Development of a risk assessment model against disasters in high-rise buildings and results of a building simulation analysis

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ABSTRACT
This study developed a method to assess a building’s risk against disaster, tentatively named the Korean Integrated Disaster Evaluation Simulator (K-IDES). Based on previous studies analyzing FEMA’s risk management series in the US, the FEMA IRVS was selected as a case study for developing a framework for the K-IDES. Through the comparative analysis of domestic building design guides, codes, and special legislation related to disasters, a risk assessment methodology for quantitative results was developed. The assessment method consists of a classification system, a calculation for the quantification of risk, and a simulation in which the developed checklist for the K-IDES is applied to similar types of high-rise buildings to validate its accuracy. The final goal was to systemize an integrated risk management strategy for a building against disasters, checking for vulnerable areas from the conceptual stage of the design, and to utilize the risk management strategy after construction.

1. Introduction
1.1. Purpose and background
As of 2018, Korea ranks 11th in the world in the density of high-rise buildings (buildings more than 150 m in height), with approximately 400 such buildings (under construction or completed, based on The Council on Tall Buildings and Urban Habitat) (CTBUH). The concentration of multifunction buildings in urban areas and the continuous increase in the number of high-density and functionally complex high-rise buildings in older cities can become a threat in a disaster, specifically if buildings and property incur physical damage (Lee 2009, 2012). The 9/11 terrorist attack in New York City is a good example. In addition to the collapse of the World Trade Center (WTC), the damage also spread to the surrounding high-rise buildings, which amplified the consequences of the explosion. The facade structure was further damaged by collapsing debris, and fire caused more loss and destruction (FEMA 2007b).

To reduce risk and loss in the case of a disaster, studies have been conducted domestically to improve buildings’ performance against disasters by strengthening standards for material, equipment, and evacuation against fire, as well as reinforcing structural standards after seismic occurrences (Su, Yoon, and Ju 2012; KOSIS). However, most of these studies have focussed on partial improvements, where the buildings need to be evacuated in the event of an individual disaster. Studies on evaluation criteria, evaluation methods, and design guides for reinforcing buildings against various catastrophic disaster risks are insufficient (Kang et al. 2010; Kang, Park, and Lee 2011; Choi et al. 2012; Kang and Lee 2014; Kang et al. 2018, 2019). This study aims to construct a disaster risk assessment model (tentatively named the Korean Integrated Disaster Evaluation Simulator or K-IDES) for Korean high-rise buildings to fill this research gap (Kim and Lee 2018a, 2018b).

Preliminary studies have been conducted on the risk management series of US Federal Emergency Management Agency (FEMA) to guide risk management and quantitative risk analysis, with the goal of building a risk assessment system against various disasters (Kim and Lee 2018a, 2018b). Scenarios such as explosions, fire, earthquakes, and typhoons – all likely to occur in Korea – have been studied (KOSIS). The risk assessment method of the K-IDES was established by comparing and analyzing the evaluation methods derived from a case study on the FEMA and through the application of suitable parts to domestic building codes, guidelines, and legislation related to disaster management (Kim and Lee 2018a, 2018b). Based on previous studies, we derived criteria, evaluation items, and evaluation methods for assessing the risk of high-rise buildings against disasters and analyzed simulation results for an actual urban high-rise building in Korea by using the proposed method. The results suggest future research directions for improving the accuracy and utilization of evaluation models.
1.2. Scope and method

1.2.1. Analysis of precedent research
The concept of disaster risk assessment in buildings was established through the analysis of the contents of the design guide, risk assessment method, and reference manual for risk prevention of buildings against terrorism developed by the FEMA of the US Department of Homeland Security (FEMA 2005a, 2005b, 2007a, 2007b, 2009, 2011; FEM 2011). The specific method of evaluating risk against disaster in the development of the K-IDES was applied to evaluation criteria, evaluation quantification, and the analysis of the evaluation results based on FEMA’s integrated rapid visual screening (IRVS) for integrated risk assessment against various disasters (Kim and Lee 2018a).

1.2.2. Analysis of domestic building guides and evaluation criteria related to disasters
To develop evaluation criteria and evaluation items for domestic buildings, the High-Rise Building Design Guidelines of the Seoul Metropolitan Government; the Anti-Terrorism Building Design Guidelines in Multi-Purpose Facilities of the Ministry of Land, Infrastructure, and Transportation; the Special Act on Management of Disasters in Super High-Rise Buildings and Complex Buildings With Underground Connections, and the Preliminary Disaster Impact Assessment Consultation Guidelines of the Ministry of Public Safety and Security were analyzed, classified by item, and compared by content (Ministry of Government Legislation 2015; Ministry of Public Safety and Security 2014; Seoul Metropolitan Government 2009; Ministry of Land, Infrastructure and Transportation 2010, 2017). The results were then used to develop detailed evaluation criteria for the K-IDES (Kim and Lee 2018a).

1.2.3. Development of checklist for the K-IDES’ risk assessment
The first step was to check the classification system of the risk assessment field in the IRVS evaluation system and to review the differences in building codes and design guidelines regarding high-rise buildings’ protection against disaster between the two countries. The second step of assessment of the items’ category classification system was centered on the planning element of buildings, and details of each item reflecting domestic codes and design guidelines were prepared. Finally, the criteria that could be selected for each item was divided into five attribute options (Kim and Lee 2018b).

1.2.4. Establishment of a method to quantify the weight and risk by items
Risk quantification uses expert interviews to determine the assessment rate of environmental threats and a building’s physical vulnerability to disaster (Kang, Park, and Lee 2011; Choi et al. 2012; Kang and Lee 2014). The risk score is computed using the risk calculation method devised by FEMA (2011). The value chosen for each item is based on the isometric scale of five intervals and uses a uniform scale for each item, but they are differentiated by applying weighted values to the important items (Kang, Park, and Lee 2011; Choi et al. 2012; Kang and Lee 2014; Kim and Lee 2018b). The selection of weighted items and the determination of weights were based on prioritizing important items through group interviews with experts, and the weights of the selected items were determined using the frequency of item selection by the experts (Kim and Lee 2018b; Kang et al. 2018, 2019).

