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# Design Considerations for Concrete High-Rise Buildings

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**Abstract**

Busan's Haeundae Resort project, which is currently being constructed by POSCO E&C, comprises the 101-story Landmark Tower and two 85-story residential towers. Presently, foundation and basement construction is complete, with a final completion date set for 2019. Considerations about the construction and design of the three reinforced concrete high-rise buildings will be discussed in this paper.

**Keywords:** Tall building, Fire resistance of high-strength concrete, Belt wall, Ground reinforcement

## 1. Introduction

Busan Haeundae Resort Project, which is designed by Samoo Architects & Engineers; Skidmore, Owings & Merrill LLP, is comprised of the 101-story Landmark Tower, at 411 meters, and two 85-story residential towers, each of 326 meters tall. Landmark tower which structural system is designed by Chunglim is composed of three belt walls and outriggers to resist lateral load. Furthermore, the 85 stories residential towers, which structural system is designed by Dong Yang, also have three belt wall and two outriggers with fin and buttress wall. Those structural systems will enhance their robustness to resist high wind load in Busan.

These buildings are the tallest reinforced concrete structures in Korea which means there are many challenges to design and construct the buildings. In consideration of this, the following strategies are needed:

- Strategy for reinforced concrete belt wall
- Strategy for ground reinforcement for the foundation
- Strategy for seismic performance evaluation through nonlinear analysis

The three points mentioned above are the most important challenges of this project, as regards structural analysis and construction, each of which needed to be duly considered to carry out the project successfully.

## 2. Challenges

### 2.1. Reinforcement Concrete Belt Wall

Landmark Tower and the residential towers use a reinforced concrete belt-wall, and this belt-wall is of great value for ensuring stiffness in the high-rise buildings. Reinforced concrete belt-walls have greater stiffness than steel belt-walls. However, unlike steel belt walls, it is difficult to install adjustment joints in reinforced concrete belt-walls. Therefore, initial stress needs to be considered during construction, and the structural designer needs to provide details for a delay joint and the construction process to the builder. Failure to do this can result in early fracture of the belt-wall due to additional stress caused by

**Figure 1.** Bird-eye view of Haeeundae resort.

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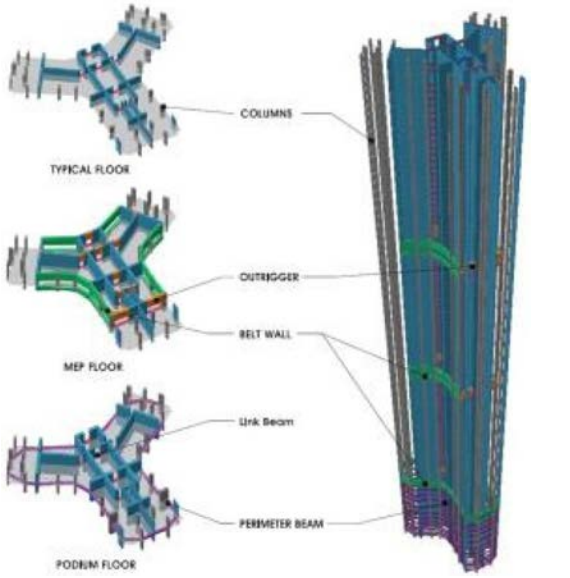



**Figure 2.** Residential tower structural system.

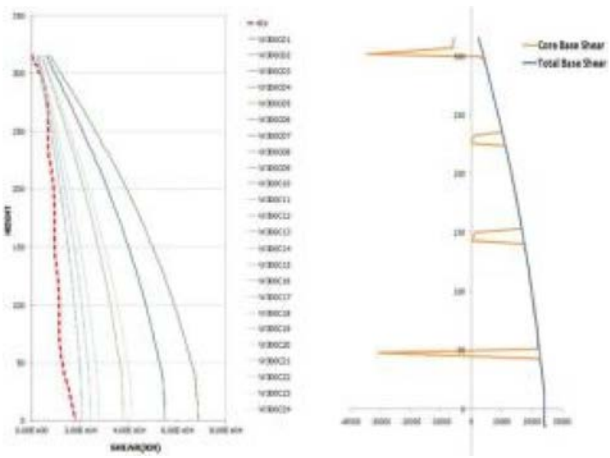



**Figure 3.** Base shear comparison.

unbalanced displacement. In Landmark Tower and the residential towers, since members that have large relative stiffness like fin walls or buttress walls are connected to the belt-wall, differential shortening is expected, as seen in the Fig. 4.

