공학석사학위논문

# 국내 지진에서 거시진도와 계기진도의 관계

# Relationship between macroseismic intensity and instrumental seismic intensity for Korean earthquakes.

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# Abstract

It is important to assess damage by region and to communicate the information with relevant organizations in earthquake response. Timely and reliable information minimize public confusion and reduce unnecessary effort. Seismic intensity is the representative information related to earthquake damage. It is classified into macroseismic intensity and instrumental seismic intensity.

Korea is in different earthquake environment from overseas. Therefore, it is required to improve seismic intensity assessment system suitable for Korea. It should be improved in two aspects. One is related to improving the description of macroseismic intensity, and the other is related to developing the macroseismic-intensity-prediction model. The former is researched separately, and the latter was researched in this thesis.

Correlation analysis between macroseismic intensity(observed MMI) and 4 kinds of instrumental intensities were performed. Housner spectral intensity showed the highest correlation coefficient and was used for regression analysis to develop MMI prediction model. Proposed model provides more improved information than before, despite its limited applicability (MMI $<$ 6 and epicentral distance$\leq$140 km). Most cases will be in that condition, because Korean earthquakes are usually small-to-moderate. Stronger earthquake data of overseas, which are in intra-plate similar to Korea, would help to supplement the model in the future research.

Keywords

Seismic intensity, Macroseismic intensity, Instrumental seismic intensity, MMI, Intra-plate, Housner spectral intensity, Earthquake response

# Table of contents

# Contents of Figures

# Contents of Tables

# Chapter 1
# Introduction

Interest in earthquake is increasing in Korea. Earthquake is one of the largest natural disaster and it can cause severe damage. It is important to assess damage by region and to communicate the information with relevant organizations in earthquake response. Also, timely and reliable information minimize public confusion and reduce unnecessary effort.

Seismic intensity is the representative information related to earthquake damage. It provides the information about severity of ground motion by region, while magnitude provides just the information of source. It was classified into macroseismic intensity and instrumental seismic intensity in this research.

Macroseismic intensity is the qualitative evaluation result for damage by description of earthquake effect after the site investigation which takes long time. It is highly correlated to actual damage (Section 2.1). Instrumental seismic intensity is the quantitative evaluation using just ground motion records. It can be calculated immediately after the earthquake. Therefore, if we use relationship between macroseismic intensity and instrumental seismic intensity, it will be possible to assess earthquake damage by region rapidly without site investigation.

USGS(United States Geological Survey) provides ShakeMaps on their website after earthquakes (Figure 1-1). ShakeMaps are computer-generated maps that indicate an earthquake occurrence, identify the area affected, and estimate the severity of ground shaking, providing a tool to rapidly assess and mitigate damage [8]. These maps can be used for emergency response, loss estimation, and for public information through the media [18]. Relationships between MMI and PGV/PGA [19] are representative examples used to predict earthquake effect in these maps. They were developed by regression analysis through California earthquakes data. MMI is the Modified Mercalli Intensity scale, and it is the representative macroseismic intensity (section 2.1).

KMA(Korea Meteorological Administration) utilizes MMI assessment system similar to USGS. And the relationship between PGA and MMI was developed in 2006 [1], when domestic data were not


| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <0.05 | 0.3 | 2.8 | 6.2 | 12 | 22 | 40 | 75 | >139 |
| PEAK VEL.(cm/s) | <0.02 | 0.1 | 1.4 | 4.7 | 9.6 | 20 | 41 | 86 | >178 |
| INSTRUMENTAL INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |

Scale based upon Worden et al. (2012)

**Figure 1-1** Example of ShakeMap provided by USGS [17] enough. As a result, it doesn't properly evaluate seismic intensity of Korean earthquakes. For instance, it overestimates the MMI of Gyeongju earthquake(2016. 9. 12, Magnitude 5.8) overall (Table 1-1).

Korea is in intra-plate and has the strike-slip fault. So, Korea has different characteristic with overseas in inter-plate region like California, Japan, etc. Korea is mainly suffering from small-to-moderate earthquakes, frequency contents in intra-plate are different from inter-plate, for example California (inter-plate) earthquake have a lower frequency content than those in eastern North America (intra-plate) earthquake [8]. Korean structures are also different from overseas ones. Moreover, structures described in MMI were based on structures that reflected the past foreign environment. These are why it is required to improve seismic intensity assessment system suitable for Korea.

It should be improved in two aspects. One is related to improving description of macroseismic intensity suitable for Korea, and the other is related to developing the macroseismic-intensity-prediction model. The former is researched separately1), and the latter was researched in this thesis.

**Table 1-1** Comparison of pred. MMI by model [1] to Obs. MMI by KMA

| | Daegu | Ulsan | Busan |
|---|---|---|---|
| **Observed MMI** | 6 | 5 | 5 |
| **Predicted MMI by model [1]** | 7 | 9 | 5 |

1) This research is a part of the project "Development of the evaluation method of seismic intensity suitable for Korea" ordered by KMA in 2017.

Thus, Objectives of this research are as follows.

For Korean earthquakes,

1) Identifying an instrumental seismic intensity, which is highly correlated with MMI observed by KMA, through correlation analysis
2) Proposing a MMI prediction model from the instrumental seismic intensity

MMI prediction model enables to assess earthquake damage rapidly without site investigation which takes long time. It can be useful specially at initial stages, where emergency response is required.

# Chapter 2
# Seismic intensity

## 2.1 Introduction

Seismic intensity means the severity of ground motion by region. It provides the information related to actual effect by region, while magnitude provides just the source's information related to its original energy. Seismic intensity is a function of magnitude, epicentral distance and site effects. Therefore, the seismic intensity varies by region, even if earthquakes have same magnitude (Figure 2-1).

Seismic intensity was classified into the macroseismic intensity and the instrumental seismic intensity in this research (Table 2-1). Macroseismic intensity is the qualitative evaluation result for damage by description of earthquake effect after the investigation on site.

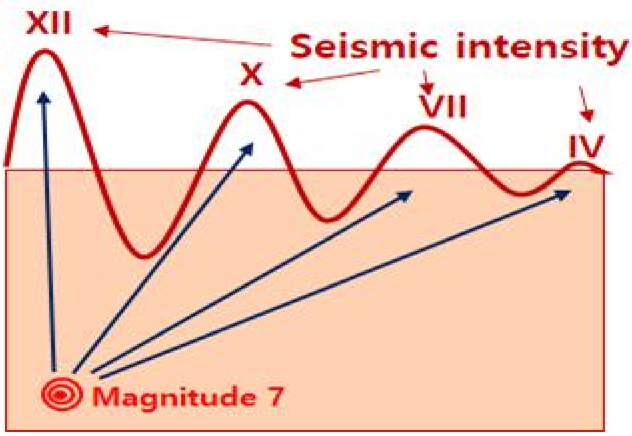



**Figure 2-1** Example of seismic intensity propagation for same magnitude

It is evaluated by Roman numeral or integer number. Integer number tends to be used more frequently today, because of calculational convenience using the computer. It takes long time to get the information and has subjectivity due to the characteristic of site investigation by each people. However it's highly correlated with actual damage, because it is based on actual site damage investigation. MMI is the Representative example of marcroseismic intensity. Various kinds of macroseismic intensity are explained in section 2.2.

Instrumental seismic intensity is the quantitative assessment result using ground motion records. It is possible to evaluate rapidly, but required to research to know how much it is related to actual damage. Various kinds of instrumental seismic intensity are explained in section 2.3.

**Table 2-1** Explanation about macroseismic intensity & instrumental seismic intensity

| **Macroseismic intensity** | **Instrumental seismic intensity** |
|---|---|
| · Qualitative assessment after site damage investigation [ex. MMI]<br>· High correlation with actual damage<br>· Long time to get the information<br>⇒ Unable to utilize in earthquake response | · Quantitative assessment using ground motion records<br>· Available immediately after the event<br>· Necessity to analyze a correlation with the actual damage |

## 2.2 Kinds of macroseismic intensity

It was the Rossi-Forel Scale(1883), which was widely used at the first as macroseismic intensity, since then, there has been continuous development by several researchers [16]. The representative is MMI, which is Modified Mercalli Intensity scale. The version of 1931(Wood and Neumann's) is used by USGS today. Korean Meteorological Administration(KMA) also uses it.

MMI has 12 degrees of description for earthquake effects. All description are explained in one paragraph, without separate category for effected objects. Structural damage is described from the degree of 6 (Appendix 1).

EMS is European Macroseismic Scale. The basis for establishing the EMS was the MSK scale, which itself is an update relying on the experiences being available in the early 1960s from the application of the Mercalli-Cancani-Sieberg Scale (MCS), the Modified Mercalli scale (MM-31 and MM-56) and the Medvedev scale, known also as the GEOFIAN-scale, from 1953. The recent version was developed in 1998 [5].

EMS has 12 degrees of description for earthquake effects similar to MMI. It has 3 categories(people / objects and nature / buildings) for the object of effects (Appendix 2). Structural damage is described from the degree of 6. It defines a vulnerability class according to types of structures, so can equivalently evaluate the damage in different types of structures (Figure 2-2). It also subdivides the structural damage into 5 grade (Figure 2-3).