1.2.5. Simulation test and results analysis through the K-IDES and IRVS
To verify the evaluation model, nine high-rise buildings with completion dates of less than 10 years and a height of 100 m or more were selected from three cities: Seoul, Incheon, and Busan. Environmental indicators were simulated using FEMA IRVS and the K-IDES. Through the comparative analysis of their assessed risk results, the limitations of the IRVS were examined. By analyzing the risks by disaster through the K-IDES, the exposure of high-rise buildings in Korea to disaster and

Figure 1. The framework of the study.
major risk areas for reflecting design guidelines to prepare for disaster was identified.

This study confirms the evaluation method and evaluation items of the K-IDES based on two existing studies and presents the results of a simulation analysis on domestic buildings using the K-IDES, which was developed as part of a disaster risk assessment program.

2. Review of precedent research

2.1. Analysis of IRVS risk assessment

The IRVS, developed by the FEMA, refers to a quantifiable risk assessment of critical vulnerability in various types of buildings against a terrorist attack or natural disasters. Risk scoring involves calculating the individual risk for each disaster and integrating these individual risks. This risk quantification is accomplished by assessing each of the following-tiered categories: consequence, threat, and vulnerability (FEMA 2011; FEM 2011).

The consequence is the assessment of the degree of damage to a building (property) and the loss of the building’s operating system due to a disaster. The threat is the assessment of the degree of hazard for a natural disaster, social disaster, potential events, signs, and behavioral threat factors that lead to loss of assets, injury of individuals, or damage to organizations (FEMA 2011; FEM 2011). Lastly, vulnerability is the assessment of the vulnerable factors of the building that can cause damage to assets in the event of a disaster. Vulnerability is further divided into eight subcategories: site, architecture, envelope, structure, MEP, fire, security, and cybersecurity. Vulnerability assessment consists of evaluating the application level of a design guide to protect a building from disaster (FEMA 2005a, 2011). Risk scores by the disaster are calculated by multiplying the evaluated values of consequence, threat, and vulnerability to sum up the value by assessing each item in these categories. Disaster areas for buildings’ risk assessment and calculation formulas for the risk scoring in the IRVS are described in Table 1.

2.2. Limitations of IRVS application on domestic buildings

First, as the IRVS model is designed to cover all types of buildings, it is difficult to derive differential results when evaluating buildings with similar uses or characteristics. The error rate is especially high in the case of fire, security, and cybersecurity subcategories, as the evaluation items consist of qualitative analysis of buildings’ contents, and thus, a lot depends on the evaluator’s subjective choices (FEMA 2011). Furthermore, the response options of most evaluation items are limited to two, unlike other items that allow five or more selections, and thus, these evaluations reduce the sensitivity and accuracy of risk assessment (FEMA 2011). Regardless of the ratio of the number of evaluation items in consequences, threat, and vulnerability, the sum of the maximum values can be 10, and in the case of an explosion, there are 3 evaluation items each in consequences and threat, which leads to their weight being 25 times that of the 79 evaluation items in vulnerability. Therefore, the impact of the risk assessment factors on buildings’ planning is insignificant, making it difficult to find a link between disaster risk and planning elements.

Second, the error in the IRVS model is due to a change in the beta value of the individual risk calculation formula, which is caused by displacements in values below 0.9 and above 0.9. If the alpha value is above 0.9, the beta value is fixed at 3.0, but when the alpha value is close to 0.9, the beta value is closer to 5. When the beta value is close to 5, it changes from 5 to 3, and the risk score rapidly increases. For example, when $Cl = 8.9$, $Ti = 9$, $Vi = 10$ and $Cl = 9$, $Ti = 9$, $Vi = 10$, the beta value changes from 0.89 to 0.9 at a difference of 0.1 and the risk score dramatically rises from 3.82 to 9.32. There is no evidence of a sharp increase in the risk score due to the differences in displacement in these beta values, and this can be interpreted as an error. The functional relationship between the beta value and the alpha value that determines the beta value required to calculate the risk score is described in Figure 2.

Table 1. IRVS composition and risk assessment method against disasters.

| Categories | Blast | CBR | Fire | Seismic | Wind | Flood | Total sum | Remark |
|------------|-------|-----|------|---------|------|-------|-----------|--------|
| Consequence | 3* | 3* | 3* | 3* | 3* | 3* | 10 | 0 |
| Threats | 3* | 3* | 3* | 3* | 3* | 3* | 10 | 0 |
| Vulnerability | 79* | 63* | 48* | 69* | 71* | 51* | 10 | 0 |

Integrated risk calculation formula

\[ R = \sum \beta_i \]

Required values to analyze individual disaster scenarios

\[ R_i \]

\[ C_i \]

\[ T_i \]

\[ V_i \]

\[ \alpha_i = \min (C_i, T_i, V_i) \]

\[ \beta_i = \text{Beta value, } \beta_i \text{ value depends on value, if } \alpha_i \geq 0.9, \beta_i = 3.0, \text{ if } 0.1 < \alpha_i < 0.9, \text{ then } \beta_i = 3.875 + 1.25 \]

\[ n2 \] Total number of disaster scenarios

\[ R_1 \] Risk score of the disaster scenario

\[ \text{Aggregated risk} \]

\[ \text{Power value 10} \]

\[ \text{Scaling factor 1/12} \]
Figure 2. The functional relationship between the beta value and the alpha value.

