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Modal analysis of the 63 Square Building in Seoul, South Korea and its impact of subsidence and soil-structure interactions (SSI)

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Abstract. We conduct vibration analyses of 63 Building in Seoul, South Korea, using modal analysis and finite element modeling. The building is modeled as a solid structure having the shape of the real structure and with total weight and stiffness consistent with those of the real building. To better understand the fundamental periods of vibration of this structure and the associated mode shapes, we also consider structures with simplified geometry and perform modal analyses of them.

Keywords. frequency, modal analysis, mode shape, period, vibration

1. Introduction

The 63 Building, officially called the 63 SQUARE, is an iconic skyscraper on Yeouido Island, Seoul, South Korea. The name originates from its total of 63 floors–60 above-ground floors and three basement levels–with a total height of 249.6 meters. Constructed in 1985, it was one of the landmark buildings for the 1988 Summer Olympics and became a part of the identity for South Korea's rapid growth and modernization, the era of "Miracle on the Han River." At the time of its completion, it was the tallest building outside North America. The building's distinctive golden reflective glass exterior creates an imagery of the sun rising over the Han River, establishing it as an iconic structure in the Seoul skyline. The 63 Building still stands as a landmark of South Korea, known for its public accessibility and cultural icon.

This research investigates the resonance phenomenon in tall buildings, especially the relationship between the natural frequency and its vibrational response. In skyscrapers, when the natural frequencies of the structure match with those of external forces such as wind or earthquake, resonance occurs, leading to amplified oscillations and causing harmful structural damage. Thus, understanding these dynamics is crucial for both the safety and the design of the building, preventing resonance-induced failures. There have been numerous studies that focused on skyscraper vibrations; however, few have focused specifically on buildings in the region of East Asia where earthquakes frequently occur. This study focuses on filling this gap by conducting a comprehensive modal analysis of the 63 Building–a symbolic building in South Korea– using ANSYS software and the finite element method. Our main objective is to match the building's natural frequencies with the actual building; therefore, we could get accurate mode shapes in response to external loads. Additionally, the analysis with simplified geometric models, including a slender column, an H-shaped structure, and a table structure, will provide comparative data. This analysis provides a deeper understanding of the building's dynamic response to dynamic loads and offers insights broadly applicable to the design and analysis of other high-rise structures.

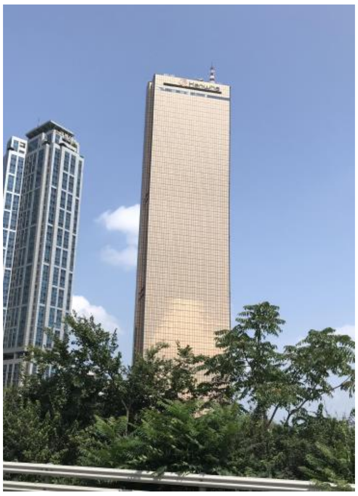

Fig. 1. Hanwha 63 Building viewed from Highway 88 in Seoul, South Korea.

2. Method of analysis

In this study, the method of analysis involved the use of the student version of Ansys[2], a comprehensive engineering simulation software, to model and analyze the frequency response of four distinct structural configurations: a slender column with a square cross-section, an H-structure, a table structure, and a structure similar to 63 Building. Many industries, including high-tech, aerospace and defense, automotive, energy, industrial equipment, materials and chemicals, consumer products, healthcare, and construction, use this engineering simulation software and services.

Using Ansys, we managed to create precise geometric models of each structure to reflect their physical dimensions and material properties accurately. The graphic properties were set as the controlled variable, with stiffness behavior designated as flexible. The coordinate system was set to the Default Coordinate System, and the reference temperature was established at room temperature (25℃). For our static structural analysis (AS), “Fixed Support” and “Force” were applied. The fixed support was added to the bottom of the models to simulate how the earth’s gravity acts on structures, ensuring that the base remains stationary while other forces are applied.

