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EVALUATION OF IN-STRUCTURE RESPONSE SPECTRA ACCORDING TO DIFFERENT STRUCTURAL TYPES OF SUBSTATIONS

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Abstract

Substation structures have various power facilities at different heights, so seismic design of the power facilities should be carried out in consideration of the amplification of the ground motion according to the height of the structure. Korea's substations are classified into 7 representative structural types, with 3 steel frame types and 4 reinforced concrete frame types. For these 7 representative substations, a structural analysis model was created using the Midas-Gen program, considering the location and mass of the power facilities. Twenty input earthquakes representing near-fault and far-field earthquakes were selected. The seismic analysis of these seven representative substations was performed, and the acceleration response for each floor was obtained, and the in-structure response spectra (ISRS) was evaluated. The acceleration amplification factor calculated from the ISRS was evaluated by comparing it with the acceleration amplification coefficients used in the seismic design of the power facilities in substations of the United States and Japan.

Keywords: in-structure response spectra; substations; power facilities

1. Introduction

The recent Gyeongju (2016) and Pohang (2017) earthquakes have raised concerns about the safety of power facilities including nuclear power plants in South Korea. A momentary power outage of about 2 seconds occurred during the Gyeongju earthquake, which raised doubts about the seismic instability of the power plant. As a result of the momentary power failure caused by the earthquake, the efforts and researches to secure the seismic performance of power facilities have been actively conducted.

There are various types of power facilities in substation structures, and the representative ones are transformers and gas insulated switchgear (GIS). Since substation structures in Korea are usually four to five stories high, the amplification of the seismic acceleration response is affected by the location of the floor where the power facility is installed. Seismic acceleration is input to the structure from the earth's surface and the acceleration increases as the height of the structure increases. Therefore, the acceleration amplification factor is used as the main variable in the seismic design of power facilities by reflecting the effect of the acceleration increase as the number of floors of the substations increases.

In this study, substations were classified into 7 representative types according to their structural types. Structural analysis models for 7 representative substation types were prepared using MIDAS-Gen program [1]. Seismic analysis was performed using various seismic acceleration records to obtain the acceleration response for each substation height, and the acceleration amplification factor was calculated as the ratio of the acceleration response for each floor to the first floor. The In-Structure Response Spectrum (ISRS), which is required for the acceleration amplification factor, was calculated using BISPEC [2], a response spectrum program, using the seismic acceleration response of each substation's floor as the input acceleration. Since most power facilities are high frequency devices with frequency in the range of 5 ~ 30 Hz, the average response of ISRS is calculated for various high frequency ranges, and the acceleration amplification factor is calculated by dividing it by the acceleration response of the first floor. The calculated amplification factors were compared with the acceleration amplification coefficients calculated by the ASCE 7-16 [3] and the Japan guidelines for seismic design diesel generators [4] for each substation structure type.

2. Representative Substation Types in Korea and Characteristics of Input Earthquake

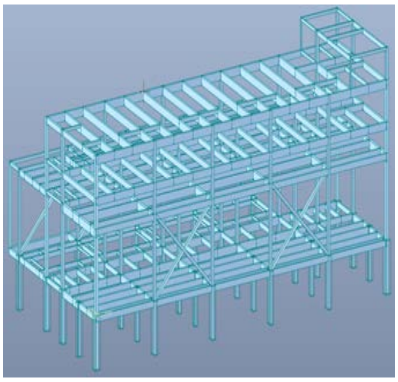
2.1 Structural analysis modeling of substations

There are various substations in Korea. Shinkimpo substation with a capacity of 345 kV costructed in 2011 as a representative steel frame type is shown in Fig. 1. Evaluating the acceleration amplification factors for all substations requires a lot of effort and time. Therefore, seven representative structural substations of Korea were selected and the structural analysis model was prepared using the MIDAS-Gen program [1]. In the substation structural analysis model, SS400, SWS400, SW490, SM400, and SM490 steel section were mainly used, and C21 model(mass density 2.4 kN/m/g) was used as concrete member. The structural modeling of the seven representative structural substations are shown in Fig. 2. The seven representative substations were named in the order of the region name and the name of the material (steel or reinforced concrete). For example, the name of the substation in the Geumo area with steel frame members is named Geumo-Steel. The seven substations for this naming are named Geumo-Steel, Shinchon-RC, Ssangmun-RC, Hannam-Steel, Shinchon-RC, Seongdong-RC, and Shinkimpo-Steel as shown in Fig. 2(a) to (g). The location distribution of specific members in the substation structural analysis model is shown in Fig. 2 (g-1) to (g-7) by selecting Shinkimpo-Steel as a representative example. For all substation structural analysis models, the dead weights of the structures and power facilities were acted as the dead weights and converted into mass to reflect in the structural analysis models.

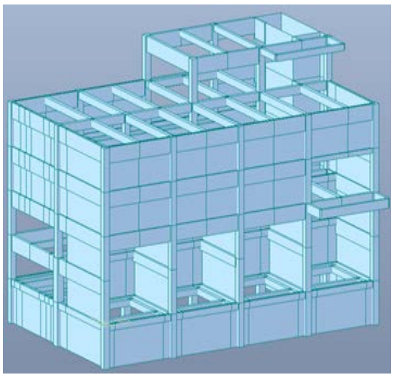
2.2 Input earthquakes

As an input earthquake for calculating the acceleration amplification factor of substation structure, real earthquake was used instead of artificially generated earthquake. The reason is that the artificially generated earthquake corresponding to the design spectrum can be used for the purpose of seismic design, but it does not have the dynamic characteristics of various real earthquakes. Therefore, it is advisable to use the real seismic acceleration record to estimate or evaluate seismic design parameters such as the acceleration amplification factor. Since there are no strong earthquakes recorded in Korea, we used 20 earthquakes measured in the United States as input ground motions. There are 10 near-fault earthquakes and 10 far-field earthquakes. In general, the near-fault earthquakes have large velocity pulses and long period components, causing large displacement responses of structures. In the condition of similar peak ground acceleration (PGA), the near-fault earthquake has a larger peak ground velocity (PGV) than the far-field earthquake. The acceleration response spectra calculated for the near-fault and far-field earthquakes used in this study are shown in Fig. 3. It can be observed that the average response of the acceleration response spectrum for 10 far-field earthquakes is about 1.5 times larger in the high frequency region above 5 Hz than that of the near-fault earthquakes.

