Disaster Assessment of Tall Buildings in Korea by K-Rapid Visual Screening System Focusing on Structural Safety

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Abstract: Multiple hazards, which threaten people’s lives and property, are the main concern for engineers in preventing dangers to buildings. In particular, densely populated areas, such as capital cities and tall buildings, are exposed to higher risks owing to multiple hazards. To rapidly evaluate the disaster assessment of tall buildings, the Federal Emergency Management Agency (FEMA) in the U.S. proposed the integrated rapid visual screening system (IRVS). However, the IRVS system only considers U.S. conditions. Therefore, a Korean-oriented rapid visual screening system should be developed because the number of buildings over 200 m in Korea ranked fourth in the world with the highest density (500 people per square kilometer) among the top five countries based on the Council on Tall Buildings and Urban Habitat’s (CTBUH) database. This study describes a Korea-rapid visual screening (K-RVS) system that focuses on the structural safety of tall buildings in Korea. The K-RVS system was modified based on the IRVS, considering the Korean design standard (KDS) and Korean conditions. With the weight value for each characteristic, the scores for each hazard and final scores combined from the scores by multi-hazard can be obtained to conduct a disaster assessment of tall buildings subjected to multiple hazards.

Keywords: disaster assessment; tall buildings; rapid visual screening system; K-RVS; IRVS

1. Introduction

There are various hazards that threaten life and property. Recently, civil engineers tried to prevent damage in buildings subjected to multiple hazards and to prepare their resilience [1–3]. To evaluate the effects of hazards on buildings, the Department of Homeland Security (DHS) in the United States set out to develop a multi-hazard risk assessment system after the events of 11 September 2001 [4]. This system, also known as integrated rapid visual screening (IRVS), was based on the framework set forth in the design guides [5–7] and rapid visual screening (RVS) [8–10] for safety and mitigation of several hazards (earthquake, fire, winds, blast, etc.) by the Federal Emergency Management Agency (FEMA). IRVS is available for evaluating risk assessment under multiple hazards and provides opportunities for gathering building information data of not only public buildings but also private ones.

The risks posed by multiple hazards are maximized in densely populated areas, such as capital cities and tall buildings. In the case of Korea, the risks of multiple hazards are higher than those of developed countries because the number of buildings over 200 m currently ranks 4th in the world, with the highest density (500 people per square kilometer) among the top five countries based on the Council on Tall Buildings and Urban Habitat’s (CTBUH) database [11]. The Korean government enacted the first high-rise building law for disaster management to prevent multiple hazards and reduce their occurrence. However, this law focused on the egress plan related to post-disaster. Therefore, design considerations to prevent disasters and reduce risks related to pre-disaster were barely considered; however, several studies on risk assessment for disaster prevention in Korea
have been conducted [12–15]. Lee and Kim proposed an improved direction for the design procedure considering architectural factors in building security control systems [12], and Kang et al. studied the vulnerability assessment of high-rise buildings in Korea via explosive terror risk investigations based on the RVS of FEMA [13]. Yu et al. evaluated the terror risk of tall buildings in Korea using the modified RVS and IRVS systems [14], and Lee and Yoon assessed the strong wind risk of tall buildings in Korea using IRVS [15]. Kang et al. classified architectural design elements of multiuse buildings considering terror risk by investigating the RVS system [16]. In addition, Kang et al. surveyed the perspectives of architectural design practitioners on the anti-terrorism design of multiuse buildings to suggest design guidelines [17]. Kim et al. systemized an integrated risk management strategy for high-rise buildings subjected to various disasters using the Korean Integrated Disaster Evaluation Simulator (K-IDES) [18], and also developed a K-IDES system with a risk assessment method and building simulations [19]. Disaster assessment guidelines for tall buildings in Korea using RVS according to Korean conditions have been proposed [20].

Asprone et al. [21] proposed a probabilistic model for multi-hazard risk related to limit state collapse for concrete structures under the post-earthquake blast. Explosions both inside and outside the structure were considered for the blast scenario. Various structural types were proposed as the further research target for this condition. Kameshwar and Padgett [22] described a parameterized fragility based multi-hazard risk assessment for highway bridges under earthquakes and hurricanes. In addition, hurricane wave and surge loading were additional risks for assessing the risk of the bridges. Gentile et al. [3] proposed the Indonesia school program to increase resilience to assess the seismic risk of concrete buildings and calculate Papathoma tsunami vulnerability. Koks et al. [23] presented the first global estimates for assessing multi-hazard risk for road and railway infrastructure assets with the global expected annual damage index. Dabbeek and Silva [24] proposed an exposure model for multi-hazard risk assessments of residential buildings in the Middle East. Kwag et al. [25] proposed a novel framework to find the governed hazards based on the performance-based design requirement under earthquake and wind loads. Wei et al. [26] proposed a quantitative multi-hazard risk assessment of buildings in the Jiuzhaigou Valley, one of the natural heritage sites in Western China, that is endangered by rockfalls and debris flows.

In this study, the K-RVS system was proposed by making IRVS dependent on Korean conditions and the Korean design standard (KDS) [27] to assess major disasters (earthquake, wind, fire, blast) for tall buildings, and its validation was obtained. Because the number of tall buildings in Korea ranks fourth in the world with the highest density among the top five countries, the Korean government enacted the first high-rise building law for disaster management. This law aims to prevent multiple hazards and reduce their occurrence. However, as numerous tall buildings were already built before enacting the law, a rapid assessment system for existing tall buildings under multi-hazards should be developed. Thus, the disaster assessment system (K-RVS) is a method that provides guidance and explanations on interpreting the severity of potential hazards over the identified risk assessment of tall buildings in Korea, focusing on structural safety.