To describe the fixed support mathematically, consider the support conditions at the bottom of the structures. The boundary conditions can be expressed as:

$$\boldsymbol{u}(\boldsymbol{x},\boldsymbol{t}) = \boldsymbol{0} \text{ for } x \in \Gamma_{fixed} \text{ , (1)}$$

where $\boldsymbol{u}(\boldsymbol{x},\boldsymbol{t})$ represents the displacement vector at position x at time $\boldsymbol{t}$, and Γ_{fixed} denotes the region where the fixed support is applied. This condition ensures that the displacement at the base of the structures is zero, effectively anchoring them in place.

The force application can be expressed as:

$$\boldsymbol{F}_{\boldsymbol{applied}} = \mathbf{200}\boldsymbol{i}, \ (2)$$

where $\boldsymbol{F}_{\boldsymbol{applied}}$ is the applied force vector and $\boldsymbol{i}$ is the unit vector in the direction of the force (left to right). The resulting swaying motion can be analyzed to determine the natural frequencies of the structure.

To analyze the natural frequencies, we solve the eigenvalue problem for the dynamic system:

$$(\mathrm{K}-\omega^2\mathrm{M})\varphi = 0, \ (3)$$

where K is the stiffness matrix, M is the mass matrix, ω represents the natural angular frequencies, and φ denotes the mode shapes.

By incorporating these boundary conditions and forces into our Ansys models, we could simulate the realistic physical behavior of the structures under various loading conditions, providing insights into their frequency response and dynamic characteristics. The force was applied to the left surface of the model to induce swaying motion, allowing us to observe the natural frequency of the building at different modes. Specifically, a force of 200 N was applied. This setup helps us understand the dynamic behavior and resonant frequencies of the structures under lateral loads.

3. Modal analysis of generic structures

3.1. Slender column structure

We modeled a simple slender column structure to investigate the effect of mesh size on the dynamic response of this structure. The structure modeled in this analysis is based on the type of buildings mostly present in New York City, USA, characterized by the slender and tall figure of the towers. The ratio of the column structure was set to 1:1:20 (W:L:H), creating a similar silhouette to real life pencil towers. With the software Ansys, we prescribed a Young's modulus of $E = 200GPa$, Poisson's ratio of $v = 0.3$, and mass density of $\rho = 7.85\mathrm{M}g/m^3$, which correspond to the properties of steel. We modeled the structure with 3, 5, and 10 hexahedral elements arranged in a vertical column. Table 1 shows that for Mode #1, all three models show a natural frequency of approximately 2 Hz. However, the natural frequencies decrease as the mesh is refined. The same trend is true with the other modes. These results clearly show that with more elements, the structure exhibits a more flexible response. This is because the model is able to capture the smooth deformed shape of the structure more accurately as more elements are used. Table 2 shows the modes generated by the slender column structure with 10 elements, while Figure 2 shows the shapes of the first three sway mode.

Table 1. Comparison of frequencies (in Hz) generated in a slender column structure. Note that the natural frequencies decrease as the number of elements increases.

Mode #	3 elements	5 elements	10 elements
1	2.139	2.088	2.060
2	14.798	13.269	12.803
3	39.132	38.303	35.426
4	53.510	39.130	39.129
5	63.863	63.547	63.336

Table 2. Modes generated by the slender column structure with 10 hexahedral elements.

Mode #	Frequency (Hz)	Style
1	2.14	Sidesway
2	14.80	Sidesway
3	39.13	Torsion
4	53.51	Sidesway
5	63.86	Sidesway

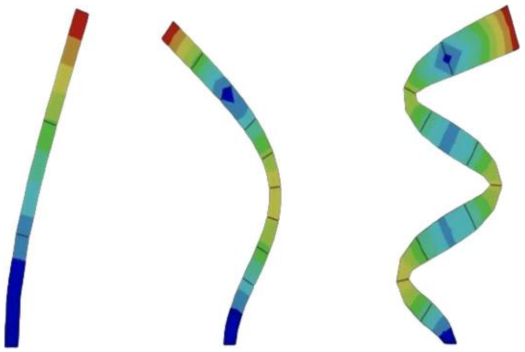

Fig. 2. First three sway modes of the slender column structure.