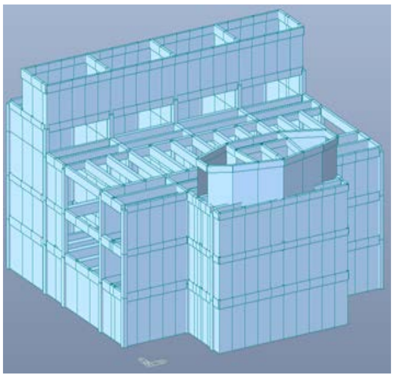
Fig. 1 - 345 kV Shinkimpo-Steel Substation



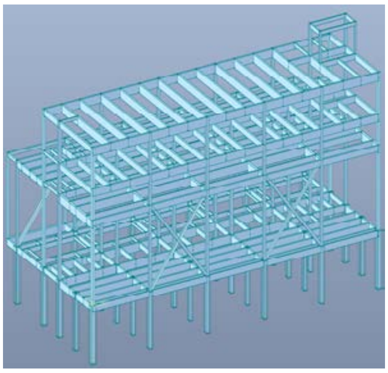
(a) Geumo-Steel



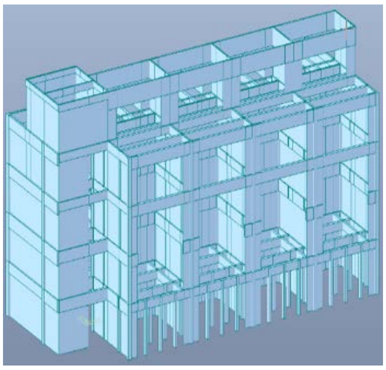
(b) Shinchon-RC



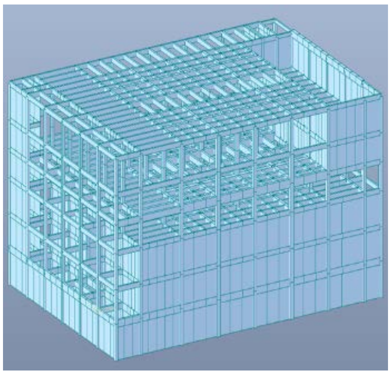
(c) Ssangmun-RC



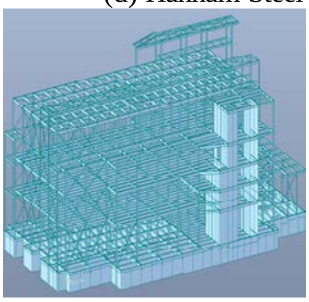
(d) Hannam-Steel



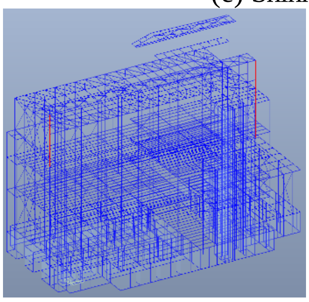
(e) Shinnae-RC



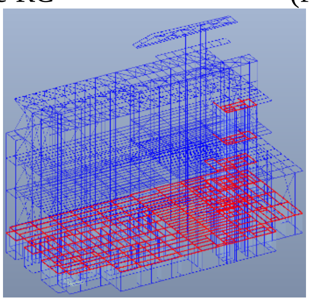
(f) Seongdong-RC



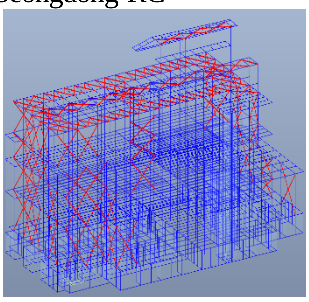
(g) Shinkimpo-Steel



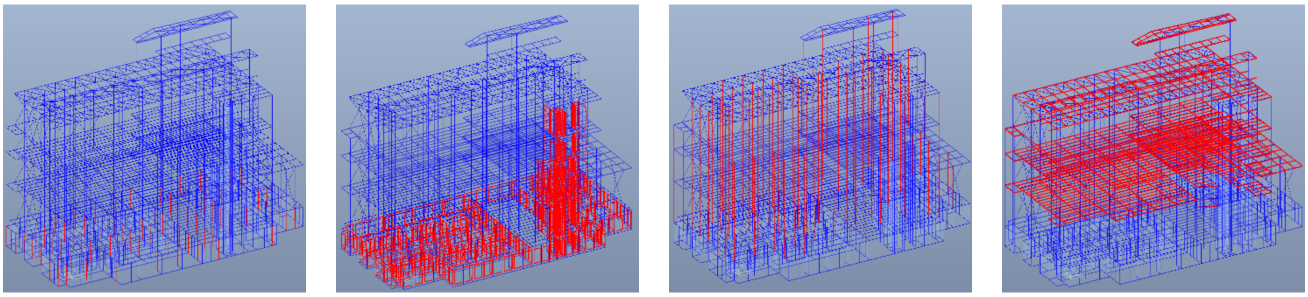
(g-1) SM400 steel column



(g-2) C240 RC beam

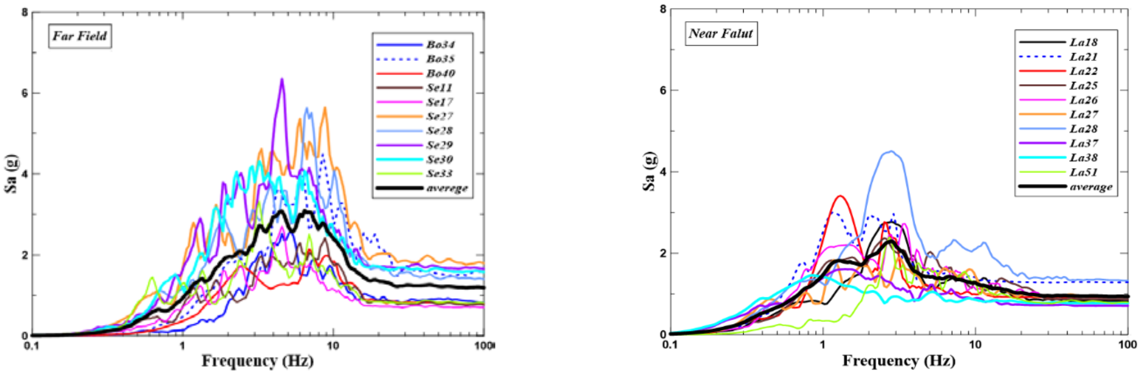


(g-3) SS400 steel brace



(g-4) C240 RC column (g-5) C240 wall (g-6) SM490 steel column (g-7) SS400 steel beam

Fig. 2 - Structural analysis modeling using MIDAS-Gen program for the seven representative substations of Korea



(a) far-field earthquakes (b) near-fault earthquakes

Fig. 3 - Acceleration response spectrum of near-fault and far-field earthquakes

3. Comparison of Existing Equations for Acceleration Amplification Coefficients

3.1 Calculation formula of acceleration amplification coefficient in Japan [4]

The acceleration amplification coefficient, α_J, of power facility in Japan is determined by the installation location of power facility according to the natural frequency and height of the structure in which the power facility is installed. The acceleration amplification coefficient, α_J, can be expressed as Eq. (1) and Fig. 4.

$$\alpha_J = \begin{cases} 1 + (A_B - 1)\frac{h}{H} : above\ ground \\ \quad 1 \quad : underground \end{cases} \tag{1}$$

Where, H is the height of the top floor of the structure from the ground level, h is the height of the location where the power facility is installed, A_B is the acceleration amplification factor of the top floor of the structure. In the case of the top story of the structure, α_J is equal to A_B. The A_B can be obtained as Eq. (2) according to the natural period, T_B, of the substation structure.