Table 2. Analysis of checkpoints between the IRVS and domestic guidelines and codes and the K-IDES checkpoint plan.

| Categories | FEMA IRVS checkpoint review (Kim and Lee 2018a; FEMA 2011) | Domestic guidelines & codes checkpoint review (Ministry of Government Legislation 2015; Ministry of Public Safety and Security 2014; Seoul Metropolitan Government 2009; Ministry of Land, Infrastructure and Transportation 2010; Ministry of Land, Infrastructure and Transportation 2017) | K-IDES checkpoints by category (Kim and Lee 2018b) |
|------------|-------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|
| Environment | - Community loss after a disaster<br>- Cause potential harm, factors such as seismic occurrences, floods, and storm frequency | - Application of Special Acts and anti-terrorism design guide for designs with floor area over 20,000 m² or 50-floor building | - Building size selection for evaluation against disaster<br>- Environmental index<br>- Land type & population density<br>- Asset value |
| Site | - Vehicle-approaching distance around the site<br>- Perimeter boundary design for visibility and access control<br>- Underground and surrounding areas, structure for security | - Securing passage and space in site for fire fighting vehicle<br>- Site entrance gate and parking lot planning<br>- Plans for entry and exit of vehicles and pedestrians considering security | - Possibility of evaluation vehicles’ stopping and rush around the site<br>- Adequate space for fire-fighting vehicles inside the site<br>- Evaluation of vehicles’ and pedestrians’ access control and control measures<br>- Building volume and floor plan type<br>- Underground parking lot plan to minimizing damage from arson & blast<br>- Separation of major facilities from explosive hazard space |
| Architecture | - Building height, volume<br>- Floor plan type and interior space location<br>- Control of vehicle and pedestrian access<br>- Parking lot location plan | - Minimize damage from explosion, suggestion of building shape and interior space planning<br>- Space planning with circulation system to pass through certain checkpoints | - By distinguishing podiums, high-rise, and rooftop according to their functions, valuation of elevation type and performance<br>- Evaluation of structural system and structure type<br>- Evaluation of sub structure settlement inside and outside building<br>- Ensuring emergency power<br>- Separation of mechanical and electrical rooms from explosion hazard space<br>- Enhancing facility performance in emergency control room |
| Envelope | - Elevation irregularity<br>- Glass usage rate in envelope<br>- Roof form & slope | - Usage recommendation of glass and finishing materials considering scattered debris in low floors and lobby | |
| Structure | - Structure type, column spacing, number of occupants, support type | - Strengthening earthquake-resistant seismic design<br>- Ensuring adequacy of fire resistance structure | |
| Mechanical, electronic, and plumbing | - Check central equipment to reflect seismic-resistant design<br>- Strengthening pipe and duct performance against explosive and seismic event | - Air intake, location & return system, screening of machinery, electric facilities and plumbing resistant to blast, seismic shocks | |
| Fire and egress | - Fire protection system based on evaluation items reflecting government firefighting standards | - Firefighting facility compartment plan appropriateness<br>- Strengthening of ventilation performance and preventing expansion of combustion<br>- Evacuation safety zoning plan and design guideline | - Strengthening performance of firefighting system<br>- Evaluation of vertical and horizontal fire protection plan<br>- Safe zone and sunken space planning for enhancing evacuation performance |
| Security | - Security monitoring systems for internal and external bombs and biochemical terrorism and system efficiency | - Security monitoring plan and facility protection plan against emergency (e.g. fire, terrorist attack and natural hazards) | - Security monitoring and facility protection plan against emergency (e.g. CCTV installation and security guard arrangement) |
Lastly, the evaluation items with high weights for regional characteristics and environmental indicators of consequence and threat differ from the domestic high-density characteristics in urban areas in Korea and the frequency and intensity of earthquakes and typhoons in the country. As a result, the potential for direct application of the IRVS’s evaluation items to domestic cases is limited. Based on this study, the domestic risk assessment model for the differential comparison of high-rise buildings systemizes the criteria by reviewing assessment items of the IRVS and analyzing the domestic design guidelines and standards against disasters.

2.3. **K-IDES evaluation system development**

The composition of evaluation items for risk assessment for the K-IDES follows the IRVS risk assessment functions of consequence, threats, and vulnerability (FEMA 2011). However, as Korean design standards and environmental indicators of high-rise buildings contrast from the US, the evaluation item’s criteria of them are established. For example, the construction cost evaluation criteria for assessing asset value, environmental threat criteria to reflect Korean environmental indicators, and evacuation criteria to reflect Korean design standards are developed. To assess the risk factors and the analysis level of high-rise buildings against disaster, the vulnerability enables quantitative assessment by classifying the reviewed items through grouping the evaluation areas by function and purpose of the building based on the design guides and codes for disasters (Kim and Lee 2018b). Detailed evaluation items, in consequence, threat, and vulnerability are developed by a comparative analysis of evaluation criteria related to the IRVS’s design guidelines for high-rise buildings’ protection against disaster, guidelines for Preliminary Disaster Impact Assessment, terror prevention design guidelines, domestic fire prevention standards, Korean high-rise building codes, and design guidelines against disasters (Ministry of Government Legislation 2015; Ministry of Public Safety and Security 2014; Seoul Metropolitan Government 2009; Ministry of Land, Infrastructure and Transportation 2010, 2017). In this study, since the review target is high-rise buildings, and the design criteria for evacuation differ between the Korean and US building codes (IBC 2015), we newly establish an evacuation category in vulnerability (Kim and Lee 2018b).