3.2. H-shaped structure

In this study, the method of analysis involved the use of Ansys, a comprehensive engineering simulation software, to model and analyze the frequency response of three distinct structural configurations: a long rectangular prism, an H-structure, and a table structure. Many industries, including high-tech, aerospace and defense, automotive, energy, industrial equipment, materials and chemicals, consumer products, healthcare, and construction, use Ansys engineering simulation software and services.

The mode shapes provide insight into the deformation patterns. Mode 1, with a frequency of 5756 Hz, exhibits a front-to-back sway, while Mode 2, at 8201 Hz, shows a left-to-right sway. Mode 3, with a frequency of 8263 Hz, involves uniform twisting. These initial modes represent relatively simpler and less stiff deformations compared to the higher modes. The drastic frequency jump from Mode 3 to Mode 4, which rises sharply to 20466 Hz, is particularly noteworthy as shown in Table 3. Figure 3 shows the fourth and fifth modes of the structure.

The drastic frequency change from Mode 3 (8262.7 Hz) to Mode 4 (20466 Hz) in the H-shaped structure can be attributed to the differing behaviors of the middle structure connecting the two prisms. In Mode 3, the middle section likely engages in uniform twisting, a relatively less stiff deformation mode. In other words, the middle prism structure would change from being contracted to being relaxed resulting in a lower natural frequency. However, in Mode 4, the middle structure, along with the prisms, undergoes symmetrical sway. This sway involves more significant bending and shear forces through the middle section, effectively increasing the overall stiffness of the structure. The higher stiffness associated with this deformation mode leads to a much higher natural frequency as there are very high tension between one side to another when only thinking about how the middle prism structure would react. Thus, this explains the substantial jump between Modes 3 and 4. This behavior highlights the critical role of the middle structure's interaction in determining the dynamic response of the entire system. Based on this finding, it could be confidently said that a structure's style being a "uniform" and another being "symmetrical" gives out very different results for the Frequency (Hz) of a certain building.

Table 3. Modes generated by the H-shaped structure.

Mode #	Frequency (Hz)	Style
1	5756	Front-to-back sway
2	8201	Left-to-right sway
3	8263	Uniform twisting
4	20466	Symmetrical sway
5	27348	Symmetrical twisting

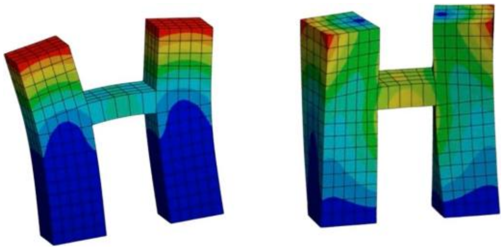

Fig. 3. Modes 4 (left, symmetrical sway) and 5 (right, symmetrical twisting) of the H-shaped structure.

3.3. *Frame structure*

Using Ansys, we made a table structure to analyze the effect of different materials on its dynamic response. To validate our method, we first began with a simplified 2D model. Then, we developed a 3D frame structure consisting of a flat square frame supported by four legs using structural steel. We used this model for our base model for the following comparisons. To investigate the effects of material variation, making the structure asymmetric, we changed the material of only one of the legs while keeping the other three legs consistent. We tested three different materials: silicon, wood, and stainless steel. Each structure had the exact same condition except for the material.

The static structural analysis showed some differences in the response of the table. While the models with silicon, stainless steel, and structural steel revealed similar dynamic results, the wood model showed a significantly large region of high stress. This suggests that wood, due to its low stiffness, leads to larger deformation under the same load conditions. Furthermore, we con- ducted a modal analysis on the basic structural steel model. We determined the natural frequencies and the corresponding mode shapes of the structure. The analysis gave us the modes and natural frequencies shown in Table 4 and Figure 4.

Table 4. Modes generated by the frame structure.