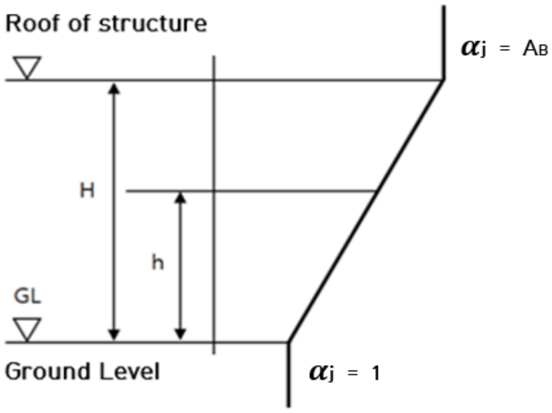


Fig. 4 - Acceleration amplification coefficient α_J for substation (Japan)

$$A_B = \begin{cases} \frac{10}{3} & : T_B < 0.6 \\ \frac{10}{3} - \frac{2}{3}\left(\frac{T_B}{0.6} - 1\right)^2 & : 0.6 \le T_B < 1.2 \\ \frac{3.2}{T_B} & : T_B \ge 1.2 \end{cases} \tag{2}$$

And, the natural period, T_B, of the structure is obtained using Eq. (3).

$$T_B = (0.02 + 0.01\beta)H \tag{3}$$

Where, β is 1 for steel frame and 0 for reinforced concrete structure.

3.2 Calculation formula of acceleration amplification coefficient in USA [3]

The acceleration amplification coefficient, α_A, is a linear proportional relationship from the height h of the location where the power facility is installed to the total height H of the structure. The α_A can be expressed as Eq. (4).

$$\alpha_A = 1 + 2\frac{h}{H} \tag{4}$$

3.2 Acceleration amplification coefficient in South Korea [5]

In Korea, the acceleration amplification coefficient, α_K, are defined in the seismic design guidelines for seismic design of diesel generators in island areas and the seismic design guidelines for transmission substations [5] as shown in Table 1.

Table 1. Acceleration amplification coefficient α_K for substation (Korea)

Installation Location	α_K
Basement and 1st story	1.0
2nd and 3rd story	2.0
Over than 4th story	Calculation from dynamic analysis

4. Estimation of In-Structure Response spectrum and Acceleration Amplification Factors according to Substation Structural Types

4.1 Evaluation procedure of the acceleration amplification factor

The process of evaluating the acceleration amplification factor, which represents the degree of amplification of the seismic acceleration response as the floor or height of the substation structure increases, takes several steps. The step-by-step procedure for the acceleration amplification factor is divided into four steps and summarized in Fig. 5.