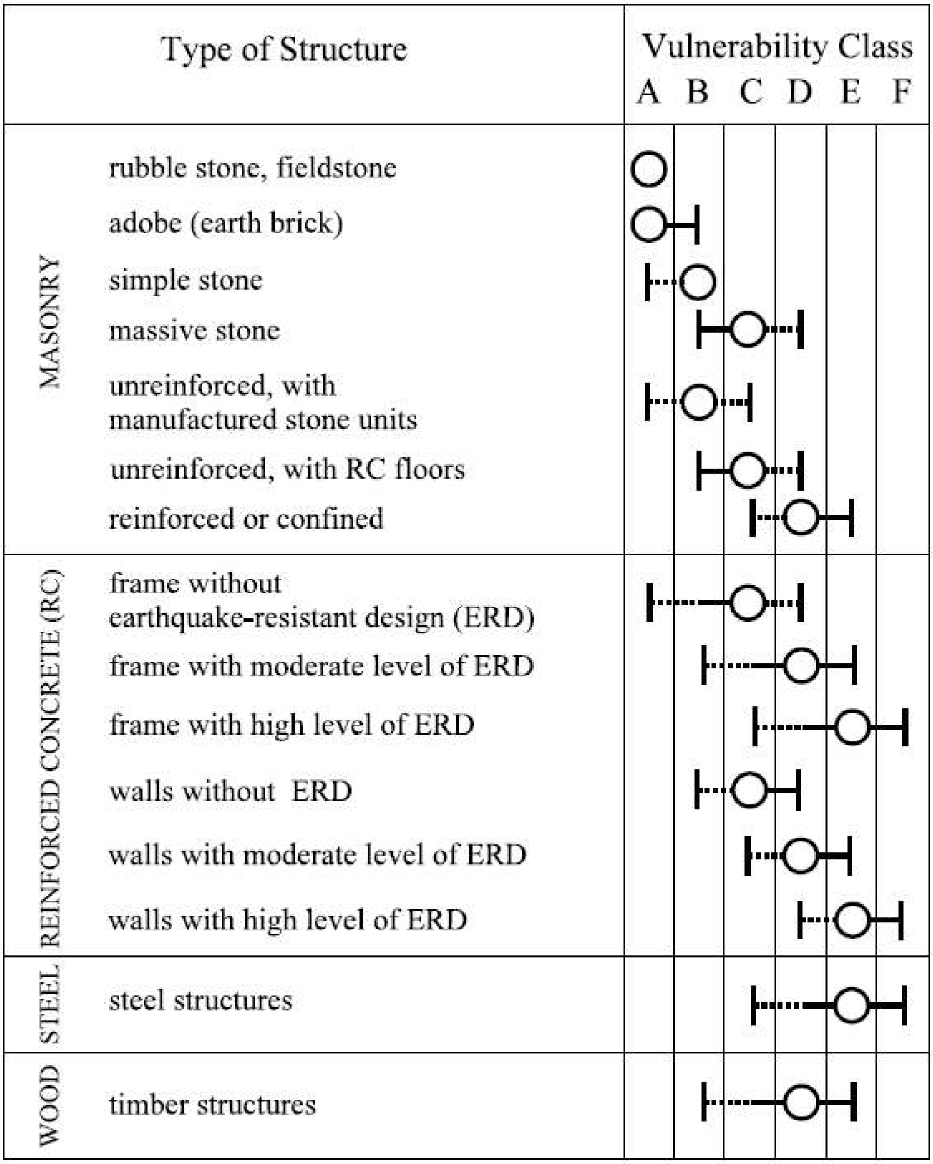



**Figure 2-2** Differentiation of structures (buildings) into vulnerability classes (Vulnerability table by EMS) [5]

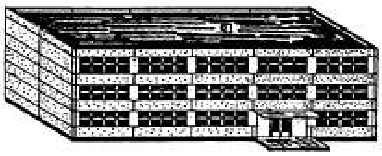
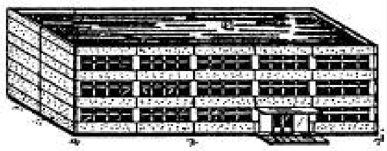
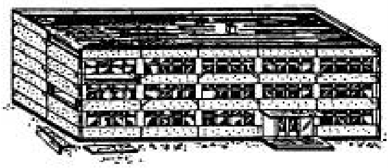
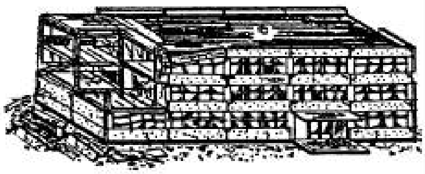
| Classification of damage to buildings of reinforced concrete | |
|---|---|
|  | **Grade 1: Negligible to slight damage**<br>**(no structural damage,**<br>**slight non-structural damage)**<br>Fine cracks in plaster over frame members or in walls at the base.<br>Fine cracks in partitions and infills. |
|  | **Grade 2: Moderate damage**<br>**(slight structural damage,**<br>**moderate non-structural damage)**<br>Cracks in columns and beams of frames and in structural walls.<br>Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels. |
|  | **Grade 3: Substantial to heavy damage**<br>**(moderate structural damage,**<br>**heavy non-structural damage)**<br>Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of conrete cover, buckling of reinforced rods.<br>Large cracks in partition and infill walls, failure of individual infill panels. |
|  | **Grade 4: Very heavy damage**<br>**(heavy structural damage,**<br>**very heavy non-structural damage)**<br>Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns.<br>Collapse of a few columns or of a single upper floor. |
|  | **Grade 5: Destruction**<br>**(very heavy structural damage)**<br>Collapse of ground floor or parts (e. g. wings) of buildings. |

**Figure 2-3** Classification of damage to buildings of reinforced concrete [5]

JMA is Japan Meteorological Agency. They have their own seismic intensity assessment system. In fact, JMA seismic intensity might be proper to classify into an instrumental seismic intensity. But it has also effect description (Appendix 3) for each degree of integer number, so be explained here. It was also included in kinds of instrumental seismic intensity in section 2.3.

It has 10 degrees of description and describes effect in various categories (Appendix 3). Degrees of 5 and 6 are subdivided into upper and low. Basically, it is described on human, indoor situation and outdoor situation. Structural damage is described into 4 categories (Wooden houses / RC buildings / Utilities and infrastructure / Large-scale structures) [7].

KMA had used JMA seismic intensity standard for evaluating earthquakes' effect until 2000, and they have used MMI standard since 2001. The data of macroseismic intensity since 2001 (by MMI standard) were used in this research.

### 2.3 Kinds of instrumental seismic intensities.

Macroseismic intensity is based on qualitative and subjective evaluation by people as explained. By the way, quantitative and objective evaluation result is required for advanced hazard analysis and earthquake response. Various kinds of instrumental seismic intensities have been proposed for this reason.

### 2.3.1 PGA

PGA is the Peak Ground Acceleration. It can be also defined by spectral acceleration at 0.01 s (figure 2-4), because the single degree of freedom system behaves like rigid body at this period. It is used to MMI prediction [19].

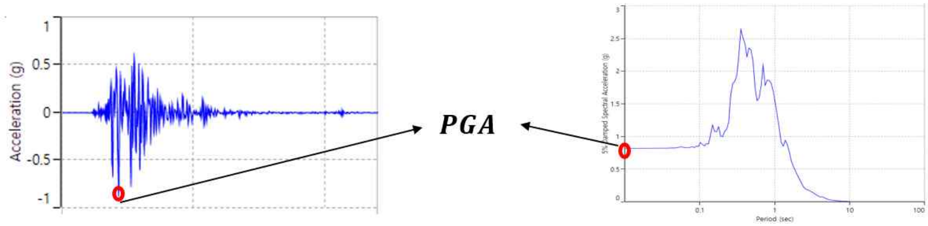



**Figure 2-4** Definition of PGA(Peak Ground Acceleration

### 2.3.2 Housner spectral intensity [6]

Housner spectral intensity is defined as a mean value of integration of pseudo spectral velocity in given period range.

$$SI = \frac{1}{2.4}\int_{0.1}^{2.5} S_v(T,\xi)\,dT \tag{2-1}$$

$T$ is the natural period and $\xi$ is the damping ratio of the single degree of freedom system. $S_v$ is the pseudo spectral velocity and it is derived from spectral displacement [3].

$$S_v = \omega_N S_d \tag{2-2}$$

Housner used the maximum elastic stress into the index of this seismic intensity by equation (2-3).

$$F_{\max} = kS_d = \frac{k}{\omega_N} S_v = \sqrt{mk} \cdot S_v \qquad (2\text{-}3)$$

$k$ is the stiffness coefficient, $\omega_N$ is the natural angular frequency, $m$ is the mass, and $F_{\max}$ is the maximum internal force acted to the system. This intensity is also related to maximum elastic strain energy of the system by equation (2-4)

$$\frac{mS_v^{\ 2}}{2} = \frac{k(S_v/\omega)^2}{2} = \frac{kS_d^{\ 2}}{2} = E_{S,\max} \qquad (2\text{-}4)$$

$E_{S,\max}$ is the maximum elastic strain energy of the system.

Integrating period section means structures' natural period considered in equation (2-1). Housner assumed structures are uniformly distributed in the interval between 0.1 s and 2.5 s.

### 2.3.3 Arias intensity [2]

Arias intensity is defined by integral for square of ground acceleration.

$$I_A = \frac{\pi}{2g} \int_0^{t_d} a^2(t) dt \qquad (2\text{-}5)$$

$g$ is the gravitational acceleration, $a$ is the ground acceleration, and $t_d$ is duration time. This intensity means total dissipated energy per unit weight. Dissipated energy per unit weight($E_d$) is derived by equation (2-6) and (2-7)

$$m\ddot{u} + c\dot{u} + ku = -ma(t) \qquad (2\text{-}6)$$

$$E_d = \frac{1}{mg}\int_0^\infty c\dot{u}^2 dt = \frac{2\xi\omega}{g}\int_0^\infty \dot{u}^2 dt = -\frac{1}{g}\int_0^\infty a(t)\dot{u}\,dt \qquad (2\text{-}7)$$

when, $u(0) = u(\infty) = \dot{u}(0) = \dot{u}(\infty) = 0$

$m$ is the mass, $c$ is the damping coefficient, $k$ is the stiffness coefficient, $u$ is the response, and $a$ is the ground acceleration. Arias assumed uniformly distributed structures' natural frequency from 0 to ∞.

$$I_A = \int_0^\infty E_d d\omega \qquad (2\text{-}8)$$

After some steps of integral calculus [2], it is expressed as follows.

$$I_A = \frac{\cos^{-1}\xi}{g\sqrt{1-\xi^2}}\int_0^{t_d} a^2(t)dt \qquad (2\text{-}9)$$

$\xi$ is the damping ratio. Then it is simplified into equation (2-5) in the range of practical damping ratio(0 to 0.2). It is noted the equation (2-5) means that this intensity is the sum of the total energies per unit weight stored in the oscillators of a population of undamped linear oscillators uniformly distributed as to their frequencies, at the moment the earthquake ends(or for that matter, at any instant after the end of ground motion) [1].

### 2.3.4 JMA seismic intensity

JMA(Japan Meteorological Agency) have their own seismic intensity assessment system. It is calculated by fourier transforming and band-pass filtering considered main structures' natural period. Calculating process is as follows.

1) Fourier-transform for the selected time window for the three components of acceleration time histories.
2) Applying Band-pass filter (2-10) in the frequency domain as shown in Figure 2-5 [9]:

$$F(f) = F_1(f)F_2(f)F_3(f) \tag{2-10}$$

in which

Period-effect filter:

$$F_1(f) = \sqrt{1/f} \tag{2-11}$$

High-cut filter

$$F_2(f) = \frac{1}{\sqrt{1+0.694x^2+0.241x^4+0.0557x^6+0.009664x^8+0.00134x^{10}+0.000155x^{12}}} \tag{2-12}$$

$$(x = \sqrt{1/f_c})$$

Low-cut filter:

$$F_3(f) = \sqrt{1-\exp(-f/f_0)^3} \tag{2-13}$$

$f$ is the frequency of the ground motion, $f_c$ is the reference frequency for high-cut filter, and $f_0$ is the reference for low-cut filter (Figure 2-5(a)).

3) Inverse-fourier-transform and vectorial composite of the three components of acceleration.

4) Take the $a_0$, satisfying duration $\tau(a \geq a_0) \geq 0.3\,\text{s}$. $a$ and $a_0$ is the inverse-fourier-transformed acceleration.

5) JMA seismic intensity($I_{JMA}$) is calculated by using equation (2-14) as a real (continuous) number [9].

$$I_{JMA} = 2.0 \log a_0 + 0.94 \qquad (2\text{-}14)$$

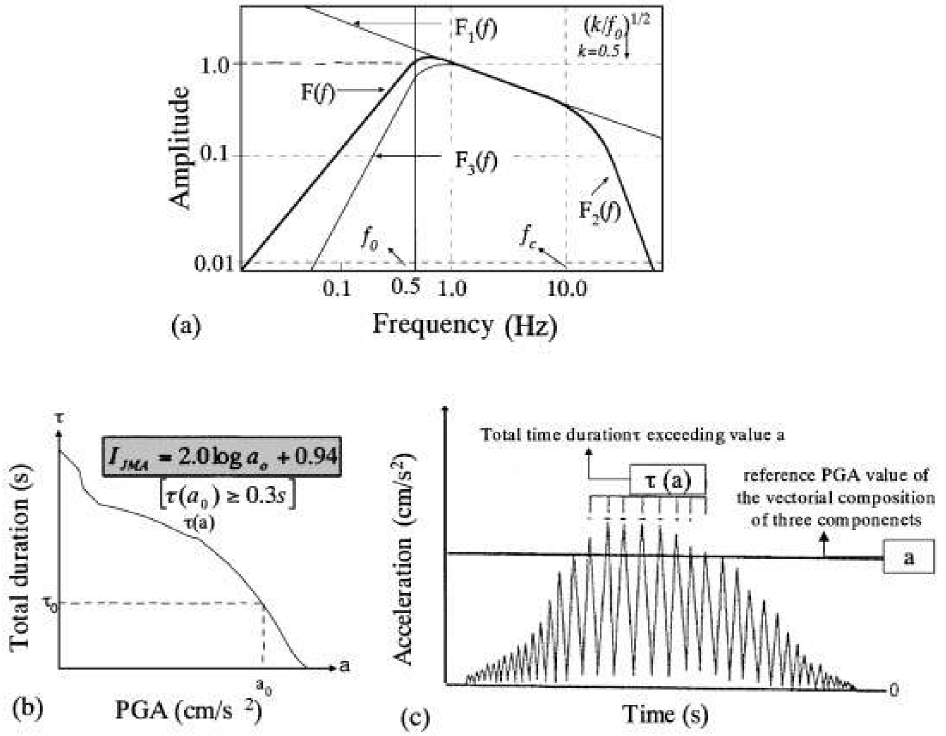



**Figure 2-5** Calculation of JMA instrumental seismic intensity (a) Band -pass filtering in the frequency domain (b) Taking $a_0$, satisfying $\tau(a \geq a_0) \geq 0.3\,\text{s}$, which is obtained in the time domain by (c) summing the time segments exceeding a reference PGA value of the vectorial composition of the three-components of acceleration records [9]

### 2.3.5 Direction problem

Acceleration records have 3 directional components. Thus, instrumental seismic intensity depends on the change of the reference coordinate axis. They are separated into horizontal and vertical axis(z-axis) basically, and horizontal component can be separated to E-W(x-axis) and N-S(y-axis) component.