3. **K-IDES risk assessment methodology**

3.1. **Quantification method**

The K-IDES’ risk assessment quantification applies the concepts of consequence, threat, and vulnerability and the formula for individual risk assessment and integrated risk assessment in the IRVS. If more than 0.9 of the beta values are generated by equalizing the maximum values of consequence, threats, and vulnerability in the IRVS, the K-IDES emphasizes analyzing the risk impact of each disaster on buildings’ vulnerability. The ratios of consequence, threats, and vulnerability were determined by limiting the average of the deviations through 15 interviews with experts (Kang et al. 2018). The maximum difference by adjusting the ratios of consequence, threats, and vulnerability was limited to the beta range from 0.1 to 0.9, and thus, the emergence of deviations that might occur in cases of values above 0.9 is prevented. Detailed design values related to consequence, threats, and vulnerability are provided in section 3.3.

3.2. **Hierarchy of evaluation categories**

To develop a checklist for evaluation, the classification of the first-level categories in the K-IDES follows the IRVS rating classification system, but detailed items and contents are derived through the analysis of domestic codes and design guidelines. In this checklist, the evaluation section related to the egress performance of new buildings that reflects the design guidelines related to evacuation zoning is different from those of the US, and the second- and third-level evaluation items were prepared by grouping buildings with similar functions. The purpose of this checklist for evaluation is to study the complementary possibility of reducing buildings’ vulnerability to disaster by reviewing the relationship between the items indicated as risk factors in the risk assessment and other items in the same group.

Among the second- and third-level evaluation items, the weighted items were selected as highly aggregated through interviews with 15 experts in each field, such as architectural design, rescue, firefighting, evacuation, MEP, and security. Using experts’ advice, factors that exert a severe impact on high-rise buildings were selected as weighted items. As a consequence, threats, and vulnerability, the K-IDES consists of 121 items, including 29 weighted items and relevant evaluation items on third-level evaluation items, which are screened based on disaster by considering their effects on buildings. Although we found differences in the distribution of subcategories for each disaster, this study interpreted each disaster as an equally independent individual scenario and did not correct for differences in the number of risk evaluation items among disasters. The detailed contents of third-level evaluation items of the K-IDES are described in Table 3.
| First level | Second level’s assessment category | Third level’s weighted items | B | F | S | W | T |
|-------------|-----------------------------------|-----------------------------|---|---|---|---|---|
| A. Consequence | A.1. Area characteristics | Surrounding building density and land type | 3 | 3 | 3 | 3 | 3 |
| | A.2. Operation recovery | n/a | 1 | 1 | 1 | 1 | 1 |
| | A.3. Asset value | n/a | 1 | 1 | 1 | 1 | 1 |
| B. Threats | B.1. Building’s functional characteristics | Resident population density | 4 | 4 | 1 | 1 | 4 |
| | B.2. Environmental indicators | Seismic frequency | 1 | 1 | 3 | 3 | 6 |
| C. Vulnerability | C.1. Road status around the site | Distance between vehicle and elevation | 3 | 0 | 0 | 0 | 3 |
| | C.1. Road status in the site | Space for entrance & activities of fire-fighting vehicles in an emergency | 4 | 4 | 4 | 0 | 4 |
| | C.1.3. Restriction and control of vehicles and people | Vehicle entrance & exit level by visiting purpose | 6 | 1 | 1 | 1 | 6 |
| | C.2. Building type | Height from ground | 5 | 2 | 6 | 6 | 6 |
| | C.2.1. Building type | Core placement type | 1 | 1 | 2 | 2 | 2 |
| | C.2.2. Floor plan type | Core placement type | 1 | 1 | 2 | 2 | 2 |
| | C.3. Internal space plan | Emergency exit plan's appropriateness | 4 | 4 | 1 | 1 | 4 |
| | C.3.1. Road plan | Major facilities' location & structure reinforcement degree | 3 | 2 | 0 | 0 | 3 |
| | C.3.4. Roof area configuration | Podium area glass specification | 3 | 0 | 0 | 0 | 3 |
| | C.3.5. Lifeboat | High level area glass specification | 0 | 3 | 3 | 3 | 3 |
| | C.3.6. Lifeboat | Connection between building exterior and main structure | 6 | 1 | 6 | 6 | 6 |
| | C.3.7. Lifeboat | Slope measurement up to bottom from pitch | 0 | 0 | 1 | 2 | 2 |
| | C.4. Road plan | Lateral force resistance ability | 3 | 2 | 2 | 3 | 3 |
| | C.4.1. Road plan | Vertical irregularity | 4 | 3 | 4 | 3 | 4 |
| | C.4.2. Road plan | Non-structural components in exterior | 6 | 6 | 4 | 3 | 6 |
| | C.4.4. Appendage structure type | n/a | 2 | 1 | 2 | 2 | 2 |
| | C.5. Major component plan | Machine room proximity to high-risk area | 3 | 2 | 3 | 0 | 5 |
| | C.5.1. Major component plan | System seismic design applicability | 4 | 0 | 4 | 1 | 4 |
| | C.5.3. Duct plan | n/a | 1 | 0 | 1 | 0 | 1 |
| C.6. Fire prevention section plan | Fire protection partition system application for vertical penetration part | 3 | 3 | 3 | 0 | 3 |
| | C.6.1. Fire prevention section plan | Sprinkler installation | 4 | 4 | 0 | 4 | 0 |
| | C.6. Fire-fighting equipment plan | Fire protection partition system application for vertical penetration part | 3 | 3 | 3 | 0 | 3 |
| | C.6.2. Fire-fighting equipment plan | Vertical space (stairscase, elevator, hallway) ventilation system | 3 | 3 | 3 | 0 | 3 |
| | C.6.3. Smoke control plan | Separation distance between evacuation stairs for egress | 5 | 5 | 5 | 5 | 5 |
| | C.7. Lifeboat conversion rate for emergency elevator | Lifeboat conversion rate for emergency elevator | 5 | 5 | 5 | 5 | 5 |
| | C.7.1. Horizontal evacuation plan | Lifeboat conversion rate for emergency elevator | 5 | 5 | 5 | 5 | 5 |
| | C.7.2. Vertical evacuation plan | Connection status check between safe area and special evacuation stairs | 3 | 3 | 3 | 3 | 3 |
| | C.7.3. Evacuation safety zone (sunken plan) | Speed gate installation for visitor access control at lobby floor | 3 | 3 | 0 | 0 | 3 |
| | C.7.4. Evacuation safety zone (sunken plan) | Speed gate installation for visitor access control at lobby floor | 3 | 3 | 0 | 0 | 3 |
| | C.8. Evacuation | Installing CCTV or sensor in the aisle for accessing buildings from outside | 3 | 3 | 0 | 0 | 3 |
| | C.8.1. In-building intrusion monitoring plan | Installing CCTV or sensor in the aisle for accessing buildings from outside | 3 | 3 | 0 | 0 | 3 |
| | C.8.2. Threat monitoring plan | Security guard management plan to monitor threats and respond to emergencies | 4 | 4 | 3 | 3 | 4 |
| | C.8.3. Out of building explosion threat monitoring plan | Security guard management plan to monitor threats and respond to emergencies | 4 | 4 | 3 | 3 | 4 |
| | C.9. Cyber security planning efficiency | n/a | 3 | 0 | 0 | 3 | 3 |
| | C.9.1. Cyber security planning efficiency | Cyber security planning efficiency related to main equipment’s operation | 3 | 3 | 2 | 2 | 3 |