The first step is to build a structural analysis model for the substation structure and then perform a response history analysis using various input earthquakes. The response history analysis was performed using the Midas-Gen program. The second step is to calculate the acceleration response, $A_i(t)$, for each floor or height of the substation structure. Where, *i* represents the number of floor. The acceleration response, $A_i(t)$, was evaluated as an average of the acceleration responses of five locations (four corners on a square plane and one central location) per floor of the substation structure. In the third step, the acceleration response spectrum, $S_a(i)$, calculated using the acceleration response, $A_i(t)$, as the input earthquake. This response spectrum is called the In-Structure Response Spectrum (ISRS) in the field of seismic design of nuclear power plants and power facilities. The ISRS was calculated using the BiSPEC program [2]. In the fourth step, the acceleration amplification factor, $F_a(i)$, can be obtained by dividing the ISRS of each floor, $S_a(i)$, by the ISRS of the first floor, $S_a(1)$.

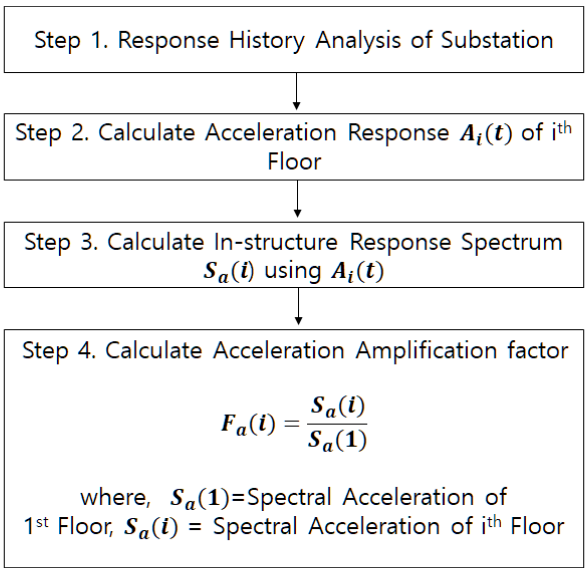
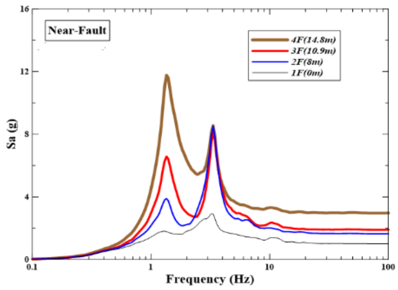


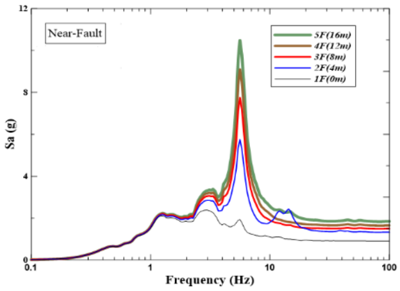
Fig. 5 - Estimation Flowchart of Acceleration Amplification Factor, $F_a(i)$, for substation

4.2 Evaluation of Acceleration Amplification Factor According to Substation Structural Type

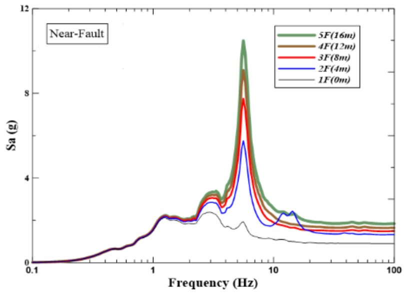
The ISRS, $S_a(i)$, of the seven substation structural types are shown in Figs. 6 and 7, divided into two group for the near-fault and far-field earthquakes, respectively. One ISRS plot represents the mean value of the ten earthquake responses, respectively, for the far-field or near-fault earthquakes. For one earthquake record, the average value of the acceleration response at five positions for each floor of the substation structure is obtained. Therefore, one ISRS plot represents the average value of 50 responses. It can be seen that the frequency range where the peak value of the response spectrum appears varies according to the type of substation structure. It can be seen that the peak value of the acceleration spectrum occurs in the frequency range of 1 to 5 Hz in Geumo-Steel, 4 to 10 Hz in Sinchon-RC, 8 to 30 Hz in Ssangmun-RC, 1 to 10 Hz in Hannam-Steel, 3 ~ 20 Hz in Sinnae-RC, 2 ~ 5 Hz in Seongdong-RC, and 0.5 ~ 10 Hz in Shinkimpo-Steel, respectively. There are three substations made of steel members and four substations made of reinforced concrete (RC) members. In steel substations, the acceleration spectrums have peak values in the low frequency region of about 1 to 5 Hz. In the substations made of reinforced concrete, the acceleration spectrums have peak values in the high frequency region of about 5 to 20 Hz. This tendency is due to the difference between the natural frequencies of the steel substation with low natural frequency and the reinforced concrete substation with high frequency.