2. Structure of the K-RVS System

2.1. General

K-rapid visual screening (K-RVS) is an assessment system for evaluating tall buildings with agile analysis via a review of the knowledge and available data on the buildings. It is a modified version of the IRVS, which was adapted for use in Korea with the goal of improving the evaluation procedure in Korean buildings, and enabling the proper assessment of buildings prone to earthquake, fire, wind, and blast risks. Furthermore, K-RVS contains pre-field data, consequences, threats, and vulnerability components similar to IRVS, as shown in Figure 1.
IRVS describes pre-field data such as relevant building identification information, threats and hazards, and datatypes that are not readily available in the field. However, this information contains some of the most important components with high weight values. In this phase, two categories were chosen to belong to pre-field data 1 and 2. Pre-field data 1 and 2 were compounded for three and thirteen characteristics, respectively, as presented in Table 1. Phase two has three categories: consequences, threats, and vulnerability. Consequences and threats were compounded for three characteristics each, and vulnerability was compounded for twenty-eight characteristics (Table 1).

Table 1. K-RVS of detailed components.

| Phase I       | Phase II               | Vulnerability                                |
|---------------|------------------------|----------------------------------------------|
| Pre-Field 1   | Pre-Field 2            | Consequences                                |
| Hazard        |                        | Threat                                       |
| Number of Occupants | Replacement Value | locality/Density Type                      |
| Occupancy Use |                        | Site Population Density                     |
| Target Density: Zone I | Topography/Slopes | Condition of Foundation                     |
|                |                        | Retaining Walls                              |
|                |                        | Potential of Soil Liquefaction               |
|                |                        | Building Height                              |
|                |                        | Overhang                                     |
|                |                        | Horizontal Irregularity                      |
| Structure Type | Target Density: Zone II | Vertical Irregularity                        |
|                |                        | Number of Bays in the Short Direction        |
|                |                        | Column Spacing                               |
|                |                        | Unbraced Column Height                       |
|                |                        | Publicly Accessible Column                  |
|                |                        | Transfer Girder Conditions                  |
|                |                        | Structural Enhancements and Weaknesses       |
|                |                        | Number of Lateral Systems                   |
|                |                        | Short Columns or Walls                      |
|                |                        | Seismic Design/Retrofit                      |
| Resiliency Computations | Target Potential: Building | Operational Redundancy                       |
|                |                        | Visibility/Symbolic Value                   |
|                |                        | Overall Site Accessibility                  |
|                |                        | Roof Span                                    |
|                |                        | Topping Slabs                                |
|                |                        | Adjacent Building Separation                 |
|                |                        | Wall Type                                    |
|                |                        | Windborne Debris Impact Protection           |
|                |                        | Exterior Fireproof Walls                     |
|                |                        | Seismic Design Category                      |
|                |                        | Allowable Story Drift                        |
|                |                        | Surface Roughness                            |
|                |                        | Enclosure                                    |
| Soil Type     | Typhoon Frequency in the Region | Impact of Physical Loss                     |
|                |                        | Overall Site Accessibility                  |
|                |                        | Windborne Debris Impact Protection           |
|                |                        | Exterior Fireproof Walls                     |
|                |                        | Seismic Design Category                      |
|                |                        | Allowable Story Drift                        |
|                |                        | Surface Roughness                            |
|                |                        | Enclosure                                    |
To properly complete the assessment of a building, four steps are necessary; the gathering of pre-fields, consequence assessment, threat assessment, and vulnerability assessment (Figure 2). During the steps in the K-RVS system, the screener deals with six variables subjected to major scoring considerations.

![Assessment Steps](image)

**Figure 2.** Assessment steps.

In this chapter, modifications of the characteristics for structural evaluation in each phase are shown, and are displayed in comparison tables (IRVS vs. K-RVS), where most of the arrangements were taken from the KDS.

### 2.2. Configuration of Phase I

Important attention was placed on pre-field data, as IRVS describes it as a phase with relevant building identification information and some of the most important components with high weight values.

#### 2.2.1. Pre-Field 1

Pre-field 1 includes hazard, structure type, and resilience computations, which are essential characteristics of the assessment. K-RVS was developed with the purpose of allowing an assessment based on hazards as in the IRVS system (Table 2). However, the hazard contained in the K-RVS was reduced because of the scope of this study. Four threats were selected when focusing on the structural safety of tall buildings: earthquake, wind, blast, and fire. The assessment of a building should present at least one of these four hazards; otherwise, no outcomes will be obtained. An essential requirement for a structure is its rigidity, which aids in utilizing the overall inertia and in sustaining localized damage without widespread collapse. This requires tensile capacity and ductility in the design of the elements and their connections [28]. The structure type is one of the characteristics that play an extremely important role; therefore, an examination of tall building structure types was conducted. Consequently, in addition to the structures specified in the table of design coefficients for structural systems in KDS [27], six more structure types for tall buildings mentioned by Ali and Moon [29] were included in the K-RVS. The IRVS system states that resiliency reflects the continuity of building operations; meanwhile, the system points it out as the capacity to adapt to hazards or a transition in conditions.
Table 2. Comparison table for pre-field 1 between IRVS and K-RVS.

| Pre-Field 1 | IRVS | K-RVS |
|-------------|------|-------|
| **Hazard**  |      |       |
| Earthquake  | Earthquake | Special reinforced concrete shear wall |
| Flood       | Wind  | Ordinary reinforced concrete shear wall |
| Wind        | Blast | Steel eccentrically braced frame (MRCLC 1) |
| Blast       | Fire  | Steel eccentrically braced frame (NMRCLC 2) |
| Chemical, biological, and radiological (CBR) | Fire | Special steel concentrically braced frame |
| **Structure type** | | |
| Wood frame  | Ordinary steel concentrically braced frame | Composite eccentrically braced frame |
| Manufactured homes | Steel eccentrically braced frame (MRCLC 1) | Ordinary composite concentrically braced frame |
| Steel moment frame | Special steel concentrically braced frame | Composite steel plate shear wall |
| Steel braced frame | Ordinary steel concentrically braced frame | Special composite shear wall |
| Steel light frame | Special steel moment frame | Special steel moment frame |
| Steel frame with cast-in-place concrete shear walls | Ordinary steel moment frame | Intermediate steel moment frame |
| Steel frame with unreinforced masonry infill walls | Special composite moment frame | Special composite moment frame |
| Concrete moment frame | Ordinary reinforced concrete moment frame | Intermediate composite moment frame |
| Concrete shears walls | Buckling-restrained braced frame (MRCLC 1) | Ordinary composite moment frame |
| Unreinforced masonry bearing walls | Special reinforced concrete shear wall | Ordinary reinforced concrete moment frame |
| Concrete frame with unreinforced masonry infill walls | Special steel plate shear wall | Buckling-restrained braced frame (MRCLC 1) |
| Precast concrete tilt-up walls | Ordinary reinforced concrete moment frame | Special steel plate shear wall |
| Precast concrete frames with concrete shear walls | Special composite moment frame | Intermediate reinforced concrete moment frame |
| Reinforced masonry bearing walls with wood or metal deck diaphragms | Special reinforced concrete moment frame | Composite partially restrained moment frame |
| Reinforced masonry bearing walls with precast concrete diaphragms | Intermediate reinforced concrete moment frame | Ordinary reinforced concrete moment frame |
| **Resiliency computations** | No resiliency computations are needed | No resiliency computations are needed |
| General | General | |
| Government | Financial | |
| Medical | Residence | |
| School K12 | | |
| Business/Financial | | |
| Retail | | |