Mode #	Frequency (Hz)	Style
1	7340	Sway in the long direction
2	7667	Sway in the short direction
3	9847	Diagonal stretching
4	10021	Twisting mode
5	11885	Long-beam bending

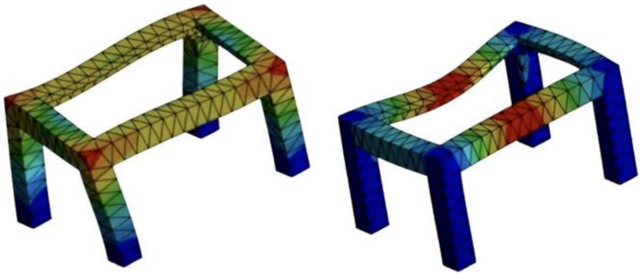

Fig. 4. Modes 4 (left, twisting) and 5 (right, long-beam bending) of the frame

4. Modal analysis of Hanwha 63 Building

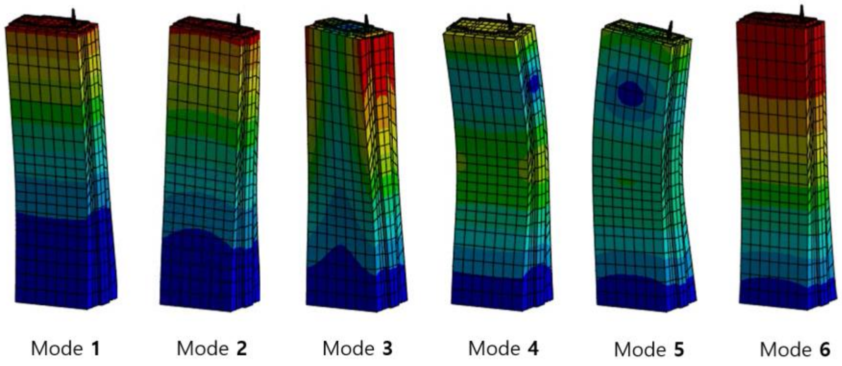

Fig. 5. Six modes of the Hanwha 63 Building structure

Table 5. Natural frequencies for the 63 Building.

Mode #	Frequency (Hz)
1	0.1837
2	0.3049
3	0.8045
4	0.9016
5	1.3777
6	1.6193

The Hanwha 63 Building modal analysis of the mode shapes and natural frequencies are shown in Table 5, Figure 5, and Figure 6. The mode shapes of the structure reveal distinct deformation patterns and associated natural frequency characteristics. Starting with a front-back sway in Mode 1, the building proceeds into a left-right sway in Mode 2, a uniform twisting in Mode 3, a front-back and a left-right bending in Mode 4 and 5, and demonstrates a vertical stretch and contract motion in Mode 6.

While the transition from Mode 1 to Mode 2 shows a moderate frequency increase of 0.12121 Hz, reflecting a change in sway direction but with similar stiffness patterns, a more pronounced frequency leap occurs between Mode 2 and Mode 3, where the frequency jumps from 0.30491 Hz to 0.8045 Hz (a leap of 0.49959 Hz). This significant leap corresponds to the shift from simple sway movement to twisting deformation. The twisting mode introduces greater structural stiffness due to the complex interaction of forces, which explains the higher frequency.

The frequency change from Mode 3 to Mode 4 (a leap of 0.09718 Hz) indicates a shift from twisting to a front-back bending in the middle section of the structure. Although this transition involves a more complex deformation pattern, the frequency increase is relatively negligible, suggesting that the stiffness change from twisting to bending is moderate.

