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EVALUACIÓN DE DESPLAZAMIENTOS EN EDIFICIOS DE HORMIGÓN ARMADO PARA EL FUNCIONAMIENTO DE ANTENAS 5G EN CHILE

ASSESSMENT OF DISPLACEMENTS IN REINFORCED CONCRETE BUILDINGS FOR THE OPERATION OF 5G ANTENNAS IN CHILE

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RESUMEN

La inminente irrupción de las redes 5G en el mercado chileno de las telecomunicaciones, ha hecho imprescindible anticipar los posibles desequilibrios que éstas podrían alcanzar cuando ocurra cualquiera de los terremotos que azotan repetidamente al país. Para ello, se ha formulado una metodología basada en el análisis elástico lineal convencional, tanto modal espectral como tiempo-historia, para estimar los desplazamientos inducidos para dos niveles diferentes de movimientos fuertes del terreno, basados en registros sísmicos obtenidos en la zona de subducción. Los resultados obtenidos han servido para obtener expresiones analíticas bastante ajustadas, formuladas a partir de una única variable del sistema, la altura del nivel, de manera que puedan ser utilizadas para estimar rápidamente los desplazamientos laterales de las antenas 5G que estarán en red, por personal que no tiene formación en dinámica estructural, pero que serán las encargadas de realizar los ajustes en los nodos de la red 5G.

***Palabras clave**: redes de comunicaciones 5G; desplazamientos laterales; derivas laterales de piso; cargas normativas accidentales; simulación numérica*

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ABSTRACT

The imminent emergence of 5G networks in the Chilean telecommunications market has made it essential to anticipate the possible imbalances that these could reach when any of the earthquakes that repeatedly strike the country occurs. To do this, a methodology based on conventional linear elastic analysis, both spectral modal and time-history, has been formulated to estimate the induced displacements for two different levels of strong ground movements, based on seismic records obtained in the subduction zone. The results obtained have served to obtain fairly adjusted analytical expressions, formulated from a single system variable, the height of the level, so that they can be used to quickly estimate the lateral displacements of the 5G antennas that will be networked, by personnel who has no training in structural dynamics, but who will be in charge of making the adjustments in the 5G network nodes.

***Keywords**: 5G communication networks; lateral displacements; lateral floor drifts; accidental regulatory charges; numerical simulation*

1. INTRODUCTION

Nowadays, mobile phones and data services are of vital importance in all areas of society for the development at all levels of use, from a personal one to the corporate one, for quick communications and for sending and/or downloading information. In Chile, because of a constant search for improvement, it is therefore planned to implement the new 5G network, which should be launched worldwide in 2020. This new network uses high frequency millimeter waves, which will avoid a saturation of the network. In addition, the large number of repeaters will prevent the existence of areas with no access to the network and, together with this, it will be possible to handle more connections for mobile traffic and direct the signal to the user, among other several advantages [1,2].

Logically, in line with these achieved or ongoing advances, it is important to deliver a stable signal throughout the day, i.e. to improve the service to users. This can be prevented by the displacements of the base of the next-generation antennas, due to the relative displacements of the stories of the structure in which they are usually installed. In order to estimate these relative displacements in buildings in Chile, the modal spectral analysis is a common code procedure used to check the interstory drifts to verify whether or not they meet the maximum value allowed by the code. Considering this, the above-mentioned analysis requires information on the complete geometry and mechanic characteristics of the structure [3].

Currently, alternative calculations have been proposed to estimate displacements or interstory drifts. In a recent study, the authors presented a formulation that estimates the maximum roof displacements of a building based on the geometry of its columns, its beams, the concrete quality, the story height and the total building weight, obtaining results comparable to those provided by the structural analysis program SAP2000, but only for four-story buildings with structural typologies used in India [4]. On the other hand, in another study, the authors estimated the interstory drifts from displacements calculated from the acceleration of the structure, achieving good results but requiring a high volume of data usually very difficult to obtain, according to the authors [5].