Total items sum (Consequence + Threats + Vulnerability) = 107 + 81 + 81 + 61 + 121
3.3. Determination of consequence, threat, and vulnerability values by disaster

In the first step, to compensate for the limitations produced by setting the same proportion of scores among consequence, threats, and vulnerability and fixing their maximum values equally in the IRVS, the ratio of scores among the reference values consequence, threat, and vulnerability for risk assessment were determined based on the arithmetic mean excluding outliers, through expert’s interviews and with consideration of disaster characteristics (Kang et al. 2018). Depending on these characteristics, the ratio of consequence, threat, and vulnerability for a blast was rated as a higher risk of a threat for the building than that for other disasters. Furthermore, the ratio of fire is considered an important factor to vulnerability than in other disasters because it has a higher influence on loss due to the building’s physical characteristics. In the case of typhoons and earthquakes, the ratio of consequence, threats, and vulnerability was equally valued by applying the characteristics of natural disasters. Next, after determining the ratios of consequence, threats, and vulnerability for each disaster, the value of vulnerability was divided into equal ratios reflecting the number of first-level categories. Finally, to compare the results with those of the IRVS, the maximum risk values for each disaster were designed so that the maximum value of each risk was equal to 10. Based on the maximum values of consequence, threats, and vulnerability for each disaster, the attribute option values of the second- and third-level category items were determined as equal ratios between the five intervals. Lastly, the weighted items were set based on the importance of items selected by the experts and the highest number of selections for each subset. The determined values of consequence, threats, and vulnerability by the disaster in the K-IDES are given in Table 4.

4. Result analysis of K-IDES simulation

4.1. Target selection for K-IDES simulation

It is necessary to apply the evaluation model to actual high-rise buildings to verify the applicability of the weighted items and the weight distribution. The high-rise buildings selected for simulation should enable a comparison of deviations for environmental factors, and in evaluating the vulnerable factors of a building, it is set up as a target that can be analyzed by the level by the items. As the simulation aims to verify the differences in environmental indicators in consequence and threat, the high-rise buildings in this study were limited to general commercial districts or central commercial districts, which are more than 500% of the floor area ratio in Seoul, Incheon, and Busan. To assess the risk of physical differences in buildings in vulnerability, eight high-rise buildings of over 150 m and one building of height between 100 m and 150 m were selected. To verify the sensitivity of the K-IDES, similar buildings were selected for the preliminary disaster impact assessment of less than 10 years since construction completion. Table 5 lists the main characteristics of the buildings selected for the simulation.

4.2. Comparison of risk assessment between the K-IDES and IRVS

Using the checklist of the K-IDES and IRVS, nine similar, complex high-rise buildings in the three cities were evaluated for an integrated risk assessment and their results are described in Table 6. The evaluation results of the integrated risk were distributed between 59.72% and 71.28%. As the standard deviation of risk assessment among the buildings was 3.43 for the K-IDES and 2.11 for the IRVS, we inferred that the K-IDES’s distinction was higher than that of the IRVS. Regarding the risk

### Table 4. Consequence, threats, and vulnerability values by disaster and value assignment of weighted items for risk assessment