It is obvious that horizontal component of the intensity is specially important because man-made structures are usually more sensitive to horizontal motions of their foundations than they are to vertical motions [2]. Thus, this research focused on Horizontal component. Vertical component was also calculated (not presented in this thesis), but didn't show better result than horizontal one.

Representative directional component should be selected on horizontal component. Table 2-2 shows the selected direction in this research. Geometric mean was selected for PGA, because it was also used to Wald *et al.*(1999a), whose research was compared to this research in section 4.2. GMRotI50 was used for *SI*, which was used to develop Korean standard horizontal design spectrum [10]. Arias intensity have same composition value, because it could be constructed into symmetrical tensor [2]. JMA seismic intensity is original vectorially composited value.

**Table 2-2** Representative horizontal direction for this research

| PGA | $SI$ | $I_A$ | $I_{JMA}$ |
|---|---|---|---|
| Geometric mean<br>$(=\sqrt{PGA_x \cdot PGA_y})$ | GMRotI50 | $I_{A,x}+I_{A,y}$<br>$(=\int_0^{t_d} a_x^2\,dt+\int_0^{t_d} a_y^2\,dt$<br>$=\int_0^{t_d} a_x^2+a_y^2\,dt$ | Original vectorially composited value |

# Chapter 3
# Correlation analysis

## 3.1 Data

131 pairs of data from 41 earthquakes were used to analyze. Marcoseismic intensity data("observed MMI" below) were obtained from 'Earthquake annual report' published by KMA(Korea Meteorological Administration). Felt-earthquakes were observed and evaluated by MMI standards from 2001 to 2016 in these reports. Ground acceleration records were obtain from NECIS(National Earthquake Comprehensive information system operated by KMA) database corresponding to the obtained macroseismic intensity data. Epicentral distance range was in 140km.

Figure 3-1 shows the magnitude distribution. Magnitudes of felt-earthquakes are in the range from 3 to 5.8. Most earthquakes are in the range from 3 to 4. But, there are also more than 40 earthquakes in the range from 4 to 6.

Figure 3-2 shows distribution of observed MMI according to magnitude range. The larger observed MMI are in the larger magnitude.

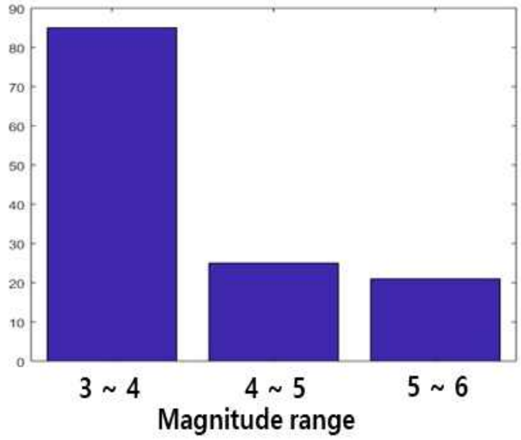



**Figure 3-1** Distribution of magnitude of obtained earthquakes

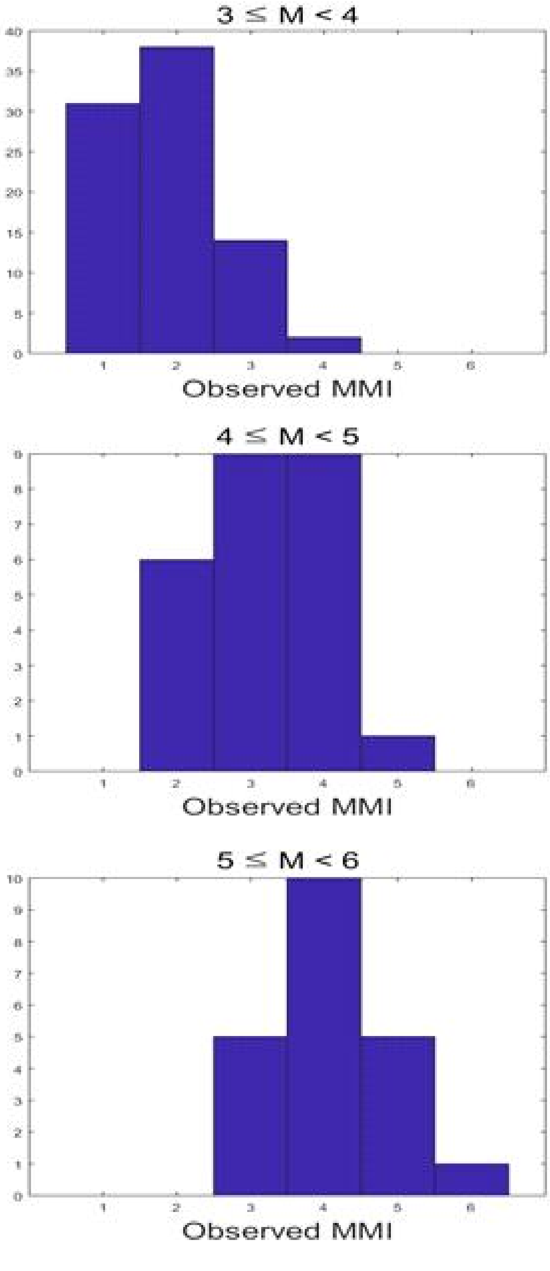



**Figure 3-2** Distribution of observed MMI versus magnitude range

## 3.2 Correlation analysis

Figure 3-3(a~d) show scattering plots of instrumental seismic intensities and observed MMI. Horizontal axis is instrumental seismic intensity and vertical axis is observed MMI. $r$ is the correlation coefficient. Instrumental seismic intensities are log scaled. There was just one data in observed MMI 6, so it was not included for the analysis.

They seem to show quite large scatter overall. It is a fundamental limitation, because MMI is qualitatively and subjectively evaluated in region, and have just one integer number. Black points are means of instrumental seismic intensities on each degree of observed MMI. '×' are $\pm 1\sigma$(standard deviation) of them. Housner spectral intensity showed the highest correlation coefficient($r = 0.767$). Damping ratio was 0.05, here.

Housner spectral intensity uses the maximum elastic stress into the index of intensity according to equation (2-1) and (2-3). It is also related to maximum elastic strain energy according to equation (2-4). Most structures' behavior would be in elastic range for Korean earthquakes, because the earthquakes are usually small to moderate. Structures would just have suffered only non-structural damage, usually. Housner spectral intensity seems to reflect this Korean earthquake characteristic well.

Housner spectral intensity can be changed according to damping ratio($\xi$) and integrating period section. Figure 3-4(a and b) show the sensitivity by them. Generally, structures' damping ratio are in the range between 0.02 and 0.2. So they were compared in this range. Integrating period section means the interval of structures' period. For instance, if it is integrated from 0.1 s to 2.5 s, it means the buildings' range to be considered is from 1 story building to 25 stories building. Housner assumed most structures are uniformly distributed in this range.

Figure 3-4(a and b) don't show large sensitivity in practical range. By the way, most RC(Reinforced Concrete) structures' damping ratios are below 0.02 in elastic range [16], and most of us are surrounded by RC structures in modern city. Therefore 0.02 damping ratio was selected in the regression analysis (Chapter 4). Correlation coefficient ($r$) is 0.77 at this ratio, slightly higher than previous one, when $\xi$ = 0.05. Integrating period section was selected from 0.1 s to 2.5 s, as it was selected by Housner (equation 2-1).

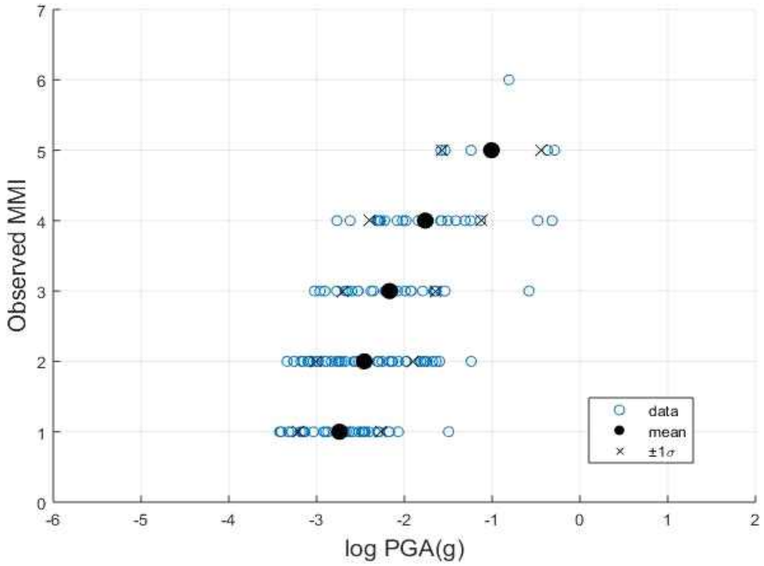



**Figure 3-3a** Scattering plot of $\log PGA$ and Observed MMI ($r$=0.608)

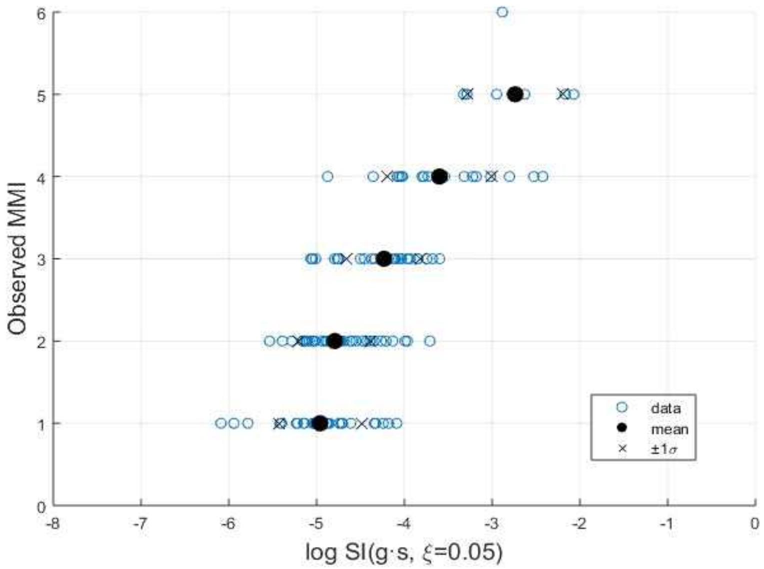



**Figure 3-3b** Scattering plot of $\log SI(\xi=0.05)$ and Observed MMI ($r$=0.767)

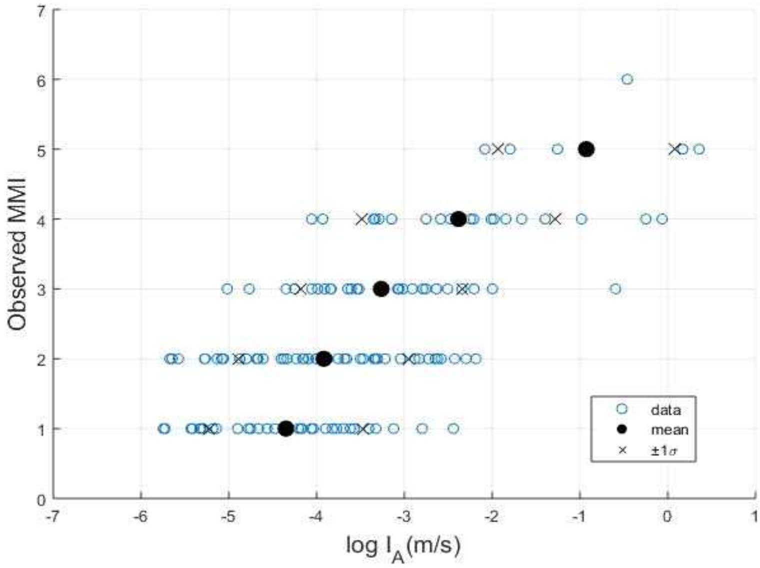



**Figure 3-3c** Scattering plot of $\log I_A$ and Observed MMI

($r$=0.656)