1. MRCLC: Moment resisting column-link connection 2. NMRCLC: Non-Moment resisting column-link connection.

2.2.2. Pre-Field 2

Pre-field 2 includes the number of occupants, replacement value, occupancy use, target density (zones I, II, and III), target potential (building and sector), seismic zone, geology, high wind speed, typhoon (hurricane in IRVS) frequency in the region, and soil type (Table 3). The number of occupants represents the potential casualties, which means the number of people with possible injuries or death owing to multiple hazards. The number of occupants values were taken from previous studies [14,30] with refitting considerations for tall buildings. The replacement value is the current value of construction per unit.
area multiplied by the gross square meters of the building. The replacement value can be changed based on construction costs with numerous conditions and use of the building. The replacement values were obtained from previous studies [14,30]. Occupancy use is related to the function of the building. In the Building Act in Korea enforced on 10 May 2013, it is stated that uses of buildings are to be classified into twenty-eight categories, and the subcategories of the building uses in each category will be prescribed by presidential decree [31]. Occupancy use indicates the purpose for which a building is occupied. Sometimes tall buildings have multiple uses; consequently, and also for K-RVS purposes, most tall buildings to be evaluated should coincide with the classification in group 3; for example, business facilities and class I-II neighborhood living facilities. Any different facility must be introduced as others based on the previous studies [20]. Target density is defined as the number of high-value objects near the building. The distance is classified into zones 1, 2, and 3. Target density excludes the subject building.

Target potential is related to the possibility that a terror event affecting the target building will happen. The seismic zone is a distinct area of seismicity activity which indicates the frequency and location of earthquakes. In KDS, the table for regional seismicity and its spectral acceleration parameter is provided. From these, two seismic zones are recognized and taken for the study. The proximity of an active seismic fault depends on active faults within an 80 km radius of the building. IRVS refers to high wind speed zone maps as a source of information about wind speeds in a specific region. Classifications were made according to the table for basic wind speed in Korea and its corresponding map provided by KDS. The frequency of hurricanes in the northwestern Pacific is normally recorded because there is no official hurricane season throughout the year. Therefore, from previous typhoon disasters that occurred in Korea, classifications per occurrence year were made. Soil type, the main parameter in the seismic resiliency, is the kind of soil/rock on which the foundation is located.

2.3. Configuration of Phase II
2.3.1. Consequences

IRVS mentions that locality/density types describe the population density and land use (Table 4). Because this study focuses on tall buildings mostly located in dense urban areas, only two categories were chosen. Operational redundancy depends on the grade to which a building can maintain a competent service and keep operational stability rather than recoverable capacity after hazards. Because the impact of physical loss shows the amount of loss after hazards, three classifications were chosen based on the scope of the study.

2.3.2. Threats

Threat assessment depends on target attractiveness, not on the likelihood of a threat, and it is related to man-made threats capable of causing loss of or damage to assets (Table 5). Therefore, the only two hazards related to these characteristics are blast and fire hazards. Site population density is defined as the number of people living near the building, excluding the population inside the building. IRVS defines the visibility/symbolic value as the importance of a building in terms of economics, cultures, and symbols. Overall site accessibility indicates the security levels of the building to prevent hazards on the building. These characteristics were modified based on the scope of the study.
Table 3. Comparison table for pre-field 2 between IRVS and K-RVS.

| Pre-Field 2 | IRVS | K-RVS |
|-------------|------|-------|
| Number of occupants | | |
| 2000 to less than 5000 | 2000 to less than 4000 |
| 5000 to less than 10,000 | 4000 to less than 6000 |
| 10,000 to less than 12,500 | 6000 to less than 8000 |
| 12,500 to less than 15,000 | 8000 to less than 10,000 |
| 15,000 to less than 17,500 | 10,000 to less than 20,000 |
| 17,500 to less than 20,000 | 20,000 to less than 40,000 |
| 20,000 or more | 40,000 to less than 60,000 |
| 60,000 to less than 80,000 | 80,000 or more |
| Replacement value | | |
| 2000 to less than 5000 | less than 60 billion won |
| 5000 to less than 10,000 | 60 billion won to less than 80 billion won |
| 10,000 to less than 12,500 | 80 billion won to less than 100 billion won |
| 12,500 to less than 15,000 | 100 billion won to less than 200 billion won |
| 15,000 to less than 17,500 | 200 billion won to less than 400 billion won |
| 17,500 to less than 20,000 | 400 billion won to less than 600 billion won |
| 20,000 or more | 600 billion won to less than 800 billion won |
| 60,000 to less than 80,000 | more than 800 billion won |
| Occupancy use | | |
| Group 1 | Other |
| Group 2 | |
| Group 3 | |
| Target density | | |
| Zone 1 | Group 3 |
| Zone 2 | |
| Zone 3 | |
| Target potential | Building Sector |
| Seismic Zone | | |
| Low | |
| Medium | |
| High | |
| Proximity to an active seismic fault | | |
| Farther than 50 miles (80 km) from a fault active or inactive. Or within 50 miles (80 km) of an inactive fault | |
| Within 50 miles (80 km) of an active fault | |
| High wind speed zone | | |
| Low zone with winds of low moderate speeds-winds below 75 mph (33.5 m/s) peak gust | Low zone with winds of low speeds-winds below 28 m/s or 100 km/h |
| Medium zone exposed to strong winds- winds between 75 mph (33.5 m/s) and 111 mph (49.6 m/s) peak gust | Medium-low zone with winds of moderate speeds-winds below 34 m/s or 120 km/h. |
| High building subjected to damaging winds with speeds of greater than 111 mph (49.6 m/s), generally in hurricane-prone or tornado-prone zones. | Medium zone exposed to strong winds- winds between 34 m/s (120 km/h) and 50 m/s (180 km/h). |
| Hurricane/typhoon frequency in the region | | |
| Never. No record of a hurricane/typhoon in the region | Rare. One or two hurricanes in the last 70 years |
| Medium. One or two hurricanes in the last 20 years | Medium Rare. One or two typhoons in the last 40 years |
| Frequent. Multiple hurricanes in the last 20 years that significantly affected the region | Medium. One or two typhoons in the last 20 years |
| Soil Type | | |
| Hard rock | Hard Rock |
| Medium | Rock |
| Poor | Very Dense Soil or Soft Rock |
| | Stiff Soil |
| | Soft Soil |
Table 4. Comparison table for consequences between IRVS and K-RVS.