One of the most complete investigations was presented by [6], who recorded earthquakes data in several countries, including Chile, and compared them to estimated structure's displacements, using the knowledge of the basic information on the building such as: number of stories, fundamental period and ductility. The procedure is performed by associating these parameters with certain factors called "beta" (β), so that the maximum lateral displacements produced by an earthquake can be estimated more quickly. There were subsequent investigations, such as those carried out by [7,8]. Aguiar [7] proposed slight adjustments to the aforementioned procedure, achieving with this comparison very good results with respect to the one computed for 3 to 6 stories reinforced concrete buildings, considering the main structural types existing in Ecuador.

Scaletti [8] proposed simplifications and adjustments factors proposed by the original author. These procedures are based on the linear elastic analysis of the structures and have a different purpose from that contemplated in other analyses in a non-linear range. In the case of the latter, the purpose is to evaluate the structural damage achieved both locally and globally [9, 10].

Other researchers have evaluated different factors that affect communication, sending and receiving data. In a recent work, a target city was modeled in 3D, including people, vehicles and buildings to test the behavior of waves and determine possible problems such as path losses, reflections and dispersion [11], in [12] the authors sought to determine errors analogous to those just mentioned but with a less expensive 2D computational model. On the other hand, in [13] used an abbreviated algorithm such as the DDFFA (Distributed Dynamic Fractional Frequency Allocation) algorithm that helps to assign and optimize different frequencies. All these research works involve new possible factors that can influence the signal of different networks and particularly the one of the new 5G networks.

The location of the antennas could be a problem, since their positioning may require the analysis and evaluation of the displacements of a large number of buildings in a specific area, to strategically locate a high amount of points (senders and receivers) that must be evaluated to build the network [14]. This implies a very high volume of information, time and costs for the intended purpose. According to the works mentioned above, it is necessary to propose a simplified method for the estimation of the displacements of typical Chilean buildings, so that professionals who are not experts in the field of civil engineering may be able to determine these displacements only knowing simple parameters and in a short time. To this end, a simple procedure to determine displacements of a building representative of the structures existing in Chile, it is proposed to incorporate the main environmental loads present in the location area.

2. METHOLOGY

The methodology includes the selection of a building representative of the structural typologies used in Chile. Then, the building is accurately modeled, using advanced computational tools. The loads determined by current regulations, including dead and live loads, are applied to the building model, and then the environmental loads corresponding to the location of the building are applied.

The types of analysis that allow the calculation of the displacements of the location points of the 5G network antennas are the following:

- Modal spectral analysis
- Wind simulation analysis
- Time-history analysis using three scaled strong-ground motions

For the wind and time-history analyses, formulations for the displacements obtained for each direction of the main structure of the building are obtained depending on the antennas heights.

2.1. Basic Information

For the development of the model, the complete set of plans of the selected building is required. The selected building must meet the design criteria of current Chilean codes [15, 16, 17]. In order to fulfill this requirement, a high-rise reinforced concrete structure using shear walls was the selected option. This building has 15 floors plus a subterranean level with a total height of 39,28 m.

2.2. Structural Modeling

The building was modeled using the Revit 2019 program [18] and to do so, the original plans of the structure were used, with the units in the international system and with the pre-existing measures.

For the modeling, some particular aspects are taken into account to ensure that the model is accurately analyzed, completed and as close to reality as possible. To this end, the walls, slabs and inverted beams are modeled as shell-type elements, leaving the frame type elements exclusively for the modeling of beams, to ensure a correct coupling and meshing between inverted beams and walls. As for the supports, fixed type, in the base level (underground 1), but adding perpendicular sliding supports to the walls located at the ground level, at level 0,0, to be able to simulate the lateral support provided by the soil. Finally, it was decided to define that each slab acts as a rigid diaphragm, reducing the number of nodes in the mesh and generating almost identical drifts per floor slab. The described exported model is shown in Figure 1.