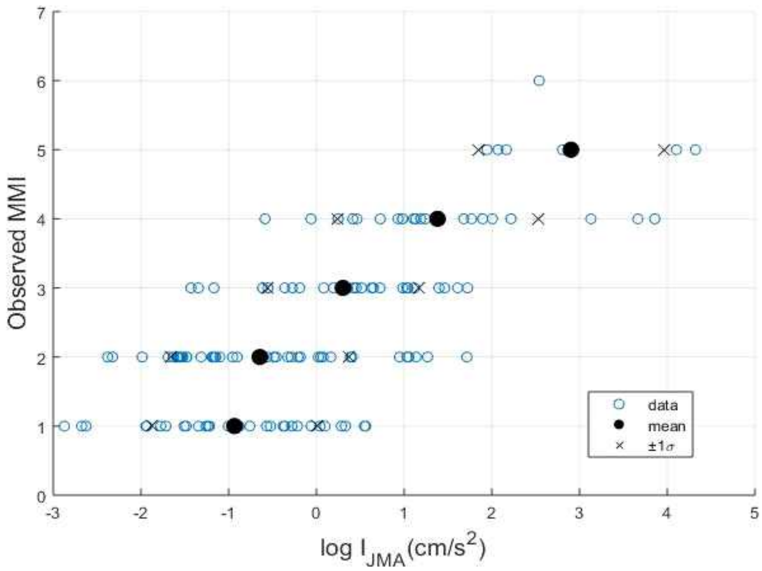



**Figure 3-3d** Scattering plot of $\log I_{JMA}$ and Observed MMI

($r$=0.701)

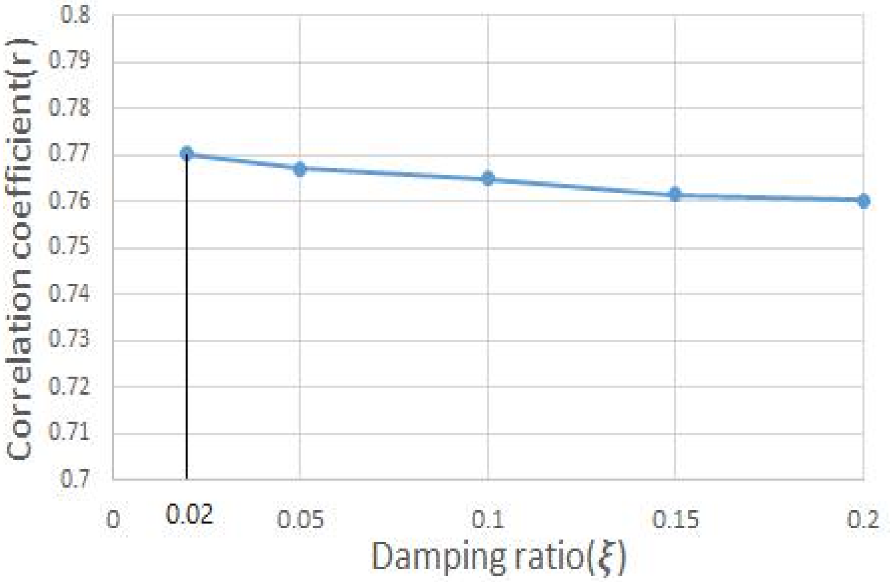



**Figure 3-4a** $r$ vs damping ratio($\xi$)

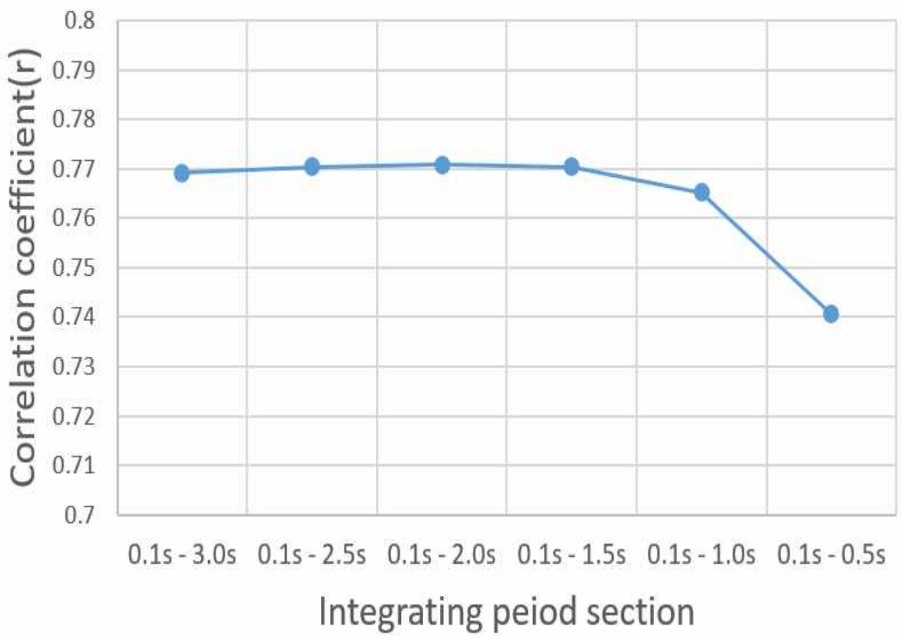



**Figure 3-4b** $r$ vs integrating period section

# Chapter 4
# Regression analysis

## 4.1 Proposing a MMI prediction model

Linear regression model was proposed in equation (4-1) using one independent variable(Housner spectral intensity). Figure 4-1 shows the black regression line. A data on observed MMI 6 was eliminated as mentioned in section 3.2.

$$\text{MMI} = 7.53 + 1.17 \log SI \qquad (4\text{-}1)$$
$$\sigma_{\text{MMI}} = 0.74$$

$SI$ is the Housner spectral intensity. Damping ratio($\xi$=0.02) and integrated section(0.1 s to 2.5 s) were selected in section 3.2. $\sigma_{\text{MMI}}$ is the RMS(Root Mean Square) error.

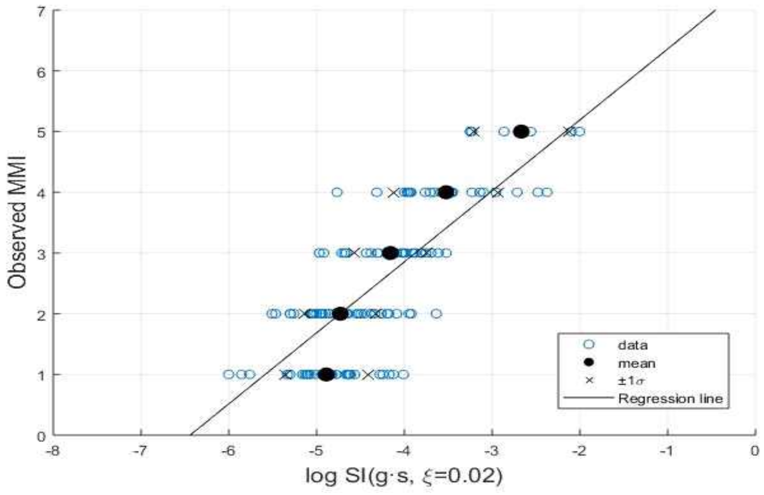



**Figure 4-1** Regression line of $\log SI$ and Observed MMI

Seismic intensity is a function of epicentral distance and magnitude, thus, their effects have to be considered for prediction model. Figure 4-2(a and b) present the epicentral distance and magnitude trends in the MMI residuals. Residuals on vertical axis are calculated by subtracting predicted MMI from observed MMI. Figure 4-2b shows higher trend of residuals at larger magnitude. The model was corrected after calibrating the trend.

$$\text{MMI} = 6.42 + 1.17\log SI + 0.29M \qquad (4\text{-}2)$$
$$\sigma_{\text{MMI}} = 0.70\ (\leftarrow 0.74)$$

$M$ is the magnitude. RMS error was reduced compared to the error by equation (4-1). Figure 4-3 shows the previous regression line(4-1) and corrected MMI by equation (4-2). '*' are the corrected MMI. Corrected MMI moved left in the range over MMI 2, and moved slightly in the range below it. They become closer to means on each degree of MMI. Figure 4-4(a and b) verifies the lack of residuals versus epicentral distance and magnitude.

Additional residual analysis were performed to confirm whether the result satisfies the assumption related to linear regression analysis. Figure 4-5 presents there is not significant problem related to linearity, homoscedasticity and independency.