| Consequences                      | IRVS                  | K-RVS               |
|-----------------------------------|-----------------------|---------------------|
| Locality/Density type             | Rural/Suburban        | Urban               |
| Semi urban/Light industrial       | Rural/Suburban        | Urban               |
| Industrial                        | Rural/Suburban        | Urban               |
| Urban                             | Rural/Suburban        | Urban               |
| Dense Urban                       | Urban                 | Dense Urban         |
| Operational redundancy            | Very high             | Very high           |
|                                  | High                  | High                |
|                                  | Moderate              | Moderate            |
|                                  | Low                   | Low                 |
|                                  | Very low or not capable  | Very low or not capable |
| Impact of physical loss           | Local                 | Regional            |
|                                  | Statewide             | National            |
|                                  | Regional              | National            |
|                                  | National              | International       |
|                                  | International         |                     |

Table 5. Comparison table for threat between IRVS and K-RVS.

| Threat                           | IRVS                  | K-RVS               |
|----------------------------------|-----------------------|---------------------|
| Site population density          | Very low (1 person per 929 m²) | Moderate (1 person per 37 m²) |
|                                  | Low (1 person per 93 m²)       | High (1 person per 3.7 m²)    |
|                                  | Moderate (1 person per 37 m²)   | Very high (1 person per 0.93 m²) |
|                                  | High (1 person per 3.7 m²)      |                      |
|                                  | Very high (1 person per 0.93 m²) |                      |
| Visibility/Symbolic value        | Very low               | Low                 |
|                                  | Low                    | Moderate            |
|                                  | Moderate               | High                |
|                                  | High                   | Very high           |
| Overall site accessibility       | Inaccessible           | Inaccessible        |
|                                  | Accessible             | Accessible          |

2.3.3. Vulnerability

The characteristics consist of the existing items in IRVS and additional items in K-RVS (Table 6). Five characteristics (exterior fireproof walls, seismic design categories, allowable story drift, surface roughness, and enclosures) were added to the vulnerability assessment. Nearby structural characteristics indicate the potential for additional damage in nearby structures. Slope means the slope near the building, and slope failure (landslide) can influence negative effects. The condition of the foundation refers to the overall status of the foundation. A retaining wall should withstand the soil and water pressure. Liquefaction indicates the extremes of vibration or flow of soil during earthquakes because of less consolidation. The overhang characteristic is related to occupied space and the overhang is the distance between the exterior enclosure and the inside face. Horizontal irregularity (plan irregularity) contains re-entrant corners of buildings. This may cause unexpected twists around the vertical axis. In addition, irregular vertical configurations may cause dangerous stress concentrations. Based on KDS, the horizontal and vertical irregularity characteristics were considered in K-RVS. Wall type is defined by facades; screeners should decide this by site-visiting or asking the designers. The windborne debris impact protection characteristic should be considered in the most dangerous accident. Bay means the spacing between structural columns, and unbraced column height. Column height is related to the stability of structures and publicly accessible columns may be a target of terror. Lateral systems are mainly designed for resisting lateral force. Transfer girders are a kind of deep depth girder to transfer the huge loads that occur by discontinuous columns. Structural
enhancement refers to the improving strength or stiffness of the structural members. Short columns or walls allow significant stresses which during an earthquake may crack or collapse. The seismic design or retrofit can be confirmed seismic design or retrofit from. Long-span roof members are vulnerable to the uplift of winds passing through the door or window. Topping slabs are finishings above structural slabs or components. Adjacent buildings, which are extremely close, may influence each other during hazards.

Table 6. Comparison table for vulnerability between IRVS and K-RVS.

| Vulnerability                          | IRVS               | K-RVS                  |
|----------------------------------------|--------------------|------------------------|
| Nearby structures (Underground or adjacent) | None | Small | Medium | Major |
| Topography/Slopes                      | Flat or terraced with adequate setbacks | Light slope | Moderate slope | Steep slope |
| Condition of foundation                | Excellent | Medium | Poor |
| Retaining walls                        | Noon | Good Condition | Moderate Condition | Poor Condition |
| Potential of soil liquefaction         | None | Low | Medium | High |
| Overhang                               | ≤5 feet (<1.5 m) | ≥5 feet, <10 feet (1.5–3 m) | ≥10 feet, <15 feet (3–4.6 m) | ≥15 feet (>4.6 m) | Less than 2 m | From 2 m to less than 3 m | From 3 m to less than 5 m | More than 5 m |
| Horizontal (plan) irregularity         | No. No horizontal irregularities | Torsional irregularity | Re-entrant corners | Diaphragm discontinuity | Out-of-plane offsets | Nonparallel Systems |
| Vertical irregularity                  | No. No vertical irregularities | Soft story | Irregularity | Vertical geometric irregularity | Irregularity in lateral force-resisting vertical elements | Discontinuity in strength-weak story |
|                                        | Yes. One or more horizontal irregularities |                                      |                                      |                                      |                                      |                                      |
|                                        | Yes. One or more vertical irregularities |                                      |                                      |                                      |                                      |                                      |
### Table 6. Cont.