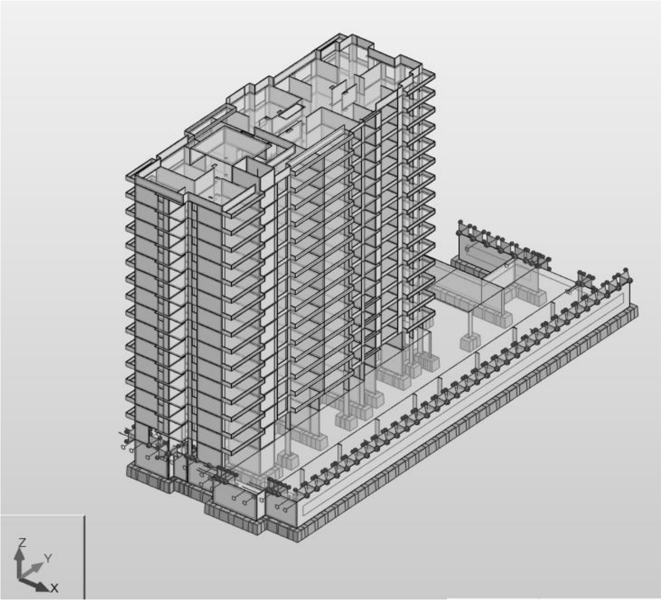

Figure 1. *Model building type exported to Robot 2019. Source: The authors*

Once the model of the structure is developed using the Revit software, the model is exported to the structural software, in which the dead and live loads of the building are defined according to the Chilean code NCh1537.Of2009 [15]. For the second load type,at the subterranean level, the load was increased to 500 kgf/cm^2 and considered a uniform load over the entire slab, without taking into account the differentiated loads for warehouses and parking areas.

To avoid discarding factors a priori or missing the potential of the model, three different types of analysis, already mentioned above, are carried out, on the basis of a linear-elastic model, considering cracking in cross sections of all the elements (beams, walls and slab) using a coefficient of 0,7.

In addition, the results will be obtained for two relevant points in each type of analysis, the first one being located at the center of mass, (coordinates: x =8.41; y =19.56) and the second one a point far from the center and close to a corner, hereinafter called PTO (coordinates: x = 12,44; y = 42,69). The selected points are shown in a plan view of the building (see Figure 2). It should be noted that the displacements of a total of 16 nodes are extracted for the center of mass and another 16 for the remote point, because each node has a different node numbering.

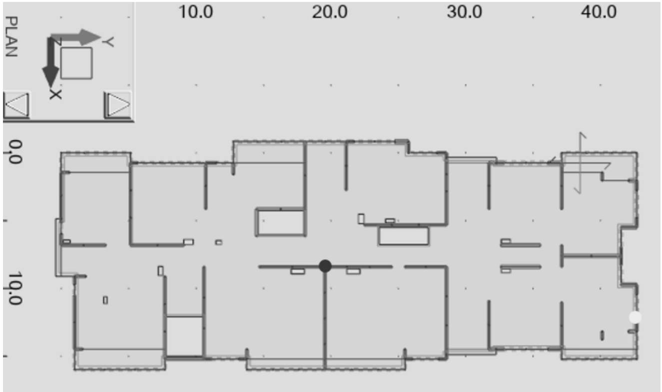

Figure 2. *Typical plan view of the building with the Center of Mass (in black) and the point PTO (in white).*
Source: The authors

2.3. Modal Spectral Analysis

This type of analysis is routinely used to obtain interstory drifts from displacements; the above procedure is applied to verify that these interstory drifts are in the expected ranges according to engineering experience and allowed by current regulations. A modal spectral analysis is then carried out according to what is stated in NCh433.Of1996 [16] and in D.S. No. 60 and 61 [19, 20]. In this case, with a spectrum with values corresponding to the type 2 building category (residential building), in seismic zone 3 (fifth region) and on a type B soil (very stiff soil).