| C, T, V values by disaster | 1st level Ratio (%) among C, T, V | 2nd level C, T, V Value | 3rd level attribute options | Weighted items | Value sum | Individual risk score |
|----------------------------|-----------------------------------|-------------------------|----------------------------|----------------|----------|-----------------------|
|                            | a | b | c | d | e | No. | (Min, Max) | Min | Max | Min | Max |
| Blast                      | C | 20.00 | 18.38 | 3.68 | 7.35 | 11.03 | 14.71 | 18.38 | 2 | 0.13 | 0.38 | 3.68 | 18.383.20 | 10.00 |
|                            | T | 25.00 | 22.96 | 4.60 | 9.19 | 13.79 | 18.38 | 22.98 | 1 | 0.17 | 0.31 | 4.60 | 22.80 |
|                            | V | 55.00 | 5.62 | 1.12 | 2.25 | 3.37 | 4.49 | 5.62 | 24 | 0.05 | 0.30 | 10.11 | 50.56 |
| Fire                       | C | 16.00 | 14.71 | 2.94 | 5.88 | 8.82 | 11.77 | 14.71 | 2 | 0.13 | 0.38 | 2.94 | 14.713.20 | 10.00 |
|                            | T | 19.00 | 17.47 | 3.49 | 6.99 | 10.48 | 13.97 | 17.46 | 1 | 0.17 | 0.31 | 3.49 | 17.46 |
|                            | V | 65.00 | 6.64 | 1.33 | 2.66 | 3.98 | 5.31 | 6.64 | 18 | 0.06 | 0.66 | 11.95 | 59.75 |
| Seismic                    | C | 18.00 | 16.55 | 3.31 | 6.62 | 9.93 | 13.24 | 16.55 | 2 | 0.13 | 0.38 | 3.31 | 16.553.20 | 10.00 |
|                            | T | 20.00 | 18.38 | 3.68 | 7.35 | 11.03 | 14.71 | 18.38 | 2 | 0.18 | 0.33 | 3.68 | 18.38 |
|                            | V | 62.00 | 6.33 | 1.27 | 2.53 | 3.80 | 5.07 | 6.33 | 16 | 0.06 | 0.50 | 11.40 | 56.99 |
| Typhoon                    | C | 18.00 | 16.55 | 3.31 | 6.62 | 9.93 | 13.34 | 16.55 | 2 | 0.13 | 0.38 | 3.31 | 16.553.20 | 10.00 |
|                            | T | 20.00 | 18.38 | 3.68 | 7.35 | 11.03 | 14.71 | 18.38 | 1 | 0.21 | 0.38 | 3.68 | 18.38 |
|                            | V | 62.00 | 7.12 | 1.42 | 2.85 | 4.27 | 5.70 | 7.12 | 10 | 0.06 | 1.00 | 11.40 | 56.99 |

* C: consequence, T: threats, V: vulnerability
** The weight values of weighted items were set through interviews with experts. The final sum of weight value by each disaster at the 2nd level was planned to be 1.00 by adjusting the weight by each weighted item. In this table, since the weight values varied from item to item, they were indicated based on the minimum and maximum values.
Table 5. Building information for K-IDES simulation.

| Building Information | A | B | C | D | E | F | G | H | I |
|----------------------|---|---|---|---|---|---|---|---|---|
| Site                |   |   |   |   |   |   |   |   |   |
| Location            | Seoul | Seoul | Busan | Seoul | Seoul | Seoul | Seoul | Incheon | Incheon |
| Land type           | GBD | GBD | GBD | GBD | GBD | GBD | GBD | GBD | GBD |
| Usage               | O, H, M | O, H, M | O, H, M | O, H, M | O, H, M | O, H, M | O, M | O, M, H | O, R, M |
| FAR (%)             | 573 | 799 | 550 | 926 | 940 | 799 | 848 | 596 | 799 |
| Building Height (m) | 55S | 338 | 289 | 284 | 246 | 185 | 110 | 305 | 152 |
| Structure           | SRC | SRC | SRC | SRC | SRC | SRC | SRC | SRC | SRC |

* GBD: General Business District, CBD: Central Business District, O: Office, H: Hotel, R: Residential, M: Mall, C: Convention, SRC: Steel Reinforced Concrete, RC: Reinforced Concrete, FAR: Floor Area Ratio, GFA: Total Ground Floor Area

Table 6. Risk assessment results of the K-IDES and IRVS.

| K-IDES Individual disaster risk score (Ri) | IRVS Individual disaster risk score (Ri) | K-IDES | IRVS |
|-------------------------------------------|-----------------------------------------|--------|------|
| NO. | Blast | Fire | Seismic | Typhoon | Blast | Fire | Seismic | Typhoon | Integrated risk (%) | Integrated risk (%) |
| A   | 6.80  | 6.75 | 6.31  | 6.90  | 4.10  | 3.90 | 1.63  | 2.55  | 67.15  | 45.40  |
| B   | 6.73  | 6.72 | 6.49  | 6.97  | 4.31  | 4.04 | 1.81  | 2.63  | 67.41  | 45.80  |
| C   | 6.69  | 6.89 | 6.46  | 6.62  | 4.48  | 4.25 | 1.79  | 3.98  | 66.76  | 46.00  |
| D   | 6.85  | 6.67 | 6.25  | 6.17  | 4.43  | 4.10 | 1.77  | 2.63  | 65.35  | 47.60  |
| E   | 6.53  | 6.22 | 5.96  | 6.00  | 4.24  | 3.86 | 1.77  | 2.59  | 62.11  | 43.40  |
| F   | 6.25  | 6.21 | 6.06  | 6.25  | 4.45  | 4.13 | 1.77  | 2.63  | 61.93  | 48.60  |
| G   | 5.95  | 5.68 | 5.97  | 6.20  | 4.34  | 4.00 | 1.94  | 2.63  | 59.72  | 42.20  |
| H   | 7.34  | 7.31 | 6.81  | 6.94  | 4.35  | 4.00 | 1.81  | 2.68  | 71.28  | 46.00  |
| I   | 7.03  | 6.91 | 6.49  | 6.74  | 4.90  | 4.20 | 1.96  | 2.61  | 68.13  | 49.00  |
| Mean| 6.69  | 6.60 | 6.31  | 6.53  | 4.40  | 4.05 | 1.81  | 2.77  | 65.54  | 46.00  |
| M.D | 0.39  | 0.45 | 0.27  | 0.36  | 0.21  | 0.12 | 0.09  | 0.43  | 3.43   | 2.11   |

Assessment of individual disasters, the risk score and deviation of the K-IDES were higher than those of the IRVS. The low-risk score and low deviation in the IRVS simulation results demonstrated the limitations of its application in domestic cases, as described in section 2.2.