In this case, additional stresses occur, as seen in Fig. 5 which shows moment proportions derived from dead load. Therefore, while constructing belt-walls, a consideration of construction time of belt-walls and fastening time of delay joints, which come from the column shortening analysis, is applied.

### 2.2. Foundation strategy

Despite the fact that this project is located above bedrock, some parts had to be reinforced, according to the

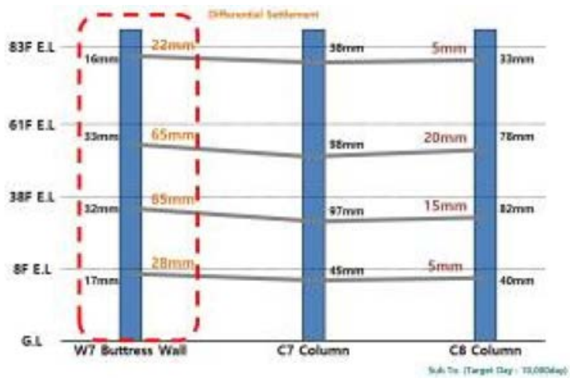



**Figure 4.** Column shortening prediction.

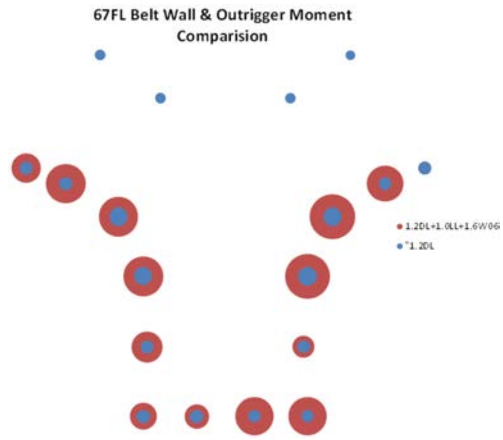



**Figure 5.** Belt wall moment comparison.

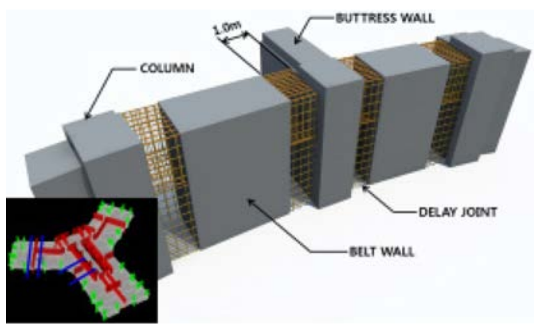



**Figure 6.** Delay joint of tower belt wall.

results of excavation, because parts of the ground were not strong enough to support a high-rise building. While the ground of both Landmark Tower and the two residential towers was replaced by placement mass concrete, some sections for Tower B had to be reinforced by installing the Disconnected Pile, on account of the depth of the replaced section. To evaluate replacement and reinforcement of soil, analysis modeling is progressed down to 100 meters below the foundation. The analysis reflected the bedrock level of drilling positions and drilling results. Also, RCD pile and replaced mass concrete was applied in the structural analysis. According to the results of analysis, in case of the residential towers, 29 mm was the maximum displacement to occur, and allowable soil bearing capacities of the residential towers and Landmark Tower were evaluated as 3,000 kN/m$^2$ and 3,500 kN/m$^2$. Especially, in the case of Tower B, comparisons were made between before and after ground reinforcing, and the comparison of displacement in case of whether pile was installed or not is shown in Fig. 7. The results of ground settlement analysis, showed the maximum settlement after ground improvement to be about 25 mm, and the maximum differential settlement is 1/1800, which is below the limit 1/500 and indicates safe behavior. The towers are currently under construction in the foundation placement and ground above construction phases, now that the ground bearing capacity tests for soil reinforcement has been completed.

### 2.3. Seismic Performance Review

As buildings and structures become higher, and with more complicated shapes, traditional design method based on a conservative lateral redundancy reduction coefficient design are limited for analyzing complicated structural systems. Therefore, a test was conducted to evaluate the seismic performance of building properly. For nonlinear time history analysis, the response spectrum was estimated by drawing a 5% damping response spectrum for each ground motion and applying the SRSS spectrum (square root of the sum of the squares spectrum) for each building period. To evaluate building performance, a total of seven seismic wave cases were selected, and building performance objectives were evaluated at "special" seismic grade, which is actually one seismic grade higher than the designed seismic performance. Also, each structure was evaluated for lifesaving and immediate occupancy level.