2.4. Wind Simulation

All existing structures are subject to environmental conditions that are proven to induce minor displacements in these structures [21]. Among these environmental conditions, the wind is one of the most influential, because of the displacements it can cause. The displacements are estimated using several available procedures and the wind simulation is one of the recognized best ways to accurately determine wind loads on structures.

The simulation is carried out according to the NCh432.Of2010 code [17]. This code provides three ways to compute wind loads: a simplified method of distributed loads in the leeward and windward directions, an analytical method that contemplates the use of factors dependent on different elements, and a method consisting in performing a simulation in a wind tunnel. For this last method, the response of the building is evaluated under the same conditions as if it were alone in a tunnel, with an incorporated wind flow towards the structure. In this study, the third option was chosen, with the use of the Robot Structural Analysis Professional 2019 software, which generates the loads automatically, with a basic wind velocity of 35 m/s corresponding to the latitude of the location of the building in the x and y directions and with defined claddings, so as to have conditions similar to the real conditions of the building with all the existing openings closed (doors and windows in the worst case scenario).

This kind of analysis is not usual in Chile, because the wind conditions are usually not higher than the conditions associated with the seismic loads. It should be noted that no claddings were used at the subterranean level because the analysis and incorporation of wind loads is carried out from the 0.0 level, since from this level the building can be exposed to the wind.

2.5. Scaled Time-History Analysis

To increase the range of interstory drifts obtained and to take into account the maximum values that are not usual, but probable, three Chilean strong ground motions were used to perform time-history analysis: Valparaíso earthquake (1985), Maule earthquake (2010) and Coquimbo earthquake (2015), corrected and modified to match the displacement spectrum of the seismic code [22]. For these three earthquakes, their longitudinal and transverse components in both directions of the building for a single station are used, given that it is not possible to know from which direction an earthquake is more likely to strike and that decomposing it requires a more sophisticated work and considering that the orientation of any other evaluated building will also be arbitrary.

All of the above is done according to the recommendation given by ACHISINA [23] regarding the number of strong ground motions assessments that have to be performed. Finally, as suggested by [24], there are three levels of earthquake depending on the return period: "Frequent" with a low return period (about 75 years), "Rare" with a return period of approximately 500 years and “Very Rare” with a return period of approximately 2500 years. In this study, earthquakes are considered at the “Rare” level, for which there is a scale factor of 1,0, and also at the “Frequent” level, for which there is a scale factor of 0,6 [24].

The purpose of all of the above-mentioned steps is to obtain the displacements of the building at the different levels of the structure. These displacements are provided by the software after the modeling explained before. For the modal spectral analysis, an extra step known as CQC Analysis, specified in the Chilean seismic code NCh433.Of1996 [16] is required.

Additionally, for the formulations to be as generic as possible, it has been decided to carry out the transformation to make the displacements dimensionless, obtaining percentage results known as global drifts (DG). The structural analysis software was configured to deliver the displacements in millimeters; these values are therefore multiplied by 100%, and divided by the maximum height, making the respective conversion of units and getting the displacements in percentage. The above formulation is seen in equation (1), with a height value of 39.28 m, corresponding to the maximum height of the building type studied.

$$DG = \frac{Desp.\cdot 100\%}{H_{max}} \qquad (1)$$

Finally, values are unified for each analysis direction in order to have the minimum amount of formulations; this point will be detailed hereafter in the results section. With this procedure, the displacements can be obtained. To obtain the final displacements, the obtained value is divided by 100 and multiplied by 39,28 m. The above-mentioned procedure is carried out for each direction.

3. RESULTS

The final formulations depend on the analyses and the results obtained for each of them. The results of the three aforementioned analyses will therefore be presented independently. They will then be compared. Finally, the final formulation will be proposed.