| Vulnerability | IRVS          | K-RVS          |
|---------------|---------------|----------------|
| Building height |               |                |
| More or equal to 150 feet (>45.7 m) | <12 floors     | Intermediate Large-Scale Building (60 m to 120 m) |
| Less than 200 feet (<61) | 12 to 15 floors | Large Scale Building (120 m to less than 200 m) |
| 200 feet to less than 500 feet (61 m–52.4 m) | 16 to 39 floors | High Rise Building (200 m to 300 m) |
| 500 feet to less than 800 feet (152.4–243.8 m) | 40 to 60 floors | Sky-Scraping Building (More than 300 m) |
| 800 feet to less than 1000 feet (243.8–304.8 m) | 60 to 80 floors | more than 80 floors |
| More than 1000 feet (>304.8 m) | >80 floors |                |
| Wall type |               |                |
| Cast in place reinforced concrete | Post-benchmark year |                |
| Curtain wall/metal framing |                |                |
| Precast panels/reinforced masonry |                |                |
| Massive unreinforced masonry |                |                |
| Light frame or slender unreinforced masonry (brick) |                |                |
| Unreinforced masonry |                |                |
| Windborne debris impact protection |               |                |
| Post-benchmark year | five or more bays |                |
| All other buildings | three or four bays |                |
| Number of bays in the short direction | Less than three bays |                |
| Column spacing |               |                |
| Less than 15 feet |               |                |
| 15 feet to less than 25 feet |             | Less than 4 m  |
| 25 feet to less than 40 feet |             | 4 m to less than 8 m  |
| 40 feet to less than 60 feet |             | 8 m to less than 12 m  |
| 60 feet or more |             | 12 m to less than 18 m  |
| Unbraced column height |               |                |
| Less than 12 feet |               |                |
| 12 feet to less than 24 feet |             | Less than 4 m  |
| 24 feet to less than 36 feet |             | 4 m to less than 8 m  |
| 36 feet or more |             | 8 m to less than 12 m  |
| Publicly accessible column |               |                |
| Yes, protected. Behind and separated from the building facade and enclosed by and architectural cover that extends at least 6 inches (15 cm) from face of column | No publicly accessible columns |                |
| Yes, massive. Height-to-width ratio of less than five |                |                |
| Yes, slender. Height-to-width ratio of more than five |                |                |
| Number of lateral systems (redundancy) |               |                |
| Greater than four |               |                |
| Four |               |                |
| Three |               |                |
| Two |               |                |
| One |               |                |
| Transfer girder conditions |               |                |
| None. All columns are continuous from roof to foundation | Interior girder supporting one column. The girder spans an interior space and supports one column above |
| Interior girder supporting more than one column. The girder spans an interior space and supports more than one column above |                |
| Exterior girder supporting one column. The girder is along the perimeter of the building and supports one column above |                |
| Exterior girder supporting more than one column. The girder is along the perimeter of the building and supports more than one column above |                |
Table 6. Cont.

| Vulnerability                  | IRVS                                                                 | K-RVS                                                                 |
|-------------------------------|----------------------------------------------------------------------|----------------------------------------------------------------------|
| Structural enhancements and weaknesses | Hardened. Designed to resist the effects of an explosive attack     | Robust. Designed or retrofit to meet current extreme loading conditions related to high levels of hurricane or earthquake loads or designed to resist progressive collapse |
|                               | Robust. Designed or retrofit to meet current extreme loading conditions related to high levels of hurricane or earthquake loads or designed to resist progressive collapse | None. No structural enhancements or weaknesses in the other attribute options (most common) |
|                               | None. No structural enhancements or weaknesses in the other attribute options (most common) | Marginal. Designed using versions of codes that are no longer considered acceptable for meeting serviceability conditions. Designed using materials or connections that have been shown to perform poorly in abnormal loading situations. Building is not well maintained. |
|                               | Marginal. Designed using versions of codes that are no longer considered acceptable for meeting serviceability conditions. Designed using materials or connections that have been shown to perform poorly in abnormal loading situations. Building is not well maintained. | Substandard. Designed to a level that has little, if any, reserve strength to withstand any abnormal loads without catastrophic failure. |
|                               | Substandard. Designed to a level that has little, if any, reserve strength to withstand any abnormal loads without catastrophic failure. |                                                                 |
| Short columns or walls        | None                                                                | Few (one or two) in single floor                                      |
|                               | None                                                                | Several (more than two) in single floor                               |
|                               | Few (one or two) in single floor                                     | Several (more than two) in single floor                               |
|                               | Several (more than two) in single floor                             | Several (more than two) in single floor                               |
| Seismic design/Retrofit       | No                                                                  | Yes                                                                  |
| Roof span                     | 20 feet or less                                                     | 6 m or less                                                          |
|                               | more than 20 feet to less than 40 feet                               | more than 6 m to less than 12 m                                      |
|                               | 40 feet or more                                                     | 12 m or more                                                         |
| Topping slabs                 | Present                                                             | Missing                                                             |
| Adjacent building separation  | No adjacent buildings                                               | Adequate (more than six inches)                                      |
|                               | Adequate (more than six inches)                                      | Not adequate (less than six inches)                                  |
| Fireproof walls               | Not apply                                                           | Yes                                                                  |
|                               | Not apply                                                           | No                                                                   |
| Seismic design category       | Not apply                                                           | A                                                                    |
|                               | Not apply                                                           | B                                                                    |
|                               | Not apply                                                           | C                                                                    |
|                               | Not apply                                                           | D                                                                    |
| Allowable story drift         | Not apply                                                           | S (0.010 h⁎ sx 1)                                                   |
|                               | Not apply                                                           | 1 (0.015 h⁎ sx 1)                                                   |
|                               | Not apply                                                           | 2 (0.020 h⁎ sx 1)                                                   |
| Surface roughness             | Not apply                                                           | A (Large city center with closely spaced tall buildings higher than 10-story) |
|                               | Not apply                                                           | B (City with closely spaced residential houses with heights of 3.5 m or so or scattered medium rise buildings) |
|                               | Not apply                                                           | C (Open terrain with scattered obstructions with heights of 1.5 to 10 m or so or scattered low-rise buildings) |
|                               | Not apply                                                           | D (Exposed open terrain with few obstructions or scattered obstructions less than 1.5 m in height or grassland, beach, airport, etc.) |
| Enclosure                     | Not apply                                                           | Enclosed                                                            |
|                               | Not apply                                                           | Partially open/without dominant opening                             |
|                               | Not apply                                                           | Partially open/with dominant opening                                |
|                               | Not apply                                                           | Open Building                                                       |