The seven seismic wave cases below were applied to for seismic performance evaluation of the building.

Each member's properties are similarly modeled by considering nonlinearity of material, which is different from elastic analysis. Especially, fiber element and inelastic shear material are applied to the properties of core wall and belt-wall.

The project building is located on the waterfront in Hae-

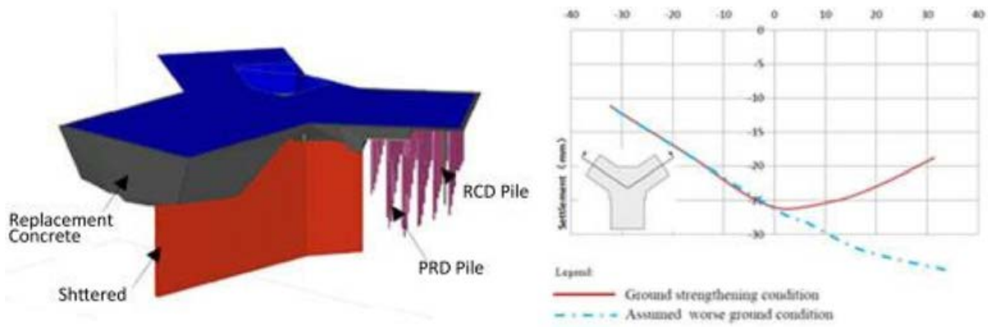
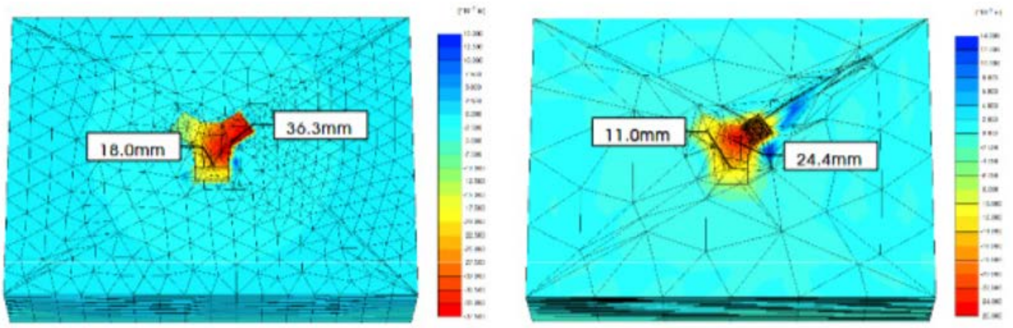



**Figure 7.** Analysis modeling of foundation and displacement of foundation.




- Maximum settlement before improvement: 36.3mm
- Maximum angle of deflection before improvement: approximately 1/1000 (δ/L=18.3mm/20m)

- Maximum settlement after improvement (concrete replacement): 24.4mm
- Maximum angle of deflection after improvement: approximately 1/1,500 (δ/L=14.4mm/20m)

**Figure 8.** Comparative analysis of ground analytical model.

**Figure 9.** Construction site under soil reinforcement.

**Table 1.** Seismic performance objectives

| Seismic Grade | Performance Objectives | |
|---|---|---|
| | Performance Standards | Degree of Seismic Damage |
| Special | Functional performance (or immediate occupancy) 1) | 1.0 times of design spectrum acceleration |
| | Life Safety | 1.5 times of design spectrum acceleration |
| I | Life Safety | 1.2 times of design spectrum acceleration |
| II | Life Safety | 1.0 times of design spectrum acceleration |

**Note:** Decided by purposed performance standard of user and designer.
According to 0306.3 Degrees of seismic damage in revised KBC2015.