3.1. Modal Spectral Results

Before presenting the results, it is necessary to mention that for the modal spectral analysis the results obtained in the z direction will not be considered, since they show very low values and are not relevant to the development of this research. Therefore, once the CQC analysis is carried out, the displacements of the CM and PTO are plotted for each direction, called respectively spectral x and spectral y and corresponding to the spectrum in each direction. Then, only the maximum displacement values found for each direction are selected. The reason for the above is that these curves are only presented to be able to compare them visually with each other in terms of shape and magnitude.

3.2. Wind Simulation Results

In a similar way as for the previous analysis, several displacements are obtained for the wind simulation analysis, since it is carried out for wind simulations from the positive and negative x directions (x+ and x-) and from the positive and negative y directions (y+ and y-). In addition, since the wind in both directions causes displacements of each node in the x and y directions, there are 8 displacement values in total for CM and PTO, on each story. The resulting displacements in the x direction and the corresponding average curve are shown in Figure 3. These displacements are obtained as the average of the displacements magnitude obtained in each respective direction of analysis. For example, for the x direction wind thrusts, the magnitudes or absolute values of the obtained maximum and minimum displacement values for PTO and CM are averaged to obtain the curve presented in each direction. The procedure and results for the y direction are analogous.

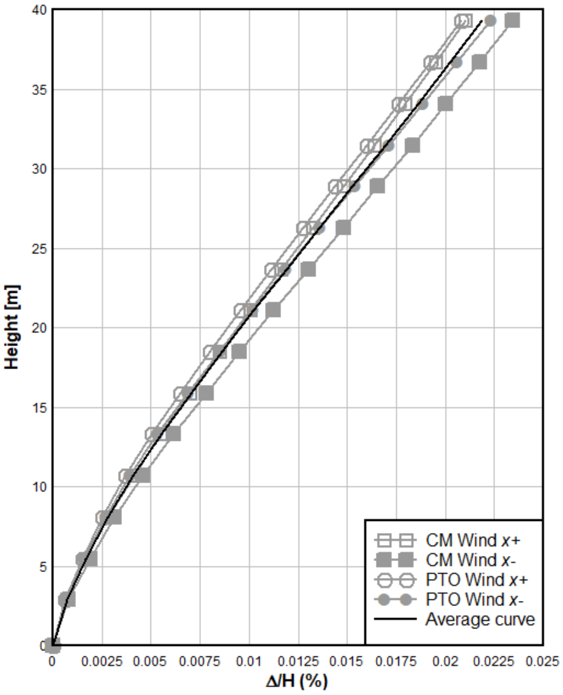

Figure 3. *Displacements for the Wind Simulation Analysis in the x direction and average curve in the same direction. Source: The authors.*

3.3. Results Time-History Analysis

The procedure is similar to that of the previous case, except that in this case, the analysis consists on evaluating the accelerations of the strong ground motions of Valparaíso, Maule and Coquimbo in the x and y directions independently. Once the maximum and minimum displacement values are obtained, an average curve is calculated for each strong ground motion in each direction. As an example, Figure 4 shows the displacements produced by the Maule earthquake in the y direction and the corresponding average curve.

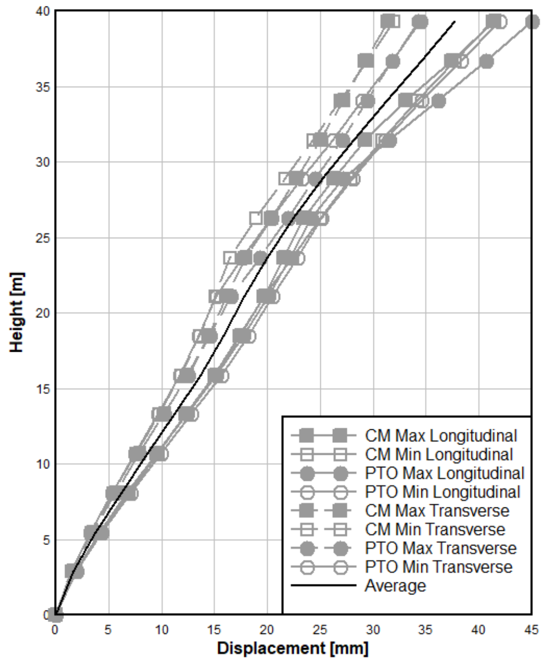

Figure 4. *Displacements in the y direction for a Time-History Analysis carried out with the Robot 2019 software for the 2010 Maule earthquake and average curve in the same direction. Source: The authors.*