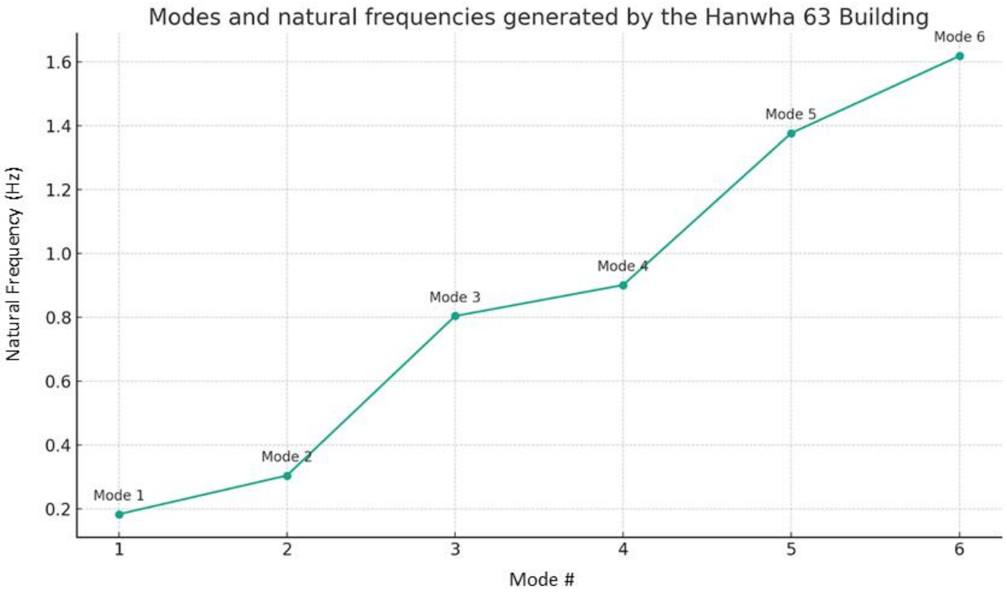

Fig. 6. Modes and natural frequencies generated by the Hanwha 63 Building

A notable increase is observed between Mode 4 and Mode 5, where the frequency rises from 0.90168 to 1.3777 Hz, a leap of 0.47602 Hz. This jump is due to the transition from front-back bending to left-right bending in the middle, a mode that involves greater structural resistance and hence results in a higher frequency. In a rectangular structure that is longer along the left-right axis like Hanwha 63 Building, the flexural rigidity or the resistance to bending will be different along the two axes. The longer dimension typically has a lower flexural rigidity and a smaller moment of inertia, making it easier to bend. Furthermore, front-back bending (Mode 4) involves a shorter moment arm and, consequently, less resistance to bending. When transitioning to left-right bending (Mode 5), the structure must resist deformation over a longer span, which requires significantly more stiffness. In left-right bending, the longer axis experiences higher bending moments and shear forces, also demanding a higher stiffness to maintain structural integrity. This higher stiffness is directly reflected in the higher natural frequency.

Finally, the frequency change from Mode 5 to Mode 6, from 1.3777 Hz to 1.6193 Hz (a leap of 0.2416 Hz), reflects a shift to up-down stretching. This increase in frequency indicates that stretching introduces additional stiffness compared to the bending modes, contributing to the overall rigidity of the structure. Axial stiffness is typically higher than flexural stiffness because materials generally resist changes in length (stretching or compression) more effectively than changes in shape (bending). During stretching, the entire cross-sectional area of the structure is engaged in resisting the deformation, utilizing the material’s full elastic potential. On the other hand, in bending modes, the stress distribution is non-uniform, with the highest stresses occurring at the outermost fibers of the cross-section and zero stress at the neutral axis. This non-uniform stress distribution results in lower stiffness compared to axial stretching that involves uniform stress distribution across the entire cross-sectional area.

The most significant frequency leap observed overall is between Mode 2 and Mode 3, highlighting the substantial difference in stiffness associated with twisting compared to simple sway modes. The leap observed when transitioning from front-back to left-right deformations highlights the more complex stress distributions and higher bending moments associated with the deformation along the longer axis of the rectangular structure. The aspect ratio and resulting flexural rigidity differences between the two directions play a crucial role in this dynamic behavior. This behavior underscores the critical role of deformation patterns in determining the dynamic response of the structure.

5. Impact of subsidence and soil-structure interactions (SSI)

As examined earlier, the dynamic response of the 63 Building to external forces such as strong winds and earthquakes highly depends on its natural frequencies. Accurate prediction of these responses, however, necessitates a comprehensive consideration of ground subsidence and soil-structure interactions (SSI).

In the following section, the comparison was made with and without soil-structure interaction effects. The soil-structure combined model was composed of soil layer, primary limestone layer, sandstone layer, then secondary limestone layer. The 63 Building was inserted into the soil layer and the contact was set bonded. The soil-structure combined model is shown in Figure 7.