1 h⁎: Allowable story drift.

Five new vulnerability characteristics (exterior fireproof walls, seismic design category, allowable story drift, surface roughness, and enclosure) that supplement K-RVS were proposed. Articles 50 and 51 (fireproof structure and fireproof wall of buildings, and buildings
in fire prevention districts) in the Korean Building Act [31] state that the main structural parts and external walls of each building in a fire prevention district should be of a fireproof structure, including apartment houses. KDS [27] maintains that all structures should be assigned to a seismic design category based on their seismic use group and design spectral acceleration. In addition, KDS describes story drift design as the difference in the displacements of the center of mass at the top and bottom of the story under consideration. Surface roughness is defined as the shorter frequency of real surfaces relative to troughs and is widely used for wind environment evaluation. The building enclosure defines the space it encloses. However, more than the building’s outer dimension, the building enclosure is the barrier that separates the external climatic environment, in this case, wind, from the interior. The properties of the building enclosure have a significant effect on efficiency and functionality against the wind.

3. Methodology of the Weight Values

A scoring system was created to evaluate the characteristics in K-RVS. Table 7 shows the different categories and the values for each one, from weight values with very high priority (100) to medium-important weight values (5).

Table 7. Weight values in K-RVS.

| Category          | Weight Value (W) |
|-------------------|------------------|
| Very Highly Important | 100              |
| Highly Important   | 80               |
| Very Important     | 25               |
| Relevant           | 15               |
| Important          | 10               |
| Medium Important   | 5                |

Thus, a score for each characteristic was given, depending on its influence and weight in compromising building security (Table 8). If a feature does not affect the corresponding hazard, a zero score for that characteristic is awarded. The heavily weighted characteristics mentioned in the structural part of IRVS, i.e., target potential building, target density, soil type, structure type, overall site accessibility, topography/slopes, transfer girder conditions, and seismic design/retrofit, are awarded high values.

In addition to the principal characteristics, another classification was made with the same purpose as the previous; however, this classification was evaluated from 1 to 5 (score), from very low to very high risk, passing through low, moderate, and high risk (Table 9).

To determine the final values of each hazard, the aforementioned weight values and scores were introduced into Equations (1) and (2) as follows:

\[
h = \frac{\sum_{i=1}^{48} W_i S_i}{\sum_{i=1}^{48} 5W_i} \times 100
\]

\[
D = \frac{\alpha h_e + \beta h_w + \gamma h_b + \delta h_f}{\alpha H_e + \beta H_w + \gamma H_b + \delta H_f} \times 100
\]

where \(h\) is the score for each hazard, \(W\) is the weight value presented in Table 7, \(S\) is the score presented in Table 9, \(D\) is the final score for disaster assessment of tall buildings focusing on structural safety, \(h_e\) is the score from the earthquake, \(h_w\) is the score from the wind, \(h_b\) is the score from the blast, \(h_f\) is the score from the fire, \(H_e\) is the highest score from the earthquake, \(H_w\) is the highest score from the wind, \(H_b\) is the highest score from the blast, \(H_f\) is the highest score from the fire, \(\alpha\) is the weight index for earthquakes (8.5), \(\beta\) is the weight index for winds (10), \(\gamma\) is the weight index for blasts (9), and \(\delta\) is the weight index for fire (5.5). These weight indices were obtained based on exploration data from IRVS.
### Table 8. Characteristics of weight values in K-RVS.