The procedure is carried out for both x and y directions and for each strong ground motion. Then, the curves obtained for the three strong ground motions in both directions are averaged, to obtain the "rare earthquake" curve with a scale factor of 1,0. The displacement values obtained in this step are multiplied by 0,6 to also create the "frequent earthquake" curve. Results can be seen in Figure 5, where the average curves for each strong ground motion and for each return period are plotted.

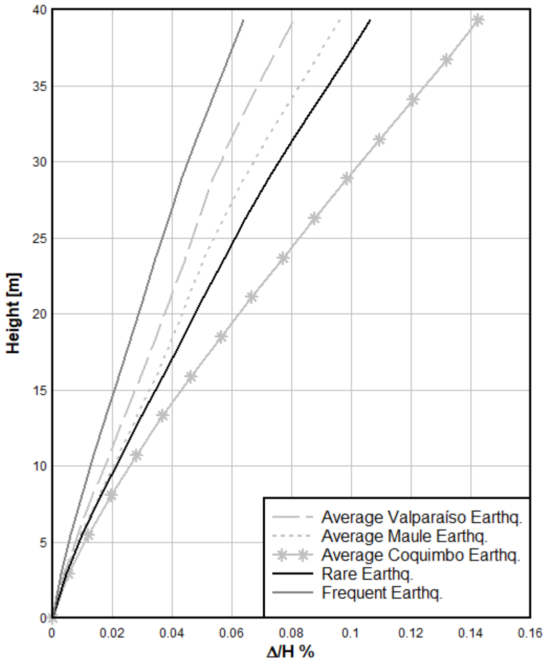

Figure 5. *Average displacements for the Time-History Analysis in the y direction, for a frequent earthquake and a rare earthquake. Source: The authors.*

Once the displacement vs height curves are obtained, the next step is to obtain curve fits with grade 3 polynomial approximations for the wind simulation, “frequent earthquake” and “rare earthquake”. The polynomial curve fit only depends on the story height H. The modal spectral analysis curve is also shown, for comparison only. The curves shown in Figure 6 and 7 correspond to the following polynomial curve fits in the x direction. Curve fit for wind-induced displacements:

The curves shown in Figure 6 correspond to the following polynomial curve fits in the x direction:

Curve fit for wind-induced displacements:

$$\llbracket \Delta X\rrbracket\_Wind\ (H) = -8.71672\cdot\llbracket 10\rrbracket\text{^}(-5)+0.00025\cdot H+1.51873\cdot\llbracket 10\rrbracket\text{^}(-5)\cdot H\text{^}2-1.88500\cdot\llbracket 10\rrbracket\text{^}(-7)\cdot H\text{^}3 \tag{2}$$

Curve fit for frequent earthquake-induced displacements:

$$\llbracket \Delta X\rrbracket\_Eqfrequent\ (H) = -0.00140+0.00198\cdot H-5.88643\cdot\llbracket 10\rrbracket\text{^}(-6)\cdot H\text{^}2+3.06136\cdot\llbracket 10\rrbracket\text{^}(-7)\cdot H\text{^}3 \tag{3}$$

Curve fit for rare earthquake-induced displacements:

$$\llbracket \Delta X\rrbracket\_Eqrare\ (H) = -0.00234+0.00330\cdot H-9.81071\cdot\llbracket 10\rrbracket\text{^}(-6)\cdot H\text{^}2+5.10226\cdot\llbracket 10\rrbracket\text{^}(-7)\cdot H\text{^}3 \tag{4}$$