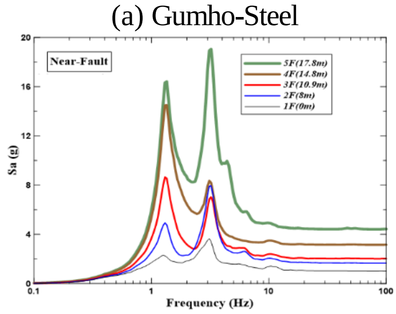
(a) Gumho-Steel



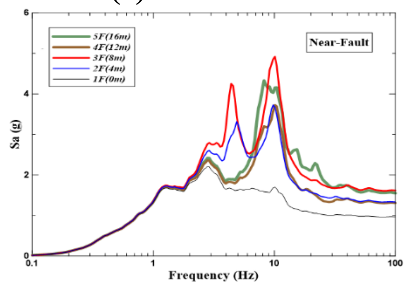
(b) Shinchon-RC



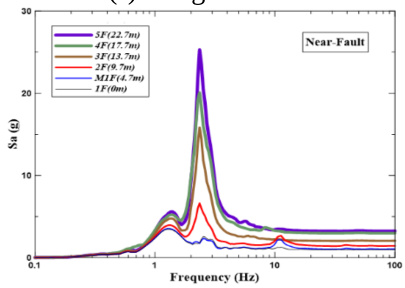
(c) Ssangmun-RC



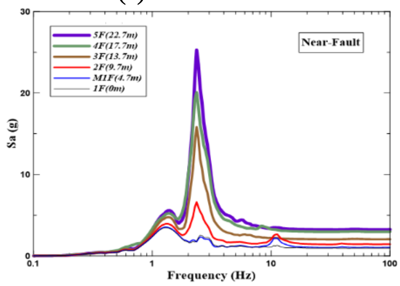
(d) Hannam-Steel



(e) Shinnae-RC



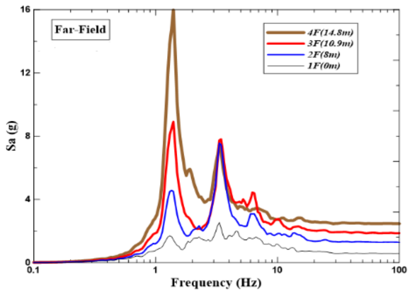
(f) Seongdong-RC



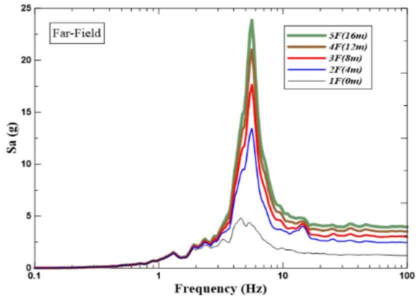
(g) Shinkimpo-Steel

Fig. 6 - Comparison of in-structure response spectrum (ISRS) according to substation structural type for near-fault earthquakes

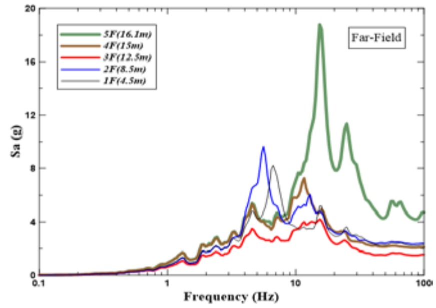
The ISRS divided into the case of far-field and near-fault earthquakes shows that the ISRS of the far-field is larger in the high frequency region of 10 Hz or more than that of the near-fault. This tendency is equivalent to the fact that the acceleration response spectra of the far-field earthquakes are larger in the high frequency region than those of the near-fault earthquakes as shown in Fig. 3, and is due to the difference in the dynamic characteristics of the input earthquakes.