| Component | No. | Characteristics                                      | Earthquake | Wind | Blast | Fire |
|-----------|-----|------------------------------------------------------|------------|------|-------|------|
| Pre-field 1 | 1   | Structure type                                      | 80         | 100  | 80    | 100  |
|           | 2   | Number of occupants                                 | 10         | 15   | 15    | 25   |
|           | 3   | Replacement value                                   | 15         | 5    | 15    | 10   |
| Pre-field 2 | 4   | Occupancy use                                       | -          | -    | 15    | 25   |
|           | 5   | Target density: Zone I                              | -          | -    | 15    | 25   |
|           | 6   | Target density: Zone II                             | -          | -    | 15    | 15   |
|           | 7   | Target density: Zone III                            | -          | -    | 15    | 15   |
|           | 8   | Target potential: Building                          | -          | -    | 25    | 25   |
|           | 9   | Target potential: Sector                            | -          | -    | 10    | 25   |
|           | 10  | Seismic zone                                        | 25         | -    | -     | 10   |
|           | 11  | Proximity to an active seismic fault                 | 25         | -    | -     | 10   |
|           | 12  | High wind speed zone                                | 5          | 10   | -     | -    |
|           | 13  | Typhoon frequency in the region                     | -          | 25   | -     | -    |
|           | 14  | Soil type                                           | 25         | -    | -     | -    |
| Consequences | 15  | Locality/Density type                               | 10         | 10   | 10    | 15   |
|           | 16  | Operational redundancy                              | 10         | 10   | 10    | 10   |
|           | 17  | Impact of physical loss                             | 10         | 10   | 10    | 10   |
| Threat | 18  | Site population density                             | -          | -    | 10    | 15   |
|          | 19  | Symbolic value                                      | -          | -    | 10    | 15   |
|          | 20  | Overall site accessibility                          | -          | -    | 25    | 25   |
| Site     | 21  | Nearby structures                                   | 15         | 5    | 15    | 10   |
|          | 22  | Topography/Slopes                                   | 25         | 25   | 25    | -    |
|          | 23  | Condition of foundation                             | 15         | -    | -     | -    |
|          | 24  | Retaining walls                                     | 10         | 5    | -     | -    |
|          | 25  | Potential of soil liquefaction                      | 15         | -    | -     | -    |
| Architectural | 26  | Building height                                     | 10         | 15   | 25    | 15   |
|          | 27  | Overhang                                            | 10         | 5    | 10    | 5    |
|          | 28  | Horizontal irregularity                             | 15         | 5    | -     | -    |
|          | 29  | Vertical irregularity                               | 15         | 5    | -     | -    |
| Vulnerability  | 30  | Number of bays in the short direction               | 5          | 5    | 15    | -    |
|          | 31  | Column spacing                                      | 5          | 5    | 10    | -    |
|          | 32  | Unbraced column height                              | 5          | 5    | 10    | -    |
|          | 33  | Publicly accessible column                          | -          | -    | 15    | 5    |
|          | 34  | Transfer girder conditions                          | 25         | 25   | 15    | -    |
| Structure | 35  | Structural enhancements and weaknesses              | 5          | 5    | 5     | -    |
|          | 36  | Number of lateral systems                           | 5          | 10   | 5     | -    |
|          | 37  | Short columns                                       | 15         | 5    | -     | -    |
|          | 38  | Seismic retrofit                                    | 25         | 10   | 15    | -    |
|          | 39  | Roof span                                           | -          | 5    | -     | -    |
|          | 40  | Topping slabs                                       | 5          | 5    | -     | -    |
|          | 41  | Building separation                                 | 15         | -    | -     | -    |
| Building Enclosure | 42  | Wall type                                           | 5          | 10   | 15    | -    |
| New | 43  | Windborne debris impact Protection                   | -          | 10   | 10    | -    |
|          | 44  | Exterior fireproof walls                            | -          | -    | 15    | 15   |
|          | 45  | Seismic design category                             | 5          | -    | -     | -    |
|          | 46  | Allowable story drift                               | 5          | -    | -     | -    |
|          | 47  | Surface roughness                                   | -          | 5    | -     | 5    |
|          | 48  | Enclosure                                           | -          | 5    | -     | 15   |
Table 9. Score values of the classification.

| Classification | Scores (S) |
|----------------|------------|
| Very low       | 1          |
| Low            | 2          |
| Moderate       | 3          |
| High           | 4          |
| Very High      | 5          |

The final score \(D\) for disaster assessment of tall buildings will be explained as values with percentages, which can be classified by colors, as shown in Table 10.

Table 10. Color table depending on the disaster assessment of tall buildings.

| Color | Final Score \((D)\) | Disaster Assessment |
|-------|---------------------|---------------------|
| Green | 0–30%               | Low risk            |
| Yellow| 30–50%              | Moderate risk       |
| Orange| 50–70%              | High risk           |
| Red   | 70–100%             | Very high risk      |

4. Verification and Discussions

4.1. K-RVS Access System

The K-RVS access system database was created using Microsoft Access, a data management system in IRVS, which is a very useful tool when many data tables are being used. The K-RVS database allows the creation of several reports from different buildings to evaluate and present results simultaneously, as shown in Figure 3.

![Figure 3. Example of K-RVS access system.](image-url)
4.2. Building Examples

A comparison between K-RVS and IRVS was done with three different building examples; two imaginary and one real. Because it was extremely difficult to obtain detailed information on tall buildings, two imaginary buildings based on existing buildings with little data and an existing building with sufficient data were selected for verification. The existing building is the KLI 63 building [32], which is located in Seoul and has a height of 249.6 m and 63 floors, including roof and mechanical facility floors. It was built in 1985, and is currently used by commercial offices. The information on KLI 63 and the two imaginary buildings is presented in Table 11.

Table 11. Information on the KLI 63 building and two imaginary buildings in IRVS and K-RVS.
Table 11. Cont.

| Component No. | Characteristics | KLI 63 Building | Imaginary Building 1 | Imaginary Building 2 |
|---------------|-----------------|-----------------|----------------------|---------------------|
| Site          |                 | IRVS K-RVS      | IRVS K-RVS           | IRVS K-RVS          |
| 21            | Nearby structures | None None | Medium Moderate | Major Major |
| 22            | Topography/Slopes | Flat Flat | Excellent Excellent | Steep Steep |
| 23            | Condition of foundation | Excellent Excellent | Excellent Moderate | Poor Poor |
| 24            | Retaining walls | None None | Low Low | Medium Medium |
| 25            | Potential of soil liquefaction | Low Low | Low Low | Low Low |
| Architectural |     | 800–1000 ft (60–80 floors) | High Rise Building (200 m to 300 m) | 200–500 ft |
| 26            | Building height | 200–500 ft | Intermediate Large Scale (60–120 m) | 500–800 ft |
| 27            | Overhang | None None | From 2 m to less than 3 m | More than 5 m |
| 28            | Horizontal irregularity | None None | Yes | Yes |
| 29            | Vertical irregularity | None None | Yes | Yes |
| Vulnerability |     | 3–5 | 3 or 4 Bays | 3–5 | 3 or 4 Bays | <3 | Less than 3 Bays |
| 30            | Number of bays in the short direction | 15–25 ft | 15–25 ft | 15–25 ft | 15–25 ft | >60 ft | More than 18 m or more |
| 31            | Column spacing | 12–24 ft | 24–36 ft | 8–12 m | >36 ft | Yes, Slender Ext. Girder Sup. > 1 Column |
| 32            | Unbraced column height | None None | Yes, Massive Int. Girder Sup.1 Column | Yes, Slender Ext. Girder Sup. > 1 Column |
| 33            | Publicly accessible column | None None | Yes, Massive Int. Girder Sup.1 Column | Yes, Slender Ext. Girder Sup. > 1 Column |
| 34            | Transfer girder conditions | None None | Yes, Massive Int. Girder Sup.1 Column | Yes, Slender Ext. Girder Sup. > 1 Column |
| 35            | Structural enhancements and weaknesses | None None | None None | Marginal Marginal |
| 36            | Number of lateral systems | 1 | One | Three | Two |
| 37            | Short columns | None None | Few in a Single Floor No | Few in a Single Floor No | Few in Several Floors No |
| 38            | Seismic retrofit | Yes Yes | Yes Yes | Yes Yes |
| 39            | Roof span | ≤20 ft | 6 m or less | >20–<40 ft | >40 ft | 12 m or more |
| 40            | Topping slabs | Present | Present | Missing | Missing |
| 41            | Building separation | No adjacent buildings | Adequate | Adequate | Adequate |
| Building Enclosure |     | Curtain Wall | Curtain Wall | Light frame | Light frame | Curtain Wall | Curtain Wall |
| 42            | Wall type | Yes | Yes | Yes | Yes |
| 43            | Windborne debris impact Protection | N/A | N/A | N/A | N/A |
| New          |     | N/A | N/A | N/A | N/A |
| 44            | Exterior fireproof walls | Yes | B | N/A | N/A |
| 45            | Seismic design category | N/A | N/A | A | B |
| 46            | Allowable story drift | 1 (0.015 hax) | 1 (0.020 hax) | N/A | N/A |
| 47            | Surface roughness | N/A | N/A | N/A | N/A |
| 48            | Enclosure | N/A | Partially Open (without dominant opening) | N/A | Enclosed |
4.3. Results and Discussions