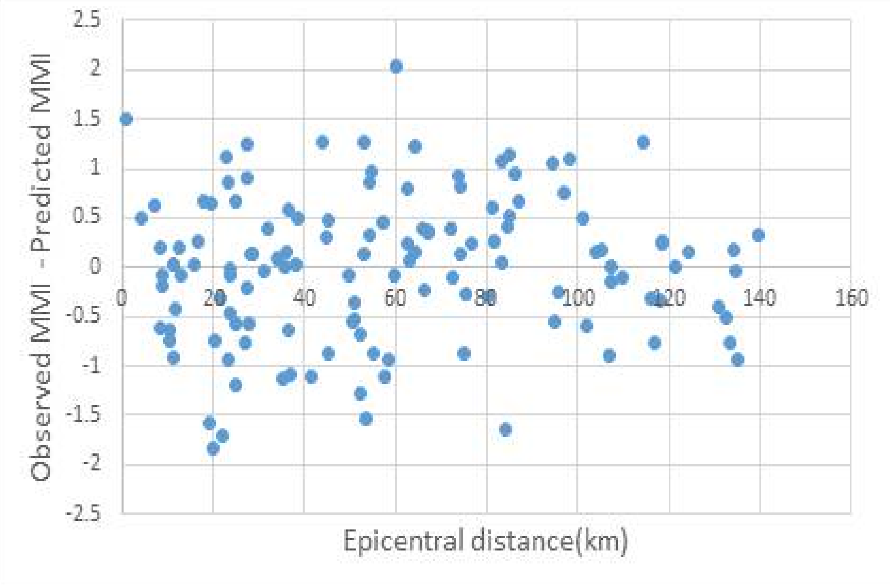



**Figure 4-2a** MMI residuals versus epicentral distance(km)

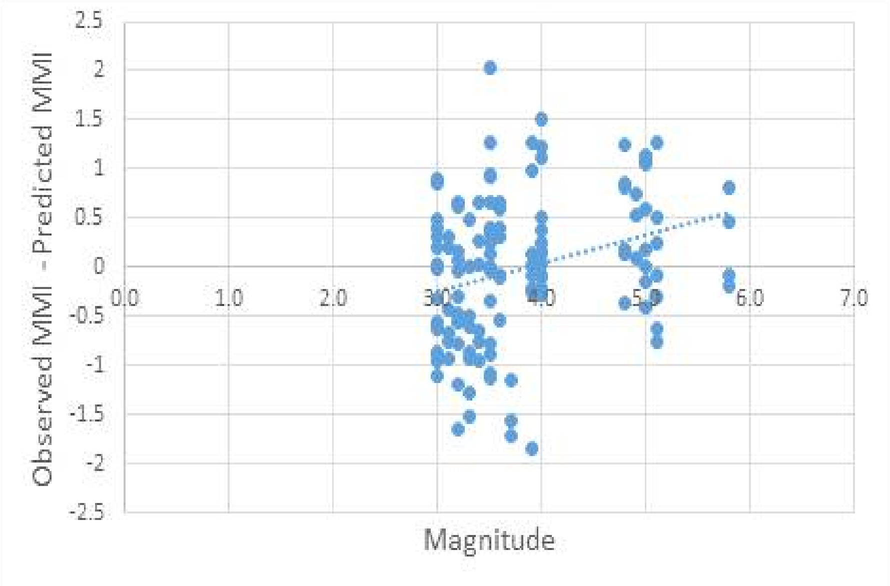



**Figure 4-2b** MMI residuals versus magnitude

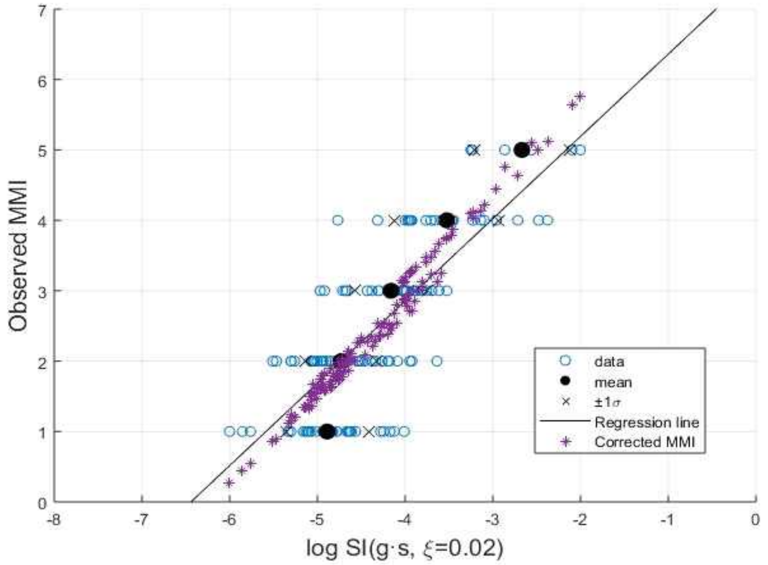



**Figure 4-3** Corrected MMI (equation 4-2) with regression line (equation 4-1)

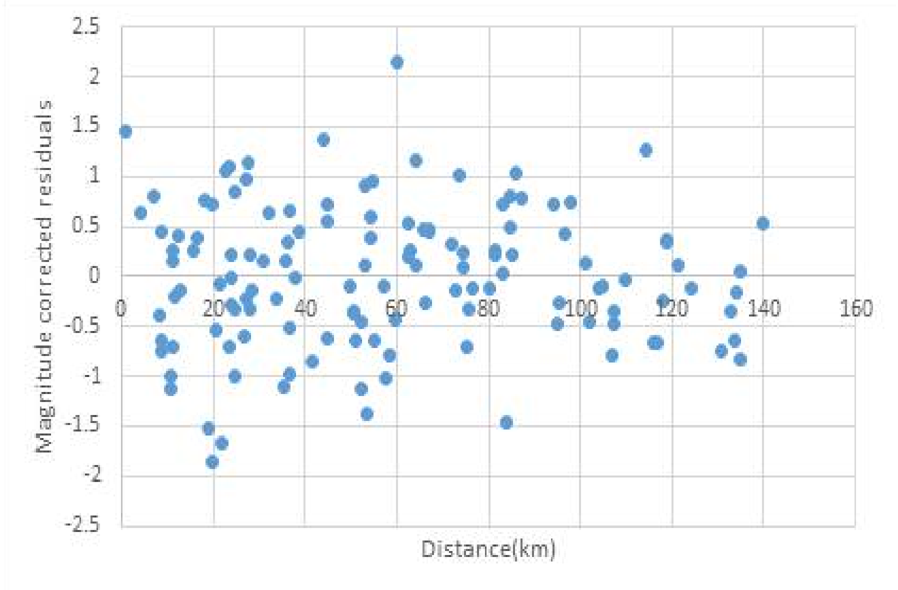



**Figure 4-4a** Magnitude corrected residuals versus epicentral distance(km)

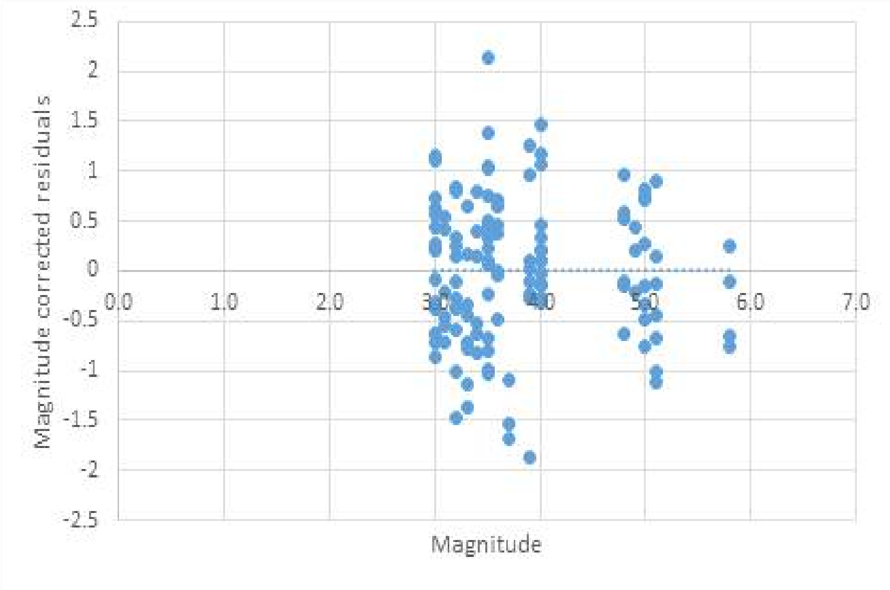



**Figure 4-4b** Magnitude corrected residuals versus magnitude

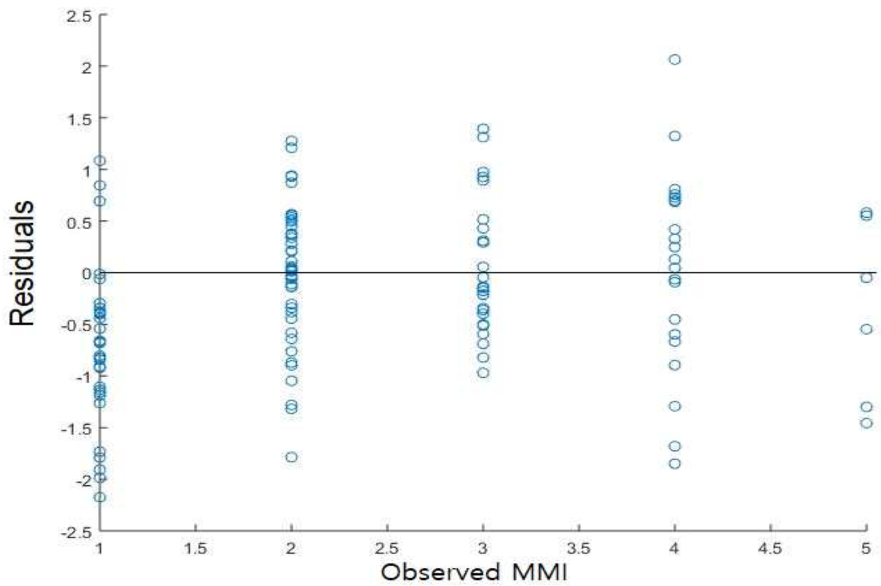



**Figure 4-5** Residuals versus observed MMI

Figure 4-6 shows Normal probability plots for residuals of Housner spectral intensities on each degree of MMI. Horizontal axis is theoretical quantiles following normal distribution, and vertical axis is sample quantiles of Housner spectral intensities on each degree of MMI. If data are closed to straight line, it can be said that it follows normal distribution.

They seem to follow normal distribution except for MMI 5. It might be said that there is certain trend for MMI 5. However, there are relatively fewer data for MMI 5, so it is not easy to say that they have certain pattern or not, yet. There are not specific trends between other degrees of MMI. It would be expected to follow normal distribution, if there were more abundant data on MMI 5.

It should be noted that this model can be applied when predicted MMI is less than 6 and epicentral distance is below 140 km, due to limited data in that range. Nevertheless, it can be applied to most Korean earthquakes, because most earthquakes are small-to-moderate in Korea, so their effect have limted effect about severity and distance range.

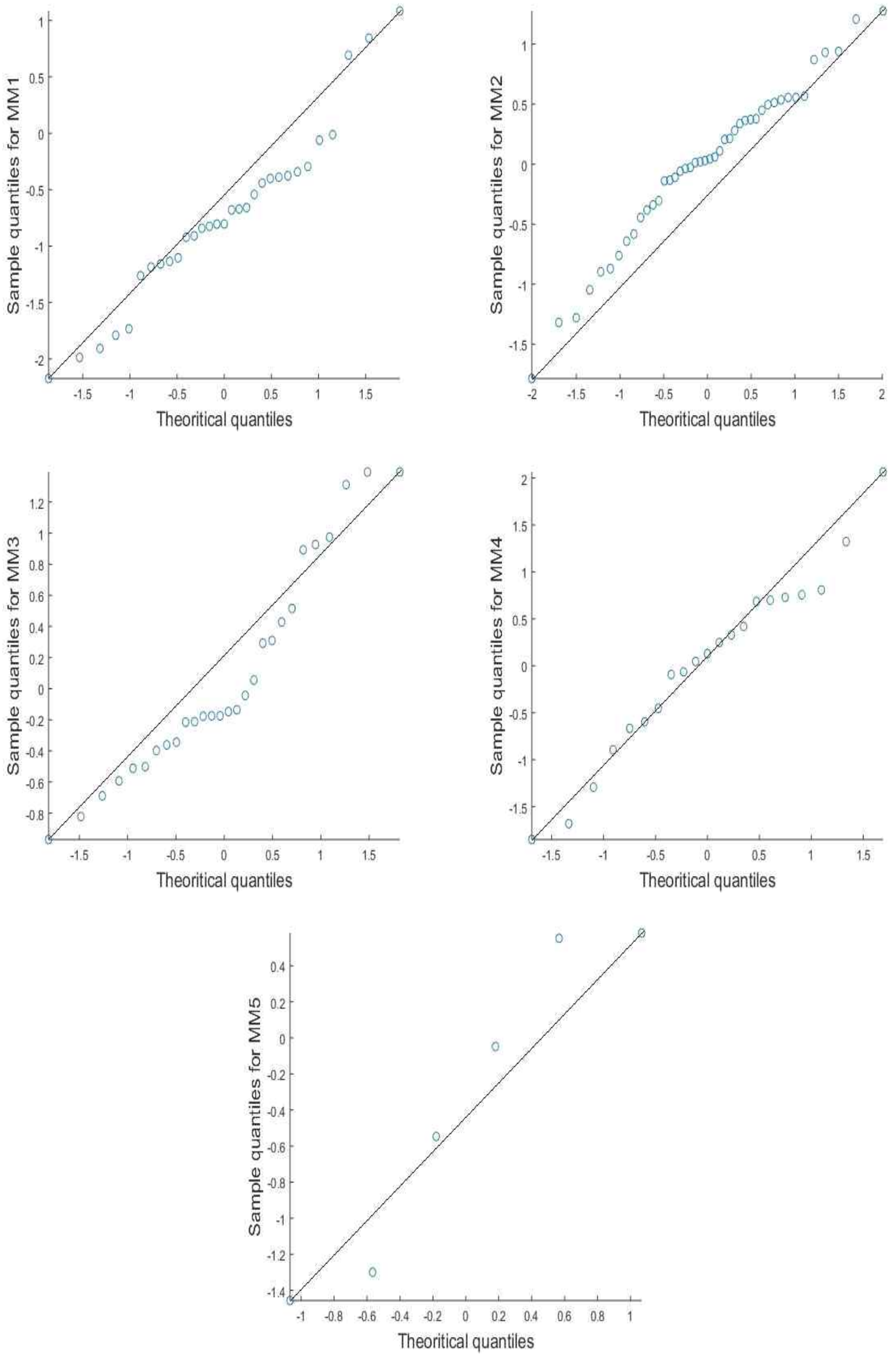



**Figure 4-6** Normal probability plot of residuals on each degree of MMI

## 4.2 Comparison to previous research

The result is compared to previous research using same data set(Figure 4-7a and Figure 4-7b) used in this research. Wald *et al.*(1999a)'s model was compared, because it is the most representative MMI prediction model. They made a model using PGA as an independent variable in the range below MMI 5, through earthquakes data of California in inter-plate.