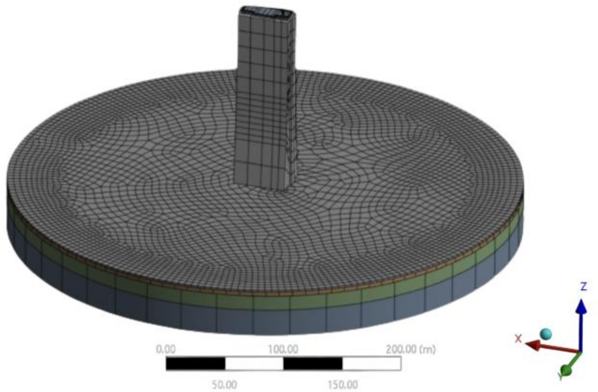

Fig. 7. Soil-structure combined model of 63 Building

In the last 7 years, Yeongdeungpo has reported over 10 subsidence hazards around the district where the 63 Building is located. According to the Ministry of Land, Infrastructure and Transport, these ground subsidence incidents have occurred due to factors such as sewer pipe damage, poor backfilling, and inadequate excavation work [1].

Ground subsidence, particularly when it leads to phenomena such as sinkholes and other ground deformations, can significantly alter the structural behavior of buildings. One of the most concerning effects is the potential for tilting of the structure shown in Figure 8. Tilting of structures can present serious safety issues, and thus, the Polish Building Regulations advises to avoid the construction of public and residential buildings where ground tilt may exceed 10 mm/m, due to the potential for structural instability [2].

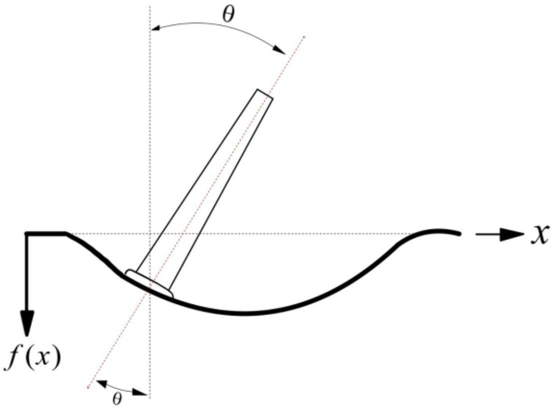

Fig. 8. Ground subsidence-induced tilting of tall buildings

Ground subsidence-induced tilting can alter the natural frequencies of a structure, thereby affecting its dynamic response. Similarly, for the 63 Building, any significant tilt resulting from subsidence could lead to changes in its natural frequencies, potentially exacerbating the building's response to dynamic loads. Such shifts in frequency could increase the likelihood of resonance with seismic or wind-induced forces, heightening the risk of structural damage. In this study, we managed to account for the potential impacts of subsidence by modeling a scenario in which the ground tilt reaches $10mm/m$.

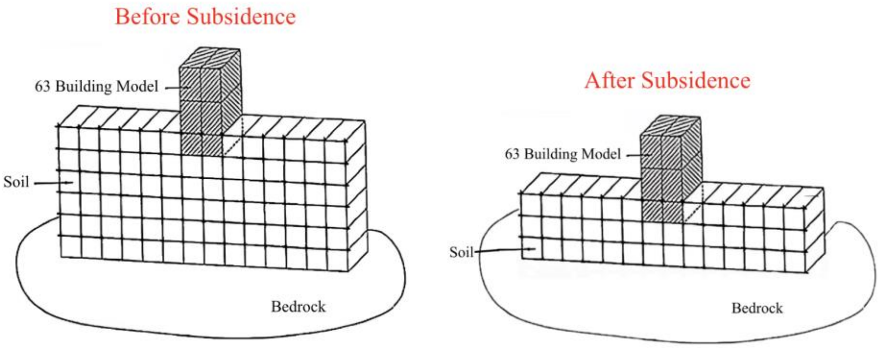

Fig. 9. Soil-structure interaction before and after subsidence [3]

In addition to tilting, ground subsidence, such as that caused by underground water extraction, alters dynamic soil properties, including shear wave velocity, shear modulus degradation, damping curves, and more critically, the thickness and shape of soil layers. As soil thickness decreases, the overall soil stiffness reduces, weakening the foundation's stiffness and consequently lowering the building's natural frequency. Figure 9 shows the common relationship between soil and building structure. When subsidence occurs, the soil thickness shrinks and only a few soil layers are left to support the structure. The resulting changes in natural frequencies will be examined through modeling of a 1 m soil thickness shrinkage scenario.