The scores for each hazard (\(h\)) and the final score (\(D\)) from the K-RVS and IRVS assessment systems for the KLI 63 building and two imaginary buildings are shown in Table 12 and Figure 4. The scores and overall trends of the KLI 63 building and two imaginary buildings in K-RVS and IRVS were similar, except for earthquake and total scores. This is why characteristics focusing on earthquake weight values, such as soil type, horizontal and vertical irregularity, seismic design category, and allowable story drift, were segmentalized. In addition, K-RVS determined that the earthquake risks of the example buildings were quite higher than those of IRVS because Korea is in a low-moderate seismic zone where weaker earthquakes occur than in the U.S. For fire and blast hazards, the scores by both systems were slightly different owing to new characteristics. For wind hazards, the scores showed inconsistent results because characteristics related to wind speed in K-RVS were more segmentalized owing to various terrain features. The scores for fire in K-RVS are lower than those in IRVS because the law related to high-rise buildings in Korea focuses on the prevention and egress of fire accidents. Besides fire, all other scores in K-RVS were higher than those in IRVS, which means that disaster assessments in Korea by IRVS were underestimated. Finally, considering the KDS and Korean conditions, the K-RVS modified from IRVS can rapidly and conservatively conduct disaster assessments of tall buildings under multiple hazards.

Table 12. Score by each hazard and final score from K-RVS and IRVS.

| Hazards      | System | KLI 63 Building | Imaginary Building 1 | Imaginary Building 2 |
|--------------|--------|-----------------|-----------------------|-----------------------|
| Fire         | K-RVS  | 76.32           | 75.67                 | 96.34                 |
|              | IRVS   | 79.06           | 79.84                 | 92.93                 |
| Blast        | K-RVS  | 65.57           | 75.67                 | 91.75                 |
|              | IRVS   | 56.93           | 65.63                 | 84.75                 |
| Earthquake   | K-RVS  | 44.30           | 62.80                 | 89.25                 |
|              | IRVS   | 8.08            | 46.35                 | 70.26                 |
| Wind         | K-RVS  | 66.39           | 75.00                 | 88.61                 |
|              | IRVS   | 67.02           | 53.31                 | 74.25                 |
| Total        | K-RVS  | 61.70           | 71.86                 | 90.03                 |
|              | IRVS   | 47.85           | 54.49                 | 84.38                 |

Figure 4. Score by each hazard and final score from K-RVS and IRVS.
5. Conclusions

This study introduces a Korean rapid visual screening (K-RVS) system that can rapidly perform disaster assessment of tall buildings subjected to four major disasters: fire, blast, earthquake, and wind. The K-RVS system was based on the integrated rapid visual screening (IRVS) system provided by FEMA in the U.S., and modified according to the Korean Design Standard (KDS) and Korean conditions. The K-RVS system includes two pre-field data: consequences, threats and vulnerability characteristics, which are classified into several categories. These categories with each weight value were used to score each hazard and calculate the final score for disaster assessment. The KLI-63 building and two imaginary buildings, based on existing buildings with little information, were selected to test the K-RVS system. The scores and overall trends of the three buildings by K-RVS and IRVS were similar, except for earthquakes. Because of segmentalized characteristics focusing on earthquakes in the K-RVS, the scores differed significantly. Finally, the scores for each hazard and final scores by the K-RVS were lower than those in IRVS because the IRVS system underestimated the disaster assessment of tall buildings in Korea, owing to the gap between the KDS and Korean conditions. For example, segmentalized characteristics in K-RVS aim to evaluate the structural assessment of the tall building in Korea because Korea is in a low-to-moderate seismic zone, which is different from the IRVS characteristics. This paper can inspire other countries with different multi-hazard conditions from IRVS to suggest a new RVS system for their own multi-hazard conditions.

Author Contributions: Conceptualization, M.J.P. and Y.K.J.; methodology, M.J.P. and Y.K.J.; software, M.J.P. and Y.K.J.; validation, Y.K.J.; formal analysis, M.J.P. and Y.K.J.; investigation, M.J.P. and Y.K.J.; resources, M.J.P. and Y.K.J.; data curation, M.J.P. and Y.K.J.; writing—original draft preparation, M.J.P. and Y.K.J.; writing—review and editing, M.J.P. and Y.K.J.; visualization, M.J.P.; supervision, Y.K.J.; project administration, M.J.P. and Y.K.J.; funding acquisition, Y.K.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. NRF-2021R1A5A1032433 & NRF-2020R1A2C3005687). The authors are grateful to the authorities for their support.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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