Kaka *et al.*(2004) also suggested a model using PGV in eastern North America(ENA), which is in intra-plate similar to Korea. However, this model could not be compared in this research, because ground velocity data are not enough yet. KMA started to install velocity meters relatively recently. There were status of observatories operated by KMA in Appendix 4. Acceleration integrating method could be considered. But noise information was unclear about provided data, so integral constant could not be decided.

Proposed model(equation 4-2) shows the better result than Wald *et al.*(1999a)'s model in **Table 4-1**. Correlation coefficient($r$) is higher, and RMS error($\sigma_{MMI}$) is lower. It also showed the better result without correction by magnitude($\sigma_{MMI} = 0.74$ in equation (4-1) ).

**Table 4-1** Comparison correlation coefficient($r$) and RMS error($\sigma$)

| | This research | Wald et al.(1999a) |
|---|---|---|
| Model | MMI = $6.42 + 1.17\log SI + 0.29M$ | MMI = $1.00 + 2.20\log PGA$ |
| $r$ | 0.77 | 0.608 |
| $\sigma$ | 0.70 | 1.15 |

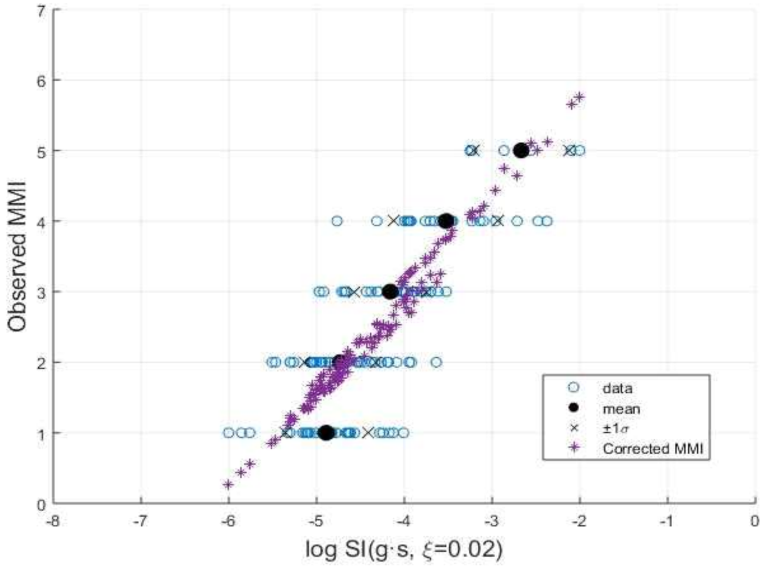



**Figure 4-7a** Predicted(and corrected) MMI by this research

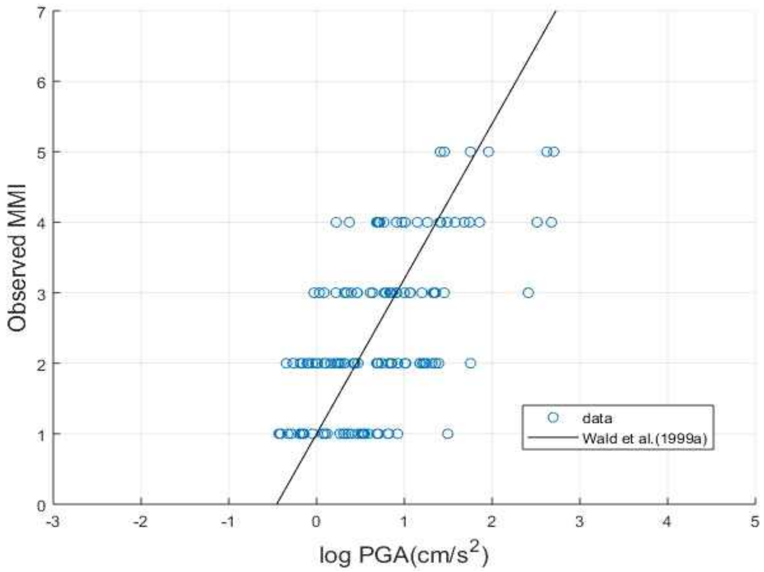



**Figure 4-7b** Predicted MMI by Wald *et al.*(1999a)

# Chapter 5
# Applications to Pohang earthquake(2017)

At 05:29:32 UTC(14:29:31 Korea Standard Time; GMT +9 hours) on 15 November 2017, magnitude 5.4 earthquake occurred in the city of Pohang, Korea. It caused quite severe damage (Figure 5-1), though it had lower magnitude than Gyeongju earthquake(2016), of which magnitude was 5.8. Relatively low focal depth(9 km), loose soil condition, etc. were estimated to reasons of those damage. Observed MMI was not yet officially announced by KMA.

Table 5-1 shows the predicted MMI by the proposed model (Equation 4-2). Ground acceleration data were obtained from NECIS database(36 stations in 140 km from epicenter). There was just one station(PHA2) in Pohang city. So predicted $\log SI$ was calculated by regression analysis between $\log SI$ and $\log R$ (Figure 5-2). $R$ is the epicentral distance. Max. MMI and Min. MMI are the value considered by error($\sigma = 0.70$). Every sites were predicted to MMI 6(rounding off)

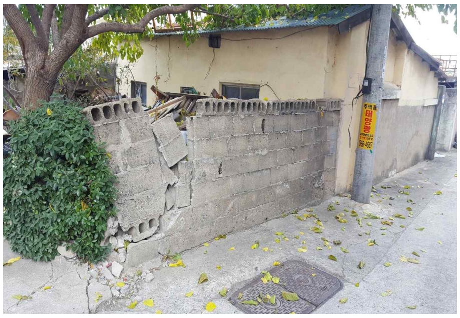
**Table 5-1** Predicted MMI by the proposed model (Equation 4-2)

| Object | Epicentral Dist.(R) | Predicted $\log SI(g{\cdot}s)$ | predicted MMI | Max. MMI | Min. MMI |
|---|---|---|---|---|---|
| Wall | 1.72 km | -1.565 | 6.16 → **6** | 6.86 → **7** | 5.46 → **5** |
| House | 1.74 km | -1.569 | 6.15 → **6** | 6.85 → **7** | 5.45 → **5** |
| School | 1.92 km | -1.610 | 6.10 → **6** | 6.80 → **7** | 5.40 → **5** |
| Apartment | 2.18 km | -1.664 | 6.04 → **6** | 6.74 → **7** | 5.34 → **5** |
| Piloti structure | 3.22 km | -1.827 | 5.85 → **6** | 6.55 → **7** | 5.15 → **5** |
| Pohang station | 4.59 km | -1.976 | 5.67 → **6** | 6.37 → **6** | 4.97 → **5** |

The considerable damage were observed in Figure 5-1. A school building and a Piloti structure were seriously failed. They were judged to be non-seismic designed building after site investigation. It might be proper to say the observed MMI is 7(or maximum 8) in these cases (Appendix 1). However, MMI should be evaluated throughout the region. It is not proper to judge with only a few cases.

Moreover, site effect was not considered. Predicted $\log SI$ is just the attenuated value by distance. As mentioned in section 2.1, seismic intensity is a function of site effects(also magnitude and epicentral distance). Loose soil was pointed out of relatively severe damage. Figure 5-2 also indicates the possibility of showing higher $\log SI$, as a result higher predicted MMI, although there is just one point.

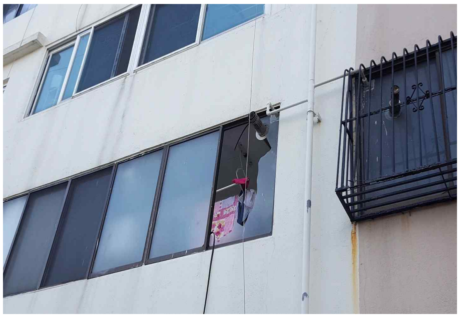
In fact, proposed model is not proper to predict MMI $\geq$ 6 as noted in section 4.1. It was discussed more about the limitation in section 6. Nevertheless, the model seemed to show quite consistent result about Pohang earthquake(2017) in the range between MMI 5 and MMI 7, though some examples seemed to be evaluated somewhat lower than observed situation. Use of words “quite” and “somewhat” is an inevitable characteristic of qualitative and subjective evaluation for MMI.



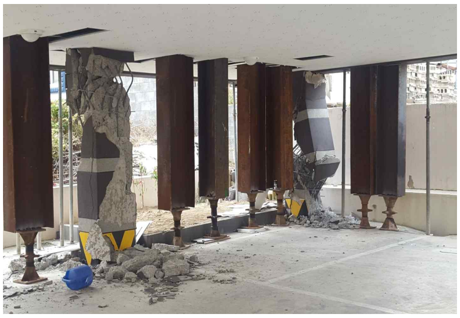
< Wall / 1.72 km >

< House / 1.74 km >

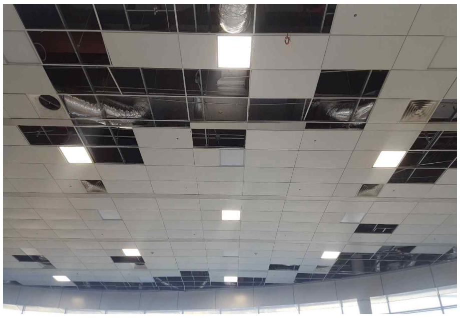
< School / 1.92 km >



< Appartment / 2.18 km >



< Piloti structure / 3.22 km >



< Pohang station / 4.59 km >

**Figure 5-1** Photos taken at the site after Pohang earthquake(2017)
< Structure type / Epicentral distance >

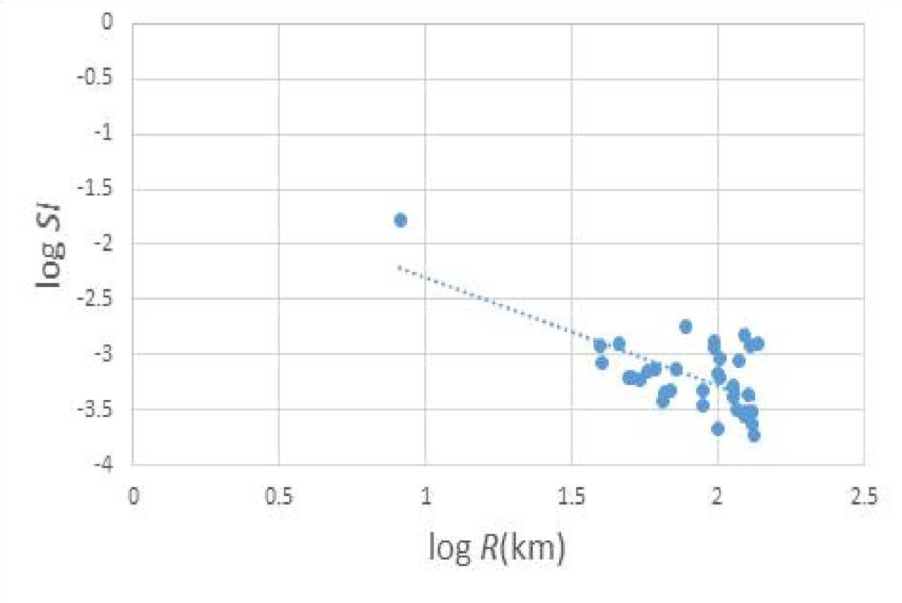



**Figure 5-2** Predicted $SI$ by regression analysis

# Chapter 6
# Discussion

MMI prediction model was proposed in section 4.1 and it was applied to Pohang earthquake(2017) in section 5. The model has definite limitations. It is not enough to explain higher intensity over MMI 6, because there were just one data in the range yet. It could be supplemented through overseas stronger earthquake data in intra-plate similar to Korea.