**Table 2.** Time history data for seismic performance evaluation

| No. | Earthquake | Year | Station Name | Magnitude | Fault Type | Rrup (km) | Vs30 (m/sec) |
|---|---|---|---|---|---|---|---|
| 1 | Coalinga-01 | 1983 | Slack Canyon | 6.36 | Reverse | 27.46 | 648.09 |
| 2 | Coalinga-01 | 1983 | Parkfield - Fault Zone 16 | 6.36 | Reverse | 27.67 | 384.26 |
| 3 | Parkfield-02_ CA | 2004 | Hog Canyon | 6 | Strike Slip | 5.28 | 376 |
| 4 | Chi-Chi_ Taiwan-03 | 1999 | TCU116 | 6.2 | Reverse | 22 | 493 |
| 5 | Chi-Chi_ Taiwan-06 | 1999 | CHY028 | 6.3 | Reverse | 34 | 543 |
| 6 | San Fernando | 1971 | Lake Hughes #1 | 6.61 | Reverse | 27.4 | 425.34 |
| 7 | Mammoth Lakes-10 | 1983 | Convict Creek | 5.34 | Strike Slip | 6.5 | 382.12 |

undae District (in the city of Busan on Korea's southern coast) and is affected by wind load. The wind load in KBC2009 which is factored load, has a return period of more than 6000 years, and Busan is an area which has the highest wind load in the country. Also, because of the characteristics of high-rise buildings, Landmark Tower and the residential towers have long-period properties of 9.13 s and 7.46 s. Therefore, the wind load effect which influences the building is about 2 to 2.5 times the effect of seismic load. The project building, however, was evaluated using nonlinear analysis software Perform 3D for accurate performance evaluation of earthquake. Model of the building includes nonlinear properties of materials, nonlinear force-deformation behavior of elements that are part of seismic force resisting system, and acceptance criteria for deformations (plastic rotations, drifts, strains, etc.) based on ASCE 41-13. Seven pairs of time history data, recorded during reference earthquakes and adjusted for this project, were used.

### *2.3.1. Shear walls*

*2.3.1.1. Plastic rotation of walls*

- Plastic hinge rotation in all the wall piers satisfy acceptance criteria for life safety (LS) specified in ASCE 41-13, Table 10-19. At the belt wall level and two levels below and above it, some of the walls experience plastic hinge