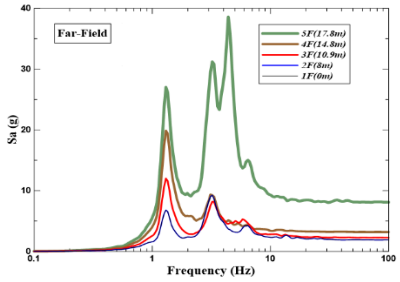
(a) Gumho-Steel



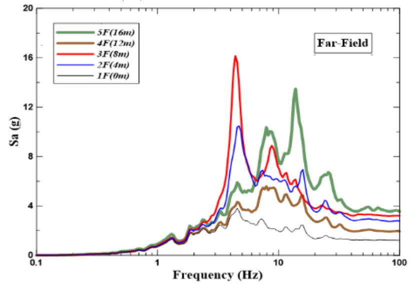
(b) Shinchon-RC



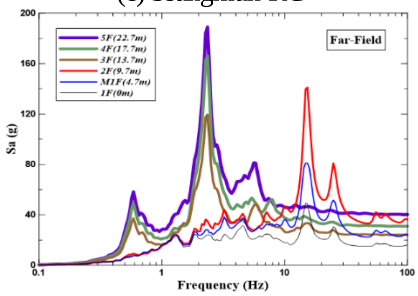
(c) Ssangmun-RC



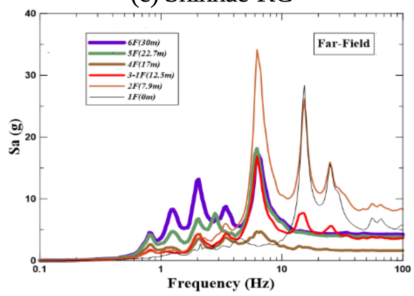
(d) Hannam-Steel



(e) Shinnae-RC



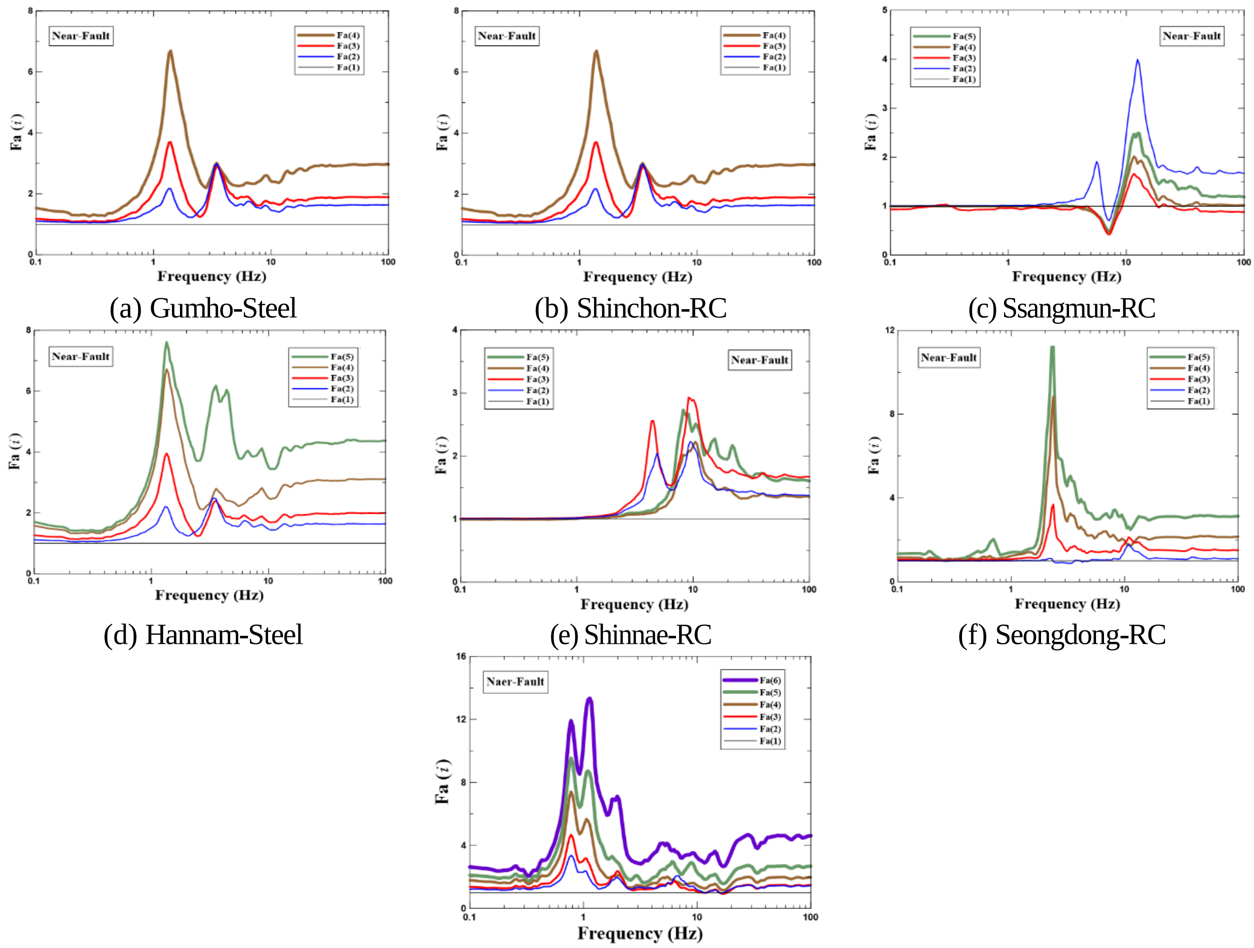
(f) Seongdong-RC



(g) Shinkimpo-Steel

Fig. 7 - Comparison of in-structure response spectrum (ISRS) according to substation structural type for far-field earthquakes

The acceleration amplification factors, $F_a(i)$, according to the seven substation structural types are shown in Figs. 8 and 9, respectively, for the near-fault and far-field earthquakes. It can be seen that the acceleration amplification factors, $F_a(i)$, show the peak values in the vicinity of 1 ~ 3 Hz for the substations mainly constructed with steel frame, Geumo-Steel, Hannam-Steel and Shinkimpo-Steel. In the case of four substations with reinforced concrete structures, it can be observed that the acceleration amplification factors, $F_a(i)$, show the peak values around 5 to 20 Hz. Also, it can be seen that the acceleration amplification factors, $F_a(i)$, for the far-field earthquakes are larger in the high frequency region of 10 Hz or more than those for the near-fault earthquakes. Most of the power facilities installed inside the substation structure is characterized by having a natural frequency of 10 Hz or more. The high frequency characteristics of these power facilities are mostly due to their strong stiffness and relatively small mass. In order to obtain the acceleration amplification factor, $F_a(i)$, for the purpose of seismic design of power facilities, it is reasonable to use the average value for the frequency range of various power facilities. In this study, the frequency range of 5 to 30 Hz was used to obtain the average value of the acceleration amplification factor, $F_a(i)$.



