.

When the building is declared safe, the requirements for applying for the SLF for the building can be fulfilled in terms of these aspects, and later this will affect the issuance of the building insurance. Because indeed one of the conditions for the issuance of building insurance, is the issuance of the SLF for the building.

Apart from playing a role in issuing SLFs, monitoring can also be carried out to determine the health of the buildings being monitored. Because, in reality, the load that acts on the building, not only the wind load, it is very possible for the building to move and shift quickly so that it can endanger the structure and the people in it. The frequency of these shifts can be a determinant of the health of the building and can be monitored using GNSS measurements and a tiltmeter. Because of this rapid shift, equipment with a sampling rate that matches the frequency of the shift must be used. Commercial tiltmeters usually have the best sampling rate of 1 Hz, while GNSS receivers commonly used in structure monitoring have a sampling rate of 10 Hz - 20 Hz. That way, the shifts that occur can be monitored at up to a resolution per second. But of course, it is necessary to determine again if what is the ideal time resolution for future research, so that the measurements are not excessive.

CONCLUSION

The results of the bending calculation that occur in the building have been modeled with an evenly distributed load method and a triangular distributed load method, and the deflection value that occurs at the highest level (76.68 m) reaches 2.832 cm, and the largest deflection angle reaches 1.792 seconds.

Based on the results of bending calculation, of a 21-story building in Bandung, the erection of these tall buildings can be measured and monitored by GNSS measurements at the top of the building, which measures the lateral displacement that occurs, as well as the triaxial tiltmeter which measures changes in deflection angle on the 3rd floor 5, 8, and 12, specifically for the conditions mentioned. The measurement sketch has been shown in FIGURE 14 so that the deflection values and the deflection angle can be measured significantly.

Based on the calculation results, the bending that occurs in the object in the simulation, is still within the existing tolerance in SNI 03-1729-2002, so that the building can be said to be safe in terms of bending due to wind loads only, and plays a role in the publishing process SLF (Building Functionality Certificate) which can be used to apply for building insurance. Monitoring of building verticality can also be done to determine the health of the building, by looking at the frequency of deflection changes that occur in the building.

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DECLARATION OF COMPETING INTEREST

None

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