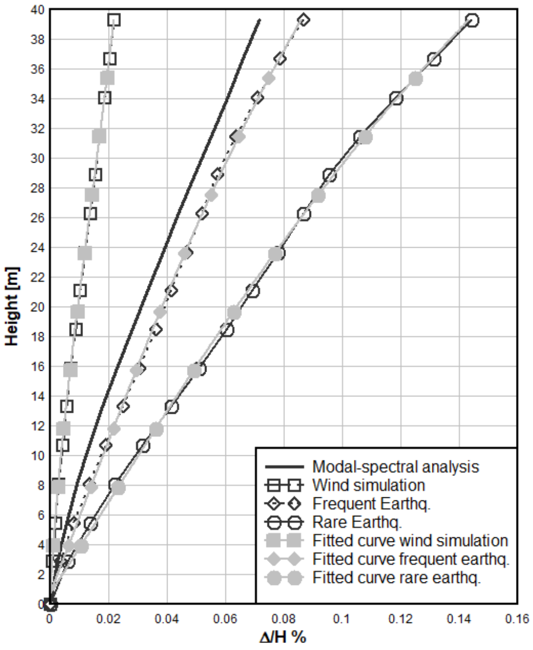

Figure 6. *Displacements according to the type of analysis and correlation curves created in the x direction. Source: The authors.*

The equations corresponding to the fitted curves for the y direction shown in Figure 7 are the following starting with the wind simulation displacements:

$$\llbracket \Delta Y\rrbracket\_Wind\ (H) = -1.90400\cdot\llbracket 10\rrbracket\text{^}(-5)+5.75081\cdot\llbracket 10\rrbracket\text{^}(-5)\cdot H+3.80659\cdot\llbracket 10\rrbracket\text{^}(-6)\cdot H\text{^}2-5.30816\cdot\llbracket 10\rrbracket\text{^}(-8)\cdot H\text{^}3 \tag{5}$$

Curve fit for frequent earthquake-induced displacements:

〚ΔY〛_Eqfrequent (H) =-0.00062+0.00125·H+1.01636·〚10〛^(-5)·H^2-4.77010·〚10〛^(-9)·H^3 (6)

Curve fit for rare earthquake-induced displacements:

〚ΔY〛_Eqrare (H) =-0.00103+0.00208·H+1.69394·〚10〛^(-5)·H^2-7.95016·〚10〛^(-9)·H^3 (7)

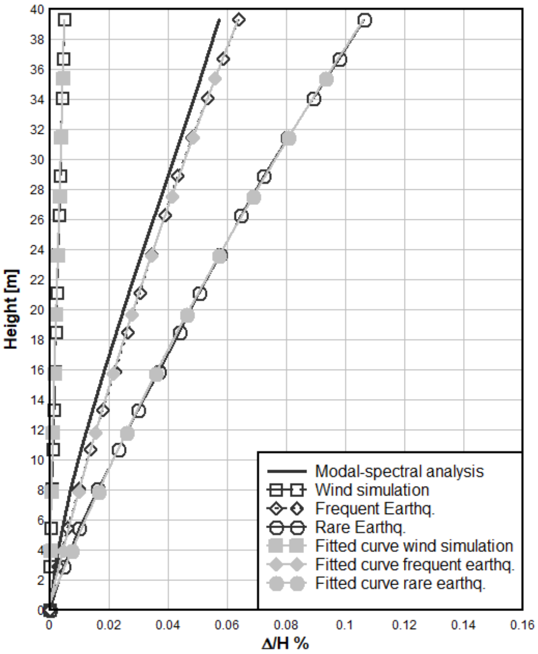

Figure 7. *Displacements according to the type of analysis and correlation curves created in the y direction. Source: The authors.*

It should be remembered that, although the height of the building "H" must be entered in meters to obtain the displacements for each formulation, the result will be dimensionless and the unit of measurement will be obtained by dividing the value by 100 and multiplying it by 39,28 m. Another important feature is the importance of the structural axes. In Figure 2, the caption shows the axes with respect to the model. It can be seen that, the y direction is the strong direction, which is relevant when trying to obtain displacements with this procedure in a similar building. In fact, the x direction will then be the direction in which the building is less stiff (weak structural direction), so the values of the stories displacements will be higher than in the strong structural direction.