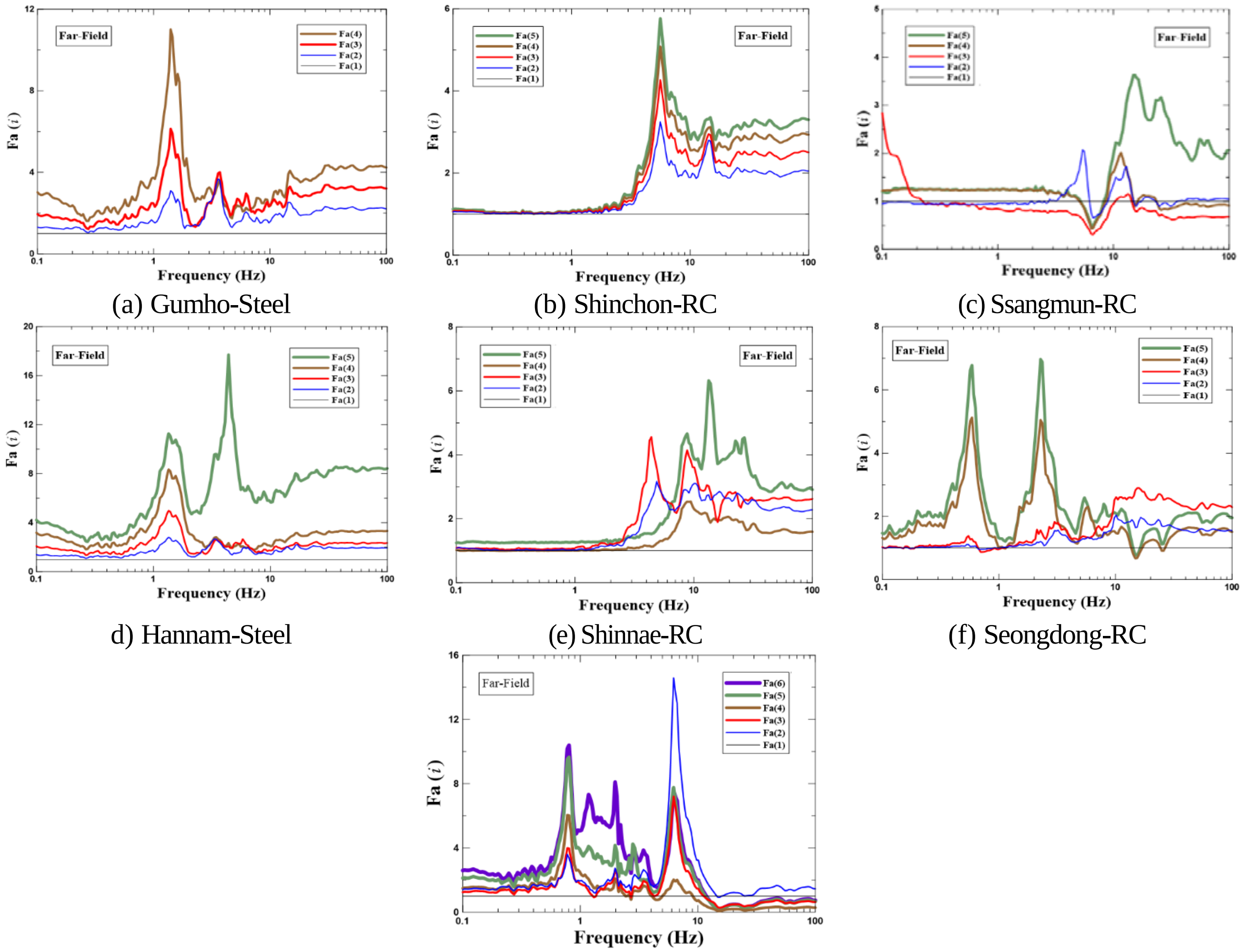
(a) Gumho-Steel (b) Shinchon-RC (c) Ssangmun-RC

(d) Hannam-Steel (e) Shinnae-RC (f) Seongdong-RC

(g) Shinkimpo-Steel

Fig. 8 - Comparison of acceleration amplification factor $F_a(i)$ according to substation structural type for near-fault earthquakes

For the frequency range from 5 to 30 Hz, the average values of the acceleration amplification factor, $F_a(i)$, according to the height of the substations are shown in Fig. 10. In Fig. 10, the acceleration amplification coefficients, α_A, α_J, and α_K according to the seismic design standards of the US, Japan, and Korea are also compared. In the case of α_A and α_J, the acceleration amplification coefficient increases linearly with the height of the substation. In the case of α_K, it means to use 2 as acceleration amplification coefficient for 2nd and 3rd floors, and to use the result obtained dynamic analysis for the further floors. It can be observed that the trend of $F_a(i)$ using the α_J evaluates slightly larger than that using the α_A, but both coefficients show a similar trend with a linear increase according to height increase.



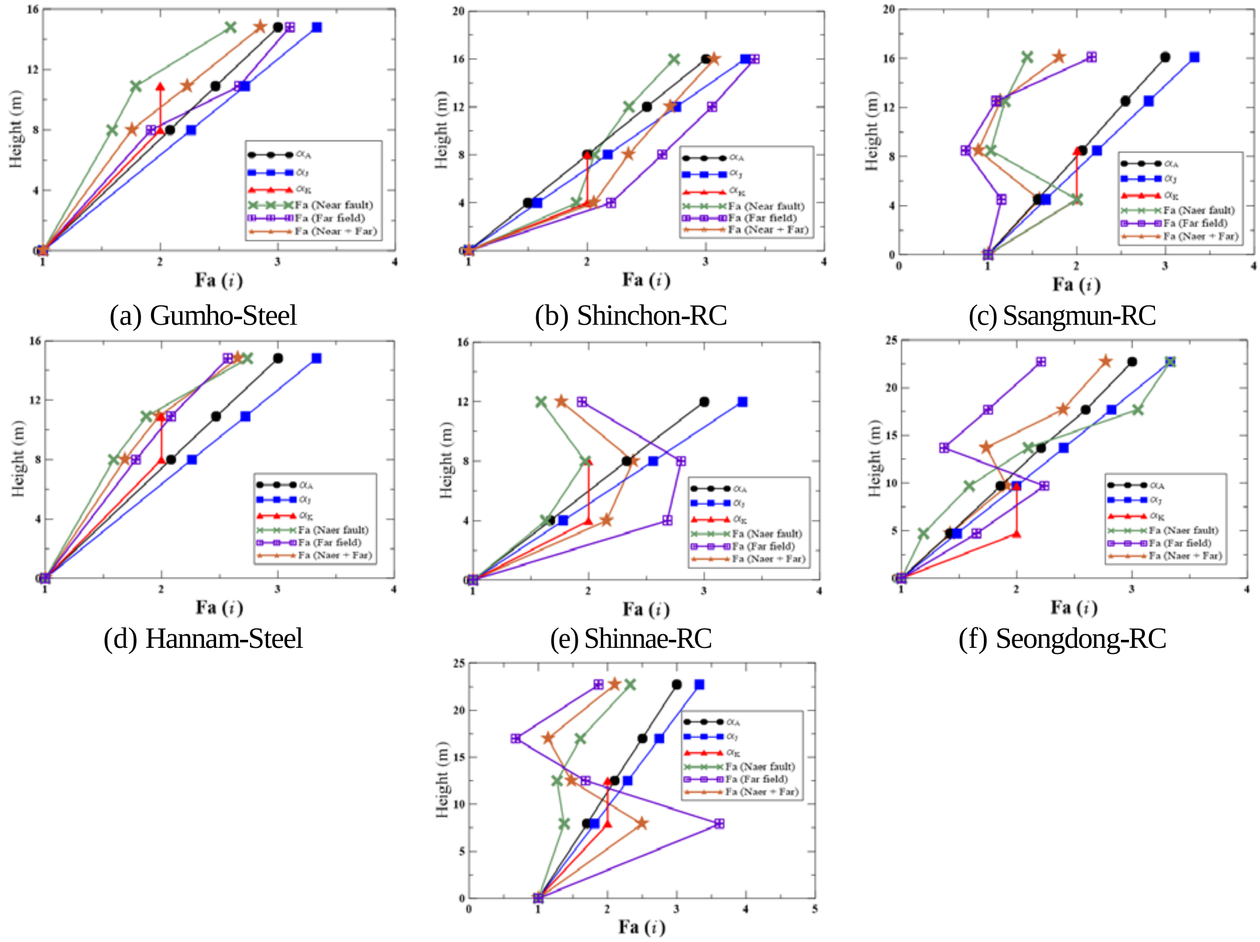
(a) Gumho-Steel (b) Shinchon-RC (c) Ssangmun-RC