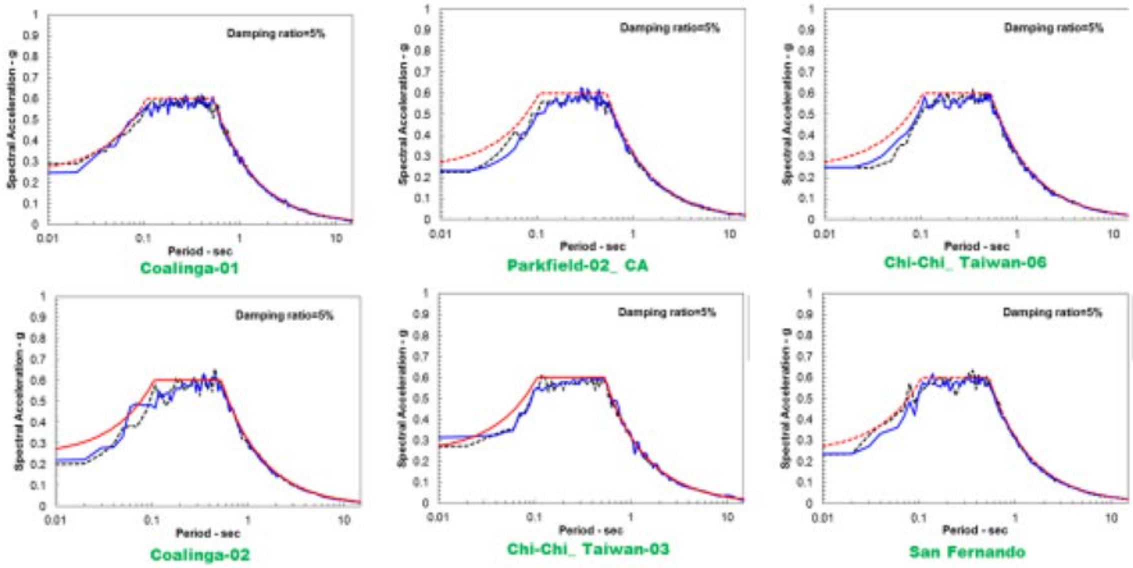



**Figure 10.** Time history data.

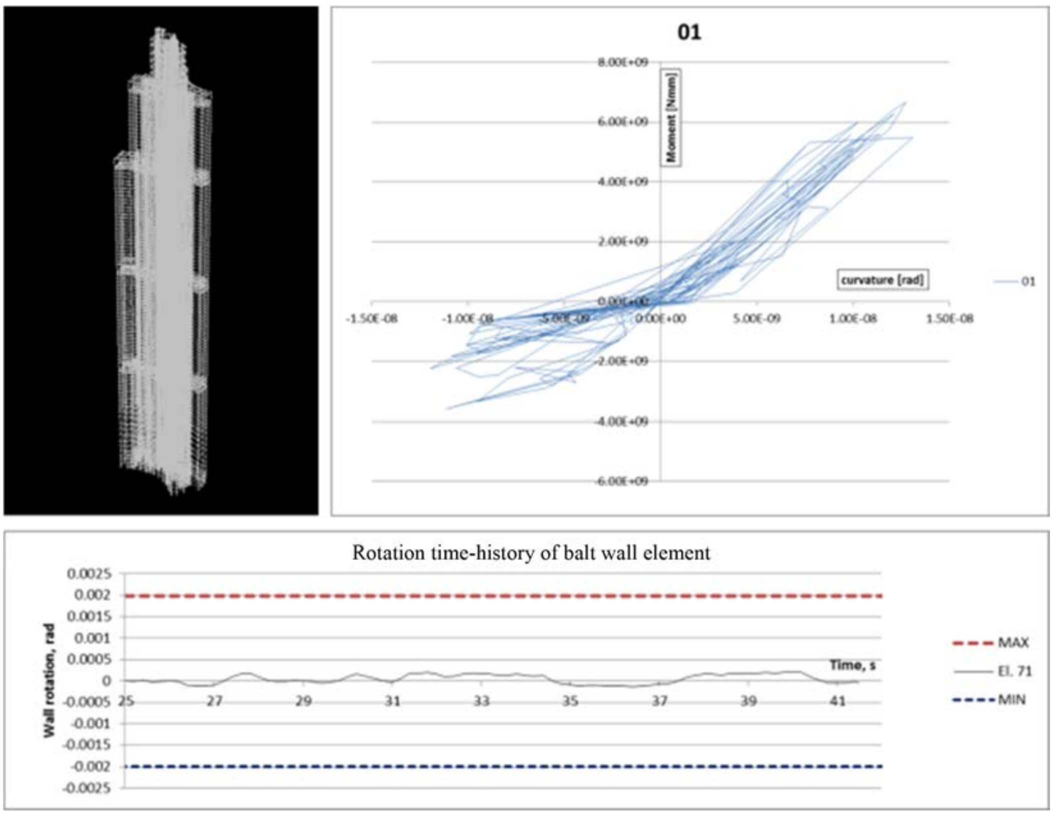



**Figure 11.** Nonlinear analysis model an result of belt-wall.

rotation between 0.3 and 0.5 of acceptable values. On the other levels plastic hinge rotation is below 0.3 of limit value.

- Two wall elements of crown level (floor 85F PIT) experience plastic rotation higher than acceptable. Those walls are not part of the seismic force resisting system and they are supported on the transfer beam.