3.4. Curves Adjustment Verification

Finally, in order to verify the adjustment of the fitted curves, the correlation coefficients obtained with respect to the original curves are presented in Table 1. The correlation coefficient takes values ranging from -1 to 1. The closer the value of the coefficient is to one, the better the adjustment. For all the proposed formulations, the adjustment is very close to one, corroborating a good fit for the results obtained with the curve formulations.

Tabla 1. *Correlation coefficients for the obtained formulations*

Case	Direction	Correlation coefficient
Wind	x	0,999976293
Frequent earthquake	x	0,999498325
Rare earthquake	x	0,999498325
Wind	y	0,999972253
Frequent earthquake	y	0,999863369
Rare earthquake	y	0,999863369

4. CONCLUSIONS

It should be remembered that the purpose of this research work is not to design any structure and therefore evaluate whether it will resist the earthquake or not, but only to estimate the possible displacements in the structure as a result of the action of the main environmental loads. By obtaining representative values of lateral displacements, it is possible to evaluate the effect on 5G networks in Chile.

Regarding the formulations, although the end user can opt for the most appropriate one to estimate how the displacement affects the operation of the 5G antennas, the general guidelines for the three independently evaluated cases in each direction and for a use in the same direction are explained below. For a daily use level, displacements close to those estimated with formulations (2) and (5) and corresponding to those induced by the effect of wind should be considered, but since Chile is not particularly subject to high winds, the wind-induced displacement values are low and it is unlikely that they will significantly influence the signal of the antennas.

As for the formulations (3) and (6), corresponding to a frequent earthquake, the displacement values become much higher than the ones mentioned earlier, and since Chile is a remarkably seismic country, the antennas should be able to support them without the need for arrangements or recalibrations, although with possible signal loss or reduction until shortly after the end of the earthquake. Finally, the formulations (4) and (7) corresponding to a rare earthquake imply major displacements, caused by an earthquake with a longer return period. These displacements should therefore be considered as displacements that could cause problems or failures in some antennas. It should however always be possible to repair the antennas so that they can be operational again as quickly as possible, thus avoiding spending too much time and money.

In addition, it should be considered that, in the most critical case, the maximum displacement could be twice as the one estimated by the formulations: as a matter of fact, since the displacements of each building have their own particularities, a situation may occur in which two buildings with antennas move with a lag in such a way that, at the point of maximum distance between the buildings, the distance between their antennas reaches a maximum of approximately twice the distance estimated by the formulations, causing signal loss.

Regarding the range of usefulness of the formulations, these are relevant for reinforced concrete buildings, built using shear walls (the most used typology in Chile) and with a maximum height of 40 m. For greater heights, it is advisable to delve into the methodology used or perform special studies. Besides, one of the prospects for the future would be to continue with this methodology, including the evaluation of more buildings in more extreme areas of the country, to strengthen the results and increase the amount of displacements used in the final estimation curves. However, the purpose of the proposed formulations should always be kept in mind, that is, the incorporation of variables that are not readily available to users for the estimation of displacements should be avoided.

On the other hand, as evidenced in Table 1, the adjustment of the curves is acceptable, so the estimates given are quite reliable considering the aforementioned limitations. But it should not be forgotten that these are still estimates, the obtained values should therefore only be considered to have an idea of the magnitude of displacements that can be expected. Finally, it is expected that these formulations will facilitate the work and installation of 5G antennas.

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