d) Hannam-Steel (e) Shinnae-RC (f) Seongdong-RC

(g) Shinkimpo-Steel

Fig. 9 - Comparison of acceleration amplification factor $F_a(i)$ according to substation structural type for far-field earthquakes

For the Geumo-Steel substation shown in Fig. 10 (a), the α_J and α_A show conservative evaluation results, and for the far-field earthquakes, $F_a(i)$ show values larger than the α_A and smaller than the α_J for three or higher floors. The average of $F_a(i)$ for the near-fault and far-field earthquakes tends to be slightly smaller than the α_A, and increases linearly with height. For the Geumo-Steel Substation, the α_A shows the closest result to the calculated $F_a(i)$ value. In the case of Sinchon-RC shown in Fig. 10 (b), it can be seen that the calculated $F_a(i)$ values are evaluated larger than the α_J and the α_A for all the floors below the 4th floor except the 5th floor. In the case of the Ssangmun-RC shown in Fig. 10 (c), it can be seen that the calculated $F_a(i)$ values are estimated to be about 50% smaller than the values of α_A, α_J and α_K except for the results of the second floor in the case of the near-fault earthquakes. In the case of Hannam-Steel shown in Fig. 10 (d), the calculated $F_a(i)$ values are generally 20 ~ 50% smaller than the values of α_A, α_J and α_K, but the trend of linear increase of $F_a(i)$ with height is clearly shown. In the case of Sinnae-RC, Seongdong-RC, and Shinkimpo-Steel, as shown in Fig. 10 (e ~ f), the $F_a(i)$ values of 2nd ~ 3th floors are evaluated to be smaller than the values of α_A, α_J and α_K. Contrary to this tendency, the values of $F_a(i)$ values in the 4th to 6th floors tend to be larger than those of α_A, α_J and α_K. In Ssangmun-RC, Sinnae-RC, and Shinkimpo-Steel, the calculated $F_a(i)$ values in the lower floors are larger than those in the higher floors. This tendency is because the mass distribution of substation structures and power facilities is more concentrated in the lower floors, so the seismic response acts more strongly in the heavy floors.



(a) Gumho-Steel (b) Shinchon-RC (c) Ssangmun-RC (d) Hannam-Steel (e) Shinnae-RC (f) Seongdong-RC (g) Shinkimpo-Steel

Fig. 10 - Comparison of average value of $F_a(i)$ over 5~30 Hz frequency range for near-fault and far-filed earthquakes and $F_a(i)$ calculated by using α_A, α_J and α_K..

5. Conclusions

The substations in Korea were classified into seven types according to the representative structural types, and the in-structure response spectrum (ISRS) was evaluated by using 10 far-filed and 10 near-fault earthquakes. The acceleration amplification factors of the substations were calculated from the ISRS and compared with the acceleration amplification coefficients, α_A, α_J and α_K presented in the existing seismic design codes. And, the following conclusions were obtained.

(1) It can be seen that the frequency-dependent tendency of the ISRS is affected by the structural type of the substation. In more detail, it can be seen that the ISRS of the steel substations has a peak value in the frequency range of 1 to 5 Hz and the ISRS of the reinforced concrete substations has a peak value in the frequency range of 5 to 20 Hz.

(2) It can be observed that the trend of $F_a(i)$ using the α_J evaluates slightly larger than that using the α_A, but both coefficients show a similar trend with a linear increase according to height increase.

(3) In Ssangmun-RC, Sinnae-RC, and Shinkimpo-Steel, $F_a(i)$ values are larger in the lower floors than in the higher floors. This tendency is because the mass distribution of substation structures and power facilities is more concentrated in the lower floors, so the seismic response acts more strongly in the heavy floors.

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