In the case of blasts and fires, the graphs of the K-IDES and IRVS were similar, and the individual risk differences were less than those for seismic events and typhoons. There were many similarities between the evaluation items for blasts and fire as evaluated by the K-IDES and IRVS because the reviewed contents of the domestic anti-terrorism design guidelines were based on the FEMA anti-terrorism design guidelines. Since in the case of blasts and fire in IRVS, the weights of consequence and threat for the environmental characteristics are designed higher than the vulnerability's weights, due to the environmental evaluation items in consequence and threats related to high-density's city location, risk assessment score is higher than that for other disasters. In the case of earthquakes, the results of the IRVS showed a difference of 0.33 between the maximum and minimum values of the risk score, which lacked the levels of distinction of risk assessment. In the case of typhoons, for an exposure frequency index of strong wind, according to the regional differences in building location, only Building C was marked at the highest risk level in the IRVS. It was difficult to accept the reliable results since due to excessive weight of one environmental index, analysis of the other evaluation items in IRVS has a low impact on risk score and it is impossible to subdivide risk level. The risk scores of individual risk and integrated risk of disasters in the simulation results of the K-IDES and IRVS differed due to the differences in the contents and weights of the evaluation items, and the ratios' distribution among consequence, threats, and vulnerability.

4.3. Result analysis of K-IDES risk assessment

The integrated risk assessment of the nine high-rise buildings established the following: In consequence and threat for evaluating environmental conditions and threats on the areas surrounding the site, A represents the highest sum for each disaster, and invulnerability for evaluating the physical risk in the buildings, I represents the highest sum (Figure 3). However, since individual risk and integrated risk scores are calculated by multiplying the total sum of consequence, threats, and vulnerability, building H is assigned the highest risk score (Table 5). Among the disasters under review, the highest consequence and threat ratio of blasts and the highest vulnerability ratio of the fire show the highest standard deviation and average total sum. The analysis of the K-IDES results is intended to identify buildings’ vulnerable factors and the level of application of the assessment items against the disaster. For this, a tiered result analysis of the second – and third-level items by disaster is necessary.

4.3.1. Blast risk assessment analysis

As the highest risk item in the risk assessment of a blast, the average score for regional characteristics,
in consequence, was 7.77 and the standard deviation was 0.7 (second rating among the evaluation items). In threats, the average score of building usage and area characteristics was 11.55, and the standard deviation was 3.06 (the first rating among the evaluation items). In vulnerability, the average score of the MEP plan, the highest, was 4.28 and the standard deviation was 0.49 (the third rating among the evaluation items). Among the risk evaluation items in consequence and threats related to the evaluation categories for environmental conditions around the building sites, the main risk impact factors related to area characteristics, in consequence, were land use and resident population density around the area and asset value by the buildings’ volume. The main risk impact factors due to the functional characteristics around the buildings in threats were recognition of the building as a landmark in the area, the purpose of the building, and the resident population density in the building.

These results prove that the relationship between the environmental characteristics around the site and the functional characteristics of the building were important factors to assess the risk in a blast; moreover, the magnitude of the standard deviation was higher than in others, which means that these evaluation items can differentiate the levels for risk assessment. In addition, among the evaluation items for the physical risk area of buildings invulnerability, the high-risk factor was the MEP plan category, which showed that the reinforcement plan for central air-conditioning systems and horizontal and vertical piping against explosions was insufficient in domestic buildings. The risk assessment of the items related to volume type, plan shape, core location, structure type, elevation type, and shape in the architecture plan, structure plan, and envelope plan in vulnerability due to the architectural similarity of the high-rise buildings were difficult to analyze because of the deviations among the high-rise buildings, but the level of risk assessment could be distinguished among them. In vulnerability’s evaluation categories, the top three standard deviations were cybersecurity plan, fire plan, and evacuation plan. Whether fires and evacuation laws apply depending on when the building’s construction was completed. The differences among subitems, protection of cyberinfrastructure facilities, the efficiency of cybersecurity personnel training program, smoke control plan, the distance between evacuation stairs, and separation of evacuation stairs from evacuation floors are also shown.

4.3.2. Fire risk assessment analysis
As the highest risk item in the risk assessment of the fire, the average score of regional characteristics, in consequence, was 6.21 and the standard deviation was 0.56 (second rating among the evaluation items). In threats, the average score of building usage and area characteristics was 8.78, and the standard deviation was 3.23 (the first rating among the evaluation items). Invulnerability, the average score of the MEP plan, the highest, was 3.88 and the standard deviation was 1.53 (third rating among the evaluation items). The highest risk item in consequence and threats was the
same as blast because although the ratio between consequence and threats was different, the evaluation items were the same. In the case of fire against blast, the risk assessment rate of vulnerability items were higher than that of consequences and threats, which indicate environmental threats. The comparison of risk average scores in the vulnerability category showed the same high-risk average scoring in the MEP plan category as blast, although the number of assessment items against blast decreased. In the vulnerability evaluation category, the top three standard deviations to analyze the distinction between the assessed high-rise buildings were the MEP plan, site plan, and cybersecurity plan. The installation method for the internal air distribution system and the proximity evaluation of the machine room with important equipment to the high-risk area in MEP plan, the road width standard for vehicle road intersections at the site, the space plan related to a fire truck traffic line in the site plan, and the cybersecurity planning efficiency related to the main

Figure 4. Blast risk assessment result.

Figure 5. Fire risk assessment result of the K-IDES.
equipment’s operation in cybersecurity plan showed the differences, irrespective of whether the Special Act applied to high-rise buildings over 200 m was reflected.