Table 6. Natural frequencies of the 63 Building with or without soil-structure interaction.

Mode #	Frequency, Hz		
	With soil	Tilting	Thickness shrinkage
1	0.156	0.137	0.144
2	0.272	0.285	0.258
3	0.709	0.754	0.672
4	0.893	0.848	0.885
5	1.311	1.499	1.281
6	1.604	1.586	1.577

Table 6 describes the changes in the natural frequencies due to 1) subsidence-induced tilting and 2) subsidence-induced soil thickness shrinkage modeling.

1) For the tilting case, the frequency changes were rather random and unpredictable. For modes that involve torsional deformations such as Mode 5, natural frequencies displayed significant changes. The tilting caused asymmetric loads on the building, increasing the instability when being exposed to external dynamic forces. Mode 2 and 5 particularly experienced the most significant change potentially due to the alignment of the ground tilting direction and the deformation (sway and bending) motion.

2) For the thickness shrinkage scenario, in lower modes, the thickness shrinkage resulted in significantly lower natural frequencies compared to the model without ground deformation. Natural frequency reductions were particularly evident in low-order modes, where the building’s fundamental vibration characteristics are most affected. This can be explained by the fact that as soil thickness decreases, the overall soil stiffness reduces, weakening the foundation's stiffness and consequently lowering the building's natural frequency. As the mode number increased, the frequency drops were observed but were negligibly small.

In conclusion, the findings from this study underscore the significant impact of ground subsidence on the natural frequencies of the 63 Building. While subsidence-induced tilting resulted in unpredictable frequency changes dependent on the mode type, soil thickness shrinkage resulted in notable reductions in natural frequencies, particularly in lower modes, where the building's fundamental vibration characteristics are most vulnerable. These changes increase the building's susceptibility to dynamic forces, such as earthquakes and strong winds, potentially leading to structural damage. Therefore, accurately modeling subsidence and soil-structure interaction is essential for ensuring the building's safety and integrity.

Fig. 10. Solid model for Hanwha 63 Building.

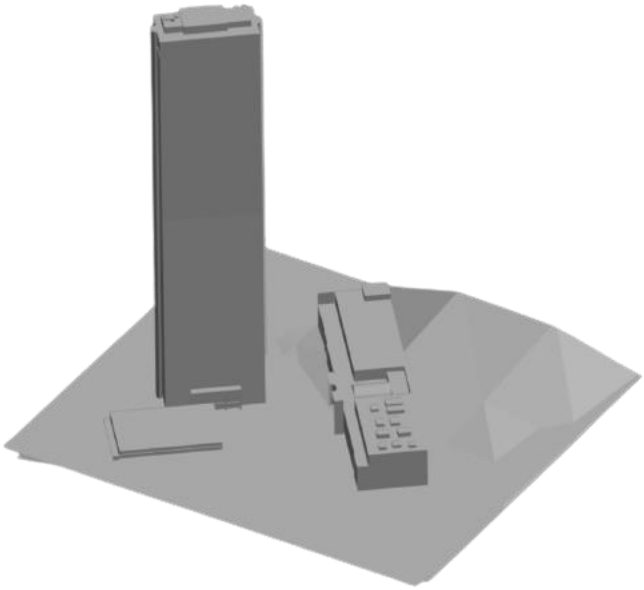

Fig 11. Full STL file model of the 63 Square Building

6. Conclusions

The natural frequency of a structure depends on the shape of the structure and the properties of the material comprising the structure (elastic modulus and mass density). The more slender the structure, the lower the natural frequency, the higher the period. The natural frequency also varies proportionally with the elastic modulus and inversely with the mass.

Credit

William Hong created the model for the H-shaped structure, ran the simulations, and wrote Sections 2, Sections 4, Sections 5, Sections 3.1; Minjung Kang created the model for the frame structure, analyzed the structure similar to 63 Building, and wrote Sections 1, Sections 3.3; Jay Lee developed the model for the slender column structure, ran the simulations, and wrote Sections 1 and 3.1; Sunmin Na created the model for the structure similar to 63 Building.

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