It might be recommended to use other instrumental intensities for an independent variable of prediction model, if regression model was applied in the range over MMI 6. Housner spectral intensity, which considers elastic response at fixed damping ratio, might not be proper, because structural damage is started in the MMI range($\geq$6). When structure experiences structural damage, inelastic response is caused and damping ratio changes.

Arias intensity, which means total dissipated energy, can be considered. PGV can be considered also. It is a parameter most directly related to kinetic energy, which in turns relates to damage [8]. PGV was not considered in this research due to limitation of data as mentioned in section 4.2.

More advanced research is required for improving hazard analysis. It is necessary to assess more specific information for precise loss estimation and decision making, although MMI prediction model can be useful for initial steps of earthquake response. For example, Hazus-MH[2] provides extensive information related natural disaster, including earthquake, based on GIS database provided by NIBS (National Institute of Building Sciences). It considers earthquake demand and structural capacity together and quantitatively assesses the physical damage to structures and system, induced damage(like inundation, fire, etc.), direct social/economic losses, as well as indirect economic losses (figure 6-1). It uses capacity spectrum method and fragility curve basically [4].

As mentioned in Chapter 1, description of MMI should be modified suitably for Korea, nowaday. It needs to supplement description related to modern structure and Korean cultural properties. Non-existing structures have to be eliminated. Damage grade should become more specified. EMS and JMA seismic intensity can be references. Capacity spectrum method and fragility curve can be also used to divide proper damage range on each grade.

However, The model proposed in this research, itself, provides more improved information than before, despite of limitations of research as mentioned. Korean earthquakes are usually small-to-moderate and the model can predict the MMI in most cases. It will be useful to communicate with relevant organizations and public specially at the initial stages of earthquake response, where emergency response is required.

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2) Hazus-MH : Risk assessment software program for analyzing potential losses from floods, hurricane winds and earthquakes [4]

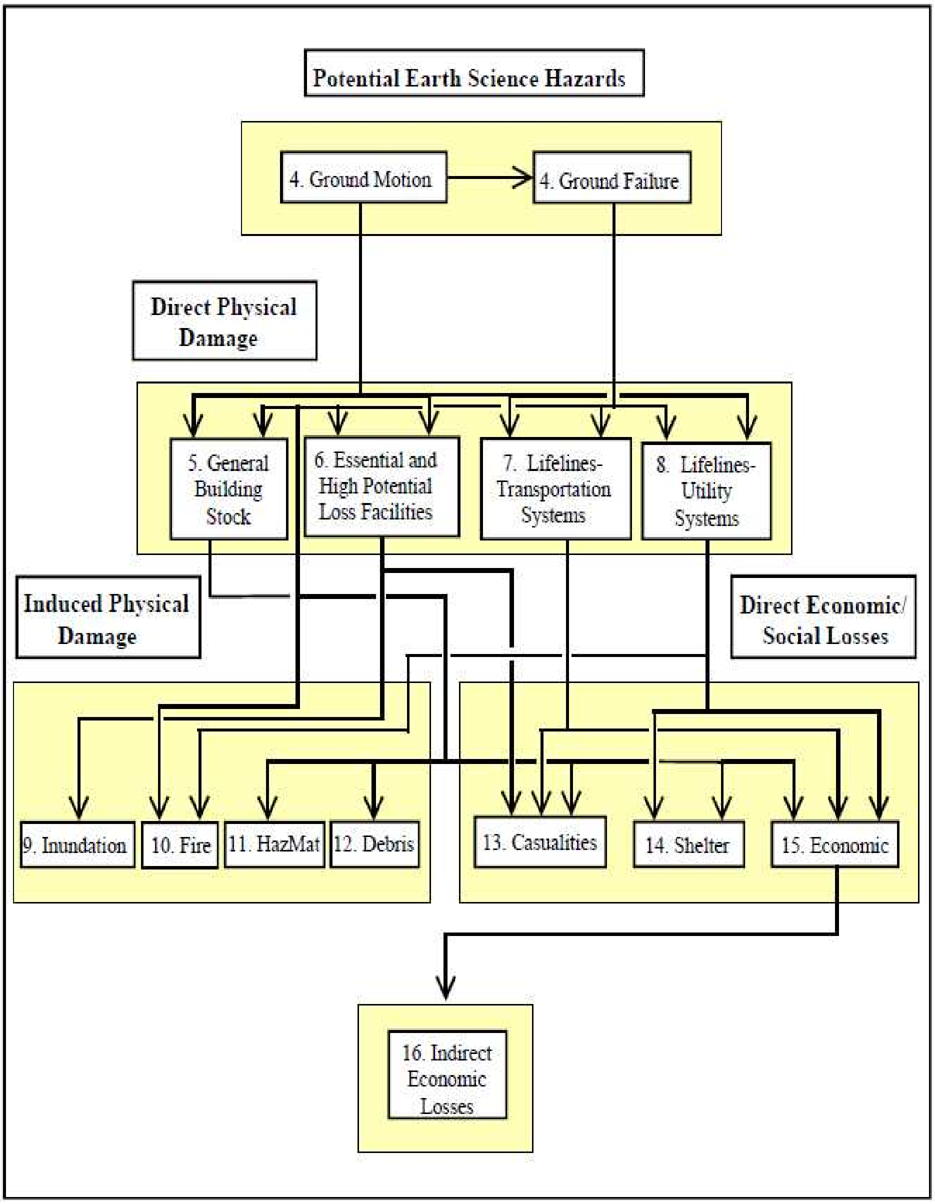



**Figure 6-1** Flowchart of the earthquake loss estimation methodology by Hazus-MH [4]

# Chapter 6
# Conclusion

Correlation analysis between macroseismic intensity(observed MMI) and 4 kinds of instrumental intensities were performed. Housner spectral intensity showed the highest correlation coefficient and it was used for regression analysis to develop MMI prediction model. The final regression model was the equation (4-2) after correcting by magnitude.

This model provides better information than before, despite its limited applicability (MMI $< 6$ and epicentral distance $\leq 140$ km). However most cases will be in that condition, because Korean earthquakes are usually small-to-moderate. Stronger earthquake data of overseas, which are in intra-plate similar to Korea, would help to supplement the model in the future research.

More advanced research is required for improving hazard analysis. Hazus-MH already has been developed into an information system based on GIS database provided by NIBS in America. It provides the information about physical damage, induced damage, direct social/economic losses, as well as indirect economic losses. Description of MMI should be modified reflecting the Korean earthquake environment, nowaday.

# Appendix 1 : Modified Mercalli Intensity of 1931 [20]

| Degree | Description |
|---|---|
| 1 | Not felt - or, except rarely under especially favourable circumstances. Under certain conditions, at and outside the boundary of the area which a great shock is felt: sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway - doors may swing, very slowly. |
| 2 | Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced. |
| 3 | Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first, duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movement may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly. |
| 4 | Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy, or heavily loaded trucks. Sensation like heavy body striking building, or falling of heavy objects to inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swing, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars slightly. |

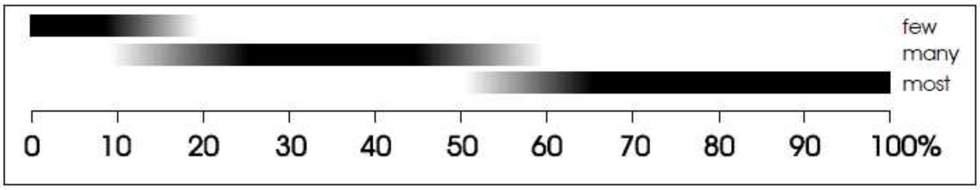
| | |
|---|---|
| 5 | Felt indoors by practically all, outdoors by many or most. Outdoors direction estimated. Awakened many, or most. Frightened few - slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes, glassware, to some extent. Cracked windows - in some cases, but not generally. Overturned small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened or closed, doors, shutters, abruptly. Pendulum clocks stopped, started, or ran fast, or slow. Moved small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees, bushes, shaken slightly. |
| 6 | Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees, bushes, shaken slightly to moderately. Liquid set in strong motion. Small bells rang -church, chapel, school etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knick-knacks, books, pictures. Overturned furniture, in many instances. Moved furnishings of moderately heavy kind. |
| 7 | Frightened all - general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-build ordinary buildings, considerable in poorly build or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, |

| | |
|---|---|
| | etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows, furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roof. Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches. |
| 8 | Fright general - alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly - branches, trunks, broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls. Cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stack, towers. Moved conspicuously, overturned, very heavy furniture. |
| 9 | Panic general. Cracked ground conspicuously. Damage considerable in (masonry) structure build especially to withstand earthquakes: threw out of plumb some wood-frame houses build especially to withstand earthquakes; great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken. |
| 10 | Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. |

| | |
|---|---|
| | Changed level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-build wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipe lines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces. |
| 11 | Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments, often for long distances. Few, if any (masonry), structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipe lines buried in earthy completely out of service. |
| 12 | Damage total - practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc. numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air. |

# Appendix 2 : European Macroseismic Scale [5]

Definitions of quantity




Definitions of intensity degrees

**Arrangement of the scale:**

a) Effects on humans

b) Effects on objects and on nature

(effects on ground and ground failure are dealt with especially in Section 7)

c) Damage to buildings

**Introductory remark:**

The single intensity degrees can include the effects of shaking of the respective lower intensity degree(s) also, when these effects are not mentioned explicitly.

### I. Not felt

a) Not felt, even under the most favourable circumstances.

b) No effect.

c) No damage.

### II. Scarcely felt

a) The tremor is felt only at isolated instances (<1%) of individuals at rest and in a specially receptive position indoors.

b) No effect.
c) No damage.

### III. Weak

a) The earthquake is felt indoors by a few. People at rest feel a swaying or light trembling.
b) Hanging objects swing slightly.
c) No damage.

### IV. Largely observed

a) The earthquake is felt indoors by many and felt outdoors only by very few. A few people are awakened. The level of vibration is not frightening. The vibration is moderate. Observers feel a slight trembling or swaying of the building, room or bed, chair etc.
b) China, glasses, windows and doors rattle. Hanging objects swing. Light furniture shakes visibly in a few cases. Woodwork creaks in a few cases.
c) No damage.

### V. Strong

a) The earthquake is felt indoors by most, outdoors by few. A few people are frightened and run outdoors. Many sleeping people awake. Observers feel a strong shaking or rocking of the whole building, room or furniture.
b) Hanging objects swing considerably. China and glasses clatter together. Small, top-heavy and/or precariously supported objects may be shifted or fall down. Doors and windows swing open or shut. In a few cases window panes break. Liquids oscillate and may spill from well-filled containers. Animals indoors may become uneasy.
c) Damage of grade 1 to a few buildings of vulnerability class A and B.

**VI. Slightly damaging**

a) Felt by most indoors and by many outdoors. A few persons lose their balance. Many people are frightened and run outdoors.

b) Small objects of ordinary stability may fall and furniture may be shifted. In few instances dishes and glassware may break. Farm animals (even outdoors) may be frightened.

c) Damage of grade 1 is sustained by many buildings of vulner- ability class A and B; a few of class A and B suffer damage of grade 2; a few of class C suffer damage of grade 1.

**VII. Damaging**

a) Most people are frightened and try to run outdoors. Many find it difficult to stand, especially on upper floors.

b) Furniture is shifted and top-heavy furniture may be overturned. Objects fall from shelves in large numbers. Water splashes from containers, tanks and pools.

c) Many buildings of vulnerability class A suffer damage of grade 3; a few of grade 4.Many buildings of vulnerability class B suffer damage of grade 2; a few of grade 3.

A few buildings of vulnerability class C sustain damage of grade 2.

A few buildings of vulnerability class D sustain damage of grade 1.

**VIII. Heavily damaging**

a) Many people find it difficult to stand, even outdoors.

b) Furniture may be overturned. Objects like TV sets, type- writers etc. fall to the ground.