4.3.3. Seismic risk assessment analysis
As the highest risk item in the risk assessment of the seismic risk category, the average score for regional characteristics, in consequence, was 6.99 and the standard deviation was 0.63 (second rating among the evaluation items). In threats, the average score of environmental indicators was 6.47 and the standard deviation was 1.24 (second rating among the evaluation items). Invulnerability, the average score of the security plan was 4.32, the highest, and the standard deviation was 0.18 (ninth rating among the evaluation categories). In the case of seismic risk, the high risks of regional characteristics and environmental indicators in consequence and threats related to the evaluation categories for the environmental conditions around the site were due to high population density and the existence of important facilities around the sites where the high-rise buildings were located. As the threat factor in a natural disasters, since the frequency of earthquakes and the impact of soil characteristics of the regional environmental indicators are important, their risk scores were calculated as high and differed depending on the location of the region. In the security plan of the vulnerability category, the high-risk average item was to secure and protect emergency power in high-rise buildings and install an emergency button for reporting emergencies in public spaces such as underground parking lots. The low standard deviation of these items showed that domestic high-rise buildings have insufficient equipment for their operation plan and for supporting the evacuation of occupants in an emergency.

In the vulnerability evaluation categories, the top three standard deviations to analyze the distinction between the assessed high-rise buildings were site plan, fire plan, and cybersecurity plan. The height of pilotis around the fire lane and the space plan related to a fire truck traffic line in the site plan, the installation and distance of sprinkler heads in a curtain wall structure, a secondary water source (rooftop), the calculation of water supply in fire plan, and the same part as a fire in cyber plan differed due to differences in the use purposes of the occupants.

4.3.4. Typhoon risk assessment analysis
As the highest risk item in the risk assessment for typhoons, the average score for regional characteristics, in consequence, was 6.99 and the standard deviation was 0.63 (second rating among the evaluation items). In threats, the average score of environmental indicators was 6.10 and the standard deviation was 1.25 (second rating among the evaluation items). Invulnerability, the security plan in the remaining areas except for the site, MEP, and fire categories, where the evaluation items are less than 1, was 4.85, the highest, and the standard deviation was 0.18 (eighth rating among the evaluation categories). The high-risk score items related to regional characteristics, in consequence, were due to high population density and the existence of important facilities around the site where the high-

![Figure 6. Seismic risk assessment result of the K-IDES.](image-url)
rise buildings were located, and they showed the same result as for other disasters. In threats, the items with the highest risk score related to environmental indicators that access the characteristics of natural disaster were the maximum wind speed and average wind speed, and depending on the building’s regional location, the simulation results of these items showed differentiation. In the vulnerability category, the items in the security plan showed the same results as in the seismic category. In the vulnerability evaluation categories, the top three standard deviations to analyze the distinction between the assessed high-rise buildings were a structure plan, evacuation plan, and cybersecurity plan. The lateral force fixing rate for self-weights of building nonstructural components in structure plan, connection, and distance from the evacuation floor to the outdoor exit, the distance between the evacuation stairs in an evacuation plan, and cybersecurity planning efficiency related to the main equipment’s operation in cyber plan showed differences due to differences in the use purpose of the occupants.

5. Conclusion

The purpose of this study was to establish a classification system for the evaluation of risk elements in Korean high-rise buildings, excluding legal standards. Another purpose was to analyze and verify the results of the simulation application of the proposed program by developing numerical measurements for risk evaluation and methodology of risk evaluation. To verify the applicability of the K-IDES, high-rise buildings over 100 m in three cities and with a construction time of under 10 years, with different environmental indicators, were selected. The evaluation results derived from the simulations using the IRVS and K-IDES were compared. As a result of the application of the IRVS to domestic buildings, since an average risk score was calculated as under 46.00% against a disaster, it was difficult to derive risk areas. The average deviation among the risk evaluation results for each disaster was 2.11%; therefore, the sensitivity of the IRVS was extremely low. This proved the limitations of domestic application of the IRVS as a risk evaluation model against disaster. To verify the K-IDES’ sensitivity to risk factors for the vulnerability of buildings, the survey targets were analyzed by limiting the environmental conditions by selecting similar buildings, except for differences in environmental indicators according to the location of the cities.

As a result, the average individual risk score, the average-integrated risk score, and the standard deviation were all found to be higher than those of the IRVS. However, there was no building in the high-risk group with an integrated risk score of over 80.00%, and it was assessed as a relatively safe building against disaster within 59.45 ~ 70.84% because it was applied to high-rise buildings that were completed less than 10 years earlier and which passed the Preliminary Disaster Impact Assessment. In the buildings that completed the Preliminary Disaster Impact Assessment, since there are no specific guidelines in some areas, there were many items with high variation among them due to differences in the application level of each category of vulnerability. By selecting these items and expanding the group to include architectural differences, it is
possible to use them as basic data for a supplementary plan embodied in the domestic design guidelines for high-rise buildings against disasters through identifying their actual current status.

Regarding the limitations of this study, first, it was difficult to assess the application to different types of buildings by interpreting the evaluation results due to the restriction of architectural types. Second, since the purpose of this study was to develop an evaluation model to screen whole buildings and not a particular section of buildings, there was a limitation in deriving the hazardous areas related to the architectural design elements by allocating the same weights of scores among vulnerability’s categories without considering the correlation with dangerous architectural parts according to disaster characteristics.

Therefore, future research is needed to verify the simulation results and analysis methods to assess the domestic buildings’ preparation level against the risk of a disaster by expanding the building types and diversification of the geographical location. In addition, with respect to the proportional allocation of consequences, threats, and vulnerability reflecting the weight of each disaster, a selection method of the weighted items, and the setting of weight value, the parameters of each expert survey in this study should be expanded to a range capable of statistical analysis; this will increase the reliability and precision of the analysis method. This research can be applied to assess vulnerable areas from the beginning of the design phase and reflect efficient alternative plans on the design for reducing risk. In case of dangerous areas in existing buildings, adjustment plans can be suggested, and the analyzed data to assess the high-rise building’s design level through surveys can be used as basic data for improving the design guidelines against disaster. This process, by developing the method of continuous data scaling and systematic management for buildings can contribute to risk management against complex disasters by extensions to various infrastructures and building types.

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