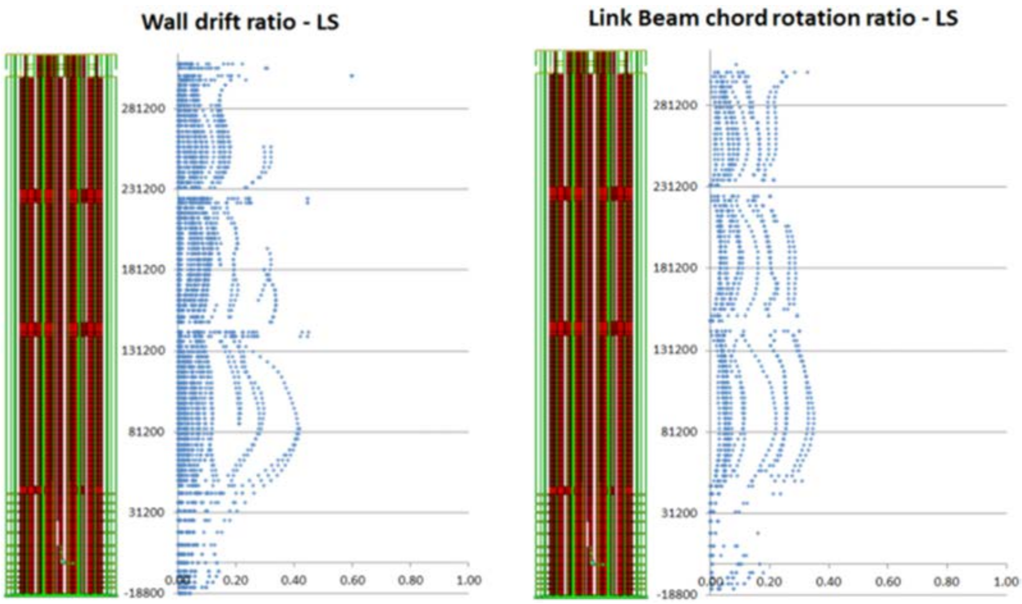



**Figure 12.** Nonlinear analysis model an result of wall drift & link beam.

*2.3.1.2. Total drift ratio*

- Acceptance criteria for total drift of the wall are specified in ASCE 41-13, Table 10-20. The maximum usage ratio for wall drift in shear walls is below 0.5.

***2.3.2. Coupling beams***

*2.3.2.1. Plastic hinge rotation*

- Plastic hinges were defined in both ends of coupling beams. Measured value of plastic hinge rotations does not exceed 0.3 of limit value defined in Table 10-19 of ASCE 41-13.

*2.3.2.2. Chord rotation*

- Chord rotation of coupling beam is connected with drift of shear walls. The limit values are defined in Table 10-20 of ASCE 41-13. Several beams in the model experience chord drifts between 0.3 and 0.4 of limit value.

***2.3.3. Belt walls***

- Belt walls work like deep beams, so the source of nonlinearity is likely to be the horizontal axial-bending and/or in-plane shear. General wall element with fibers in two perpendiculars was used together with inelastic shear material.

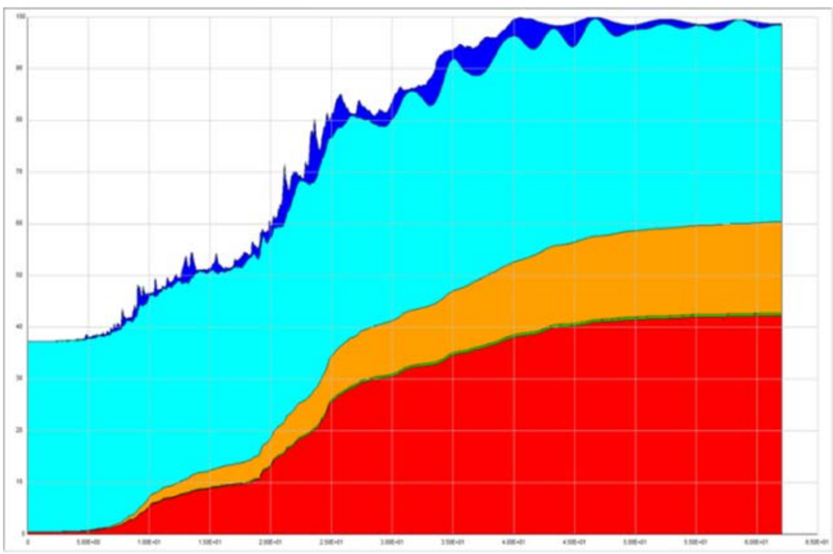


**Figure 13.** Energy balance for structure.

**Figure 14.** Construction site view.

Based on preliminary analysis, the building is capable of resisting strong earthquake with Life Safety performance level. Nonlinear behavior is observed in several elements, but acceptance criteria are not exceeded. The exception is two wall piers at crown level, where damage due to plastic hinge rotation may happen. However, as those walls are not part of seismic force resisting system and their pure role is to withstand gravity loads, the overall behavior of the building is not influenced by their failure. Design of those elements should be revised to provide higher value of flexural stiffness.

## 3. Conclusion

Haeundae Resort Project, which is being constructed with reinforced concrete, is the tallest high-rise building of its kind in Korea, and therefore a great deal of effort is needed to carry out the project successfully. There are many considerations like mass concrete placement for foundation placement, concrete placement considering spalling and other things. However, for the sake of brevity, belt-wall design method, soil reinforcement method and seismic performance evaluation method were chosen as representative examples for discussion in this paper. At this time, soil reinforcement and the lower stories of the buildings are completed, and construction is progressing with a final completion date set for 2019.

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