Tombstones may occasionally be displaced, twisted or overturned. Waves may be seen on very soft ground.

c) Many buildings of vulnerability class A suffer damage of grade 4; a few of grade 5.

Many buildings of vulnerability class B suffer damage of grade 3;

a few of grade 4.
Many buildings of vulnerability class C suffer damage of grade 2; a few of grade 3.
A few buildings of vulnerability class D sustain damage of grade 2.

**IX. Destructive**

a) General panic. People may be forcibly thrown to the ground.

b) Many monuments and columns fall or are twisted. Waves are seen on soft ground.

c) Many buildings of vulnerability class A sustain damage of grade 5.
Many buildings of vulnerability class B suffer damage of grade 4; a few of grade 5.
Many buildings of vulnerability class C suffer damage of grade 3; a few of grade 4.
Many buildings of vulnerability class D suffer damage of grade 2; a few of grade 3.
A few buildings of vulnerability class E sustain damage of grade 2.

**X. Very destructive**

c) Most buildings of vulnerability class A sustain damage of grade 5.
Many buildings of vulnerability class B sustain damage of grade 5.
Many buildings of vulnerability class C suffer damage of grade 4; a few of grade 5.
Many buildings of vulnerability class D suffer damage of grade 3; a few of grade 4.
Many buildings of vulnerability class E suffer damage of grade 2; a few of grade 3.
A few buildings of vulnerability class F sustain damage of grade 2.

**XI. Devastating**

c) Most buildings of vulnerability class B sustain damage of grade 5.

Most buildings of vulnerability class C suffer damage of grade 4; many of grade 5.
Many buildings of vulnerability class D suffer damage of grade 4; a few of grade 5.
Many buildings of vulnerability class E suffer damage of grade 3; a few of grade 4.
Many buildings of vulnerability class F suffer damage of grade 2; a few of grade 3.

**XII. Completely devastating**

c) All buildings of vulnerability class A, B and practically all of vulnerability class C are destroyed. Most buildings of vulnerability class D, E and F are destroyed. The earthquake effects have reached the maximum conceivable effects.

## Appendix 3 : JMA seismic intensity scale [7]

| Degree | Human percetion and reaction | Indoor situation | Outdoor situation |
|---|---|---|---|
| 0 | Imperceptible to people, but recorded by seismometers. | | |
| 1 | Felt slightly by some people keeping quiet in buildings. | | |
| 2 | Felt by many people keeping quiet in buildings. Some people may be awoken. | Hanging objects such as lamps swing slightly. | |
| 3 | Felt by most people in buildings. Felt by some people walking. Many people are awoken. | Dishes in cupboards may rattle. | Electric wires swing slightly. |
| 4 | Most people are startled. Felt by most people walking. Most people are awoken. | Hanging objects such as lamps swing significantly, and dishes in cupboards rattle. Unstable ornaments may fall. | Electric wires swing significantly. Those driving vehicles may notice the tremor. |
| 5 Lower | Many people are frightened and feel the need to hold onto something stable. | Hanging objects such as lamps swing violently. Dishes in cupboards and items on bookshelves may fall. | In some cases, windows may break and fall. People notice electricity poles moving. Roads may sustain damage. |

| | | | |
|---|---|---|---|
| | | Many unstable ornaments fall. Unsecured furniture may move, and unstable furniture may topple over. | |
| **5 Upper** | Many people find it hard to move; walking is difficult without holding onto something stable. | Dishes in cupboards and items on bookshelves are more likely to fall. TVs may fall from their stands, and unsecured furniture may topple over. | Windows may break and fall, unreinforced concrete-block walls may collapse, poorly installed vending machines may topple over, automobiles may stop due to the difficulty of continued movement. |
| **6 Lower** | It is difficult to remain standing. | Many unsecured furniture moves and may topple over. Doors may become wedged shut. | Wall tiles and windows may sustain damage and fall. |
| **6 Upper** | It is impossible to remain standing or move without crawling. People may be thrown through the air. | Most unsecured furniture moves, and is more likely to topple over. | Wall tiles and windows are more likely to break and fall. Most unreinforced concrete-block walls collapse. |
| **7** | | Most unsecured furniture moves and topples over, or may even be thrown to the air. | Wall tiles and windows are even more likely to break and fall. RC-block walls may collapse. |

# Appendix 4 : Status of KMA's observatory [13]

2017. 12. 21.

| No. | Code | Region | ºN | ºE | Altitude (km) | seismo-meter | velocity meter | Accelero-meter |
|---|---|---|---|---|---|---|---|---|
| 1 | ADO2 | 안동 | 36.4 | 128.9 | 0.324 | Q330S | 단주기 (CMG-40T-1) | 가속도 (ES-T) |
| 2 | BAR2 | 백령도 | 38.0 | 124.7 | 0.039 | Q330HRS | 광대역 (STS-2.5) | 가속도 (ES-T) |
| 3 | BAU | 백운산 | 35.1 | 127.6 | 0.562 | Q330HRS | 단주기 (CMG-40T-1) | 가속도 (ES-T) |
| 4 | CEJA | 청주 | 36.6 | 127.4 | 0.102 | Q330HRS | | 가속도시추공 (ES-DH) |
| 5 | CHC2 | 춘천 | 37.8 | 127.8 | 0.269 | Q330HRS | 광대역 (STS-2.5) | 가속도 (ES-T) |
| 6 | CHJ2 | 충주 | 36.9 | 128.0 | 0.247 | Q330S | 광대역 (CMG-3T) | 가속도 (ES-T) |
| 7 | CPR2 | 추풍령 | 36.2 | 128.0 | 0.287 | Q330HRS | 단주기 (CMG-40T-1) | 가속도 (ES-T) |
| 8 | CSDB | 청산도 | 34.2 | 126.9 | 0.024 | Q330HRS | | 가속도시추공 (ES-DH) |
| 9 | DACB | 대청도 | 37.8 | 124.7 | 0.081 | Q330S | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 10 | DAG2 | 경산 | 35.8 | 128.9 | 0.294 | Q330S | 광대역 (STS-2) | 가속도 (ES-T) |
| 11 | GAPB | 가평 | 37.8 | 127.5 | 0.131 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 12 | GDDB | 가덕도 | 35.0 | 128.8 | 0.048 | Q330HRS | | 가속도시추공 (ES-DH) |
| 13 | GMDB | 거문도 | 34.0 | 127.3 | 0.14 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 14 | GUM | 구미 | 36.2 | 128.3 | 0.097 | Q730 | | 가속도 (ES-T) |
| 15 | GUS | 서천 | 36.0 | 126.8 | 0.039 | Q730 | | 가속도 (ES-T) |
| 16 | GWYB | 광양 | 34.9 | 127.7 | 0.16 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 17 | HACA | 삼가 | 35.4 | 128.1 | 0.135 | Q330HRS | | 가속도시추공 (ES-DH) |
| 18 | HAMB | 함양 | 35.5 | 127.7 | 0.2 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 19 | HAWB | 화성 | 37.1 | 126.8 | 0.053 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 20 | IMWB | 임원 | 37.2 | 129.3 | 0.055 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 21 | INCA | 인천 | 37.5 | 126.6 | 0.111 | Q330HRS | | 가속도시추공 (ES-DH) |
| 22 | JEO2 | 완주 | 35.9 | 127.3 | 0.199 | Q330HRS | 광대역 (STS-2.5) | 가속도 (ES-T) |

| No. | Code | Region | ºN | ºE | Altitude (km) | seismo-meter | velocity meter | Accelermeter |
|---|---|---|---|---|---|---|---|---|
| 23 | JJU2 | 제주 | 33.4 | 126.5 | 0.525 | Q330HRS | | 가속도 (ES-T) |
| 24 | JNPA | 증평 | 36.8 | 127.6 | 0.126 | Q330HRS | | 가속도시추공 (ES-DH) |
| 25 | JUR | 중랑구 | 37.6 | 127.1 | 0.102 | Q730 | | 가속도 (ES-T) |
| 26 | MOP | 목포 | 34.8 | 126.4 | 0.073 | Q730 | | 가속도 (ES-T) |
| 27 | MUS2 | 문산 | 37.9 | 126.8 | 0.024 | Q330HRS | | 가속도 (ES-T) |
| 28 | OYDB | 외연도 | 36.2 | 126.1 | 0.095 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 29 | PHA2 | 포항 | 36.2 | 129.4 | 0.073 | Q330S | 단주기 (CMG-40T-1) | 가속도 (ES-T) |
| 30 | PORA | 보령 | 36.3 | 126.6 | 0.068 | Q330S | | 가속도시추공 (ES-DH) |
| 31 | PYCA | 면온 | 37.6 | 128.4 | 0.577 | Q330HRS | | 가속도시추공 (ES-DH) |
| 32 | SEHB | 서화 | 38.3 | 128.3 | 0.406 | Q4120 | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 33 | SKC2 | 속초 | 38.3 | 128.5 | 0.059 | Q330HRS | 단주기 (CMG-40T-1) | 가속도 (ES-T) |
| 34 | SMKB | 새만금 | 35.7 | 126.6 | 0.058 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 35 | SUCA | 순창 | 35.4 | 127.1 | 0.146 | Q330S | | 가속도시추공 (ES-DH) |
| 36 | TOHA | 동해 | 37.5 | 129.1 | 0.086 | Q330HRS | | 가속도시추공 (ES-DH) |
| 37 | ULJ2 | 온정 | 36.7 | 129.4 | 0.122 | Q330S | 광대역 (STS-2) | 가속도 (ES-T) |
| 38 | USN2 | 울산 | 35.7 | 129.1 | 0.25 | Q330HRS | 단주기 (CMG-40T-1) | 가속도 (ES-T) |
| 39 | WJU2 | 원주 | 37.4 | 128.1 | 0.423 | Q330S | 단주기 (CMG-40T-1) | 가속도 (ES-T) |
| 40 | YAYA | 강현 | 38.1 | 128.6 | 0.061 | Q330HRS | | 가속도시추공 (ES-DH) |
| 41 | YEYB | 영양 | 36.6 | 129.1 | 0.26 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 42 | YKDB | 욕지도 | 34.6 | 128.3 | 0.133 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 43 | YNCB | 연천 | 38.0 | 126.9 | 0.02 | Q4120 | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |
| 44 | YPDB | 소연평도 | 37.6 | 125.7 | 0.093 | Q330HRS | 광대역시추공 (CMG-3TB) | 가속도시추공 (ES-DH) |

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# 초 록

지진 재난대응에서 피해를 평가하고 유관기관 간에 정보를 소통하는 것은 매우 중요하다. 시의적절하고 신뢰성 있는 정보는 대중의 혼란을 최소화하고 불필요한 노력을 감소시켜 주기 때문이다. 진도는 지진피해를 평가하는 대표적인 척도이고, 거시진도와 계기진도로 구분할 수 있다.

우리나라는 외국과 다른 지진환경을 갖고 있기 때문에, 국내에 적합한 진도 평가 시스템 개선이 필요하다. 이는 거시진도의 지진피해묘사 보완과 계기진도를 이용한 거시진도 예측모델 개발의 두가지 측면으로 진행하여야 한다. 전자는 별도로 연구되고 있으며, 본 연구는 두 번째 주제를 다룬다.

4가지 종류의 계기진도와 거시진도 (관측 MMI) 간의 상관관계를 분석하였다. Housner spectral intensity가 가장 높은 상관관계를 보였고, MMI 예측 모델 개발에 적용되었다. 제안된 모델은 기존보다 향상된 정보를 제공한다. 제한된 조건 (MMI 6 이하, 진앙거리 140 km 이내) 에서 적용할 수 있지만, 국내지진은 거의 중약진지진이기 때문에 이 모델은 대부분의 경우에 활용될 수 있을 것이다. 한국과 유사한 해외 판내부 지역의 강진 자료를 수집한다면 본 모델의 보완에 도움이 될 것이다.



**주요어**

진도, 거시진도, 계기진도, MMI, 판내부, Housner spectral intensity, 지진 대응