Development of Intraplate Macroseismic Intensity Attenuation Relationship for the Korean Peninsula

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ABSTRACT:
Macroseismic attenuation parameters in the intensity attenuation relationship are derived using earthquakes with both macroseismic and instrumental data. The ergodic principle is applied in the estimation of macroseismic attenuation parameters to examine the possibility of combining Sino-Korean earthquakes to overcome the lack of high intensity data from the Korean peninsula alone. One of the most interesting findings in this study is in the comparison of two main types of datasets, intensity data points (IDP) and isoseismal radii, for the same events used in the analysis. Using derived macroseismic parameters, macroseismic focal depths are estimated in comparison with their instrumental depth. Finally, the new intensity attenuation relationships from different types of dataset are derived and compared with intensity attenuation relationships from other intraplate regions. Ultimately, the findings and the framework, including various techniques for critically evaluating historical seismicity data, is hoped to tackle similar issues in other intraplate regions.

Keywords: Intensity Attenuation, Macroseismic parameters, Isoseismal, Intraplate, Korean peninsula

1. INTRODUCTION

In low to moderate intraplate seismicity regions, earthquake engineers and engineering seismologists face challenges dealing with the considerable level of uncertainty in the estimation of seismic hazard. The major difficulties in low-strain intraplate regions not only come from the lack of strong ground motion records, but also from extremely long recurrence intervals (10^4–10^5 years) between large magnitude events. In many studies the input parameters are solely reliant on the short instrumental periods, typically less than 50 years since the establishment of World-Wide Standardized Seismograph Network (WWSSN). This makes it difficult to capture the maximum magnitude as well as to accurately understand the regional seismic characteristics.
The Korean peninsula is a region of moderate intraplate seismicity. It has relatively rich documentary records of historic earthquakes spanning about 2000 years, in addition to about 100 years of instrumental records. However, the restrictions of geographic and political boundaries, dynamic site responses, a generally over-estimated historic catalogue, and an inhomogeneous instrumental catalogue are considered to be obstacles for robust seismic hazard and risk analysis. To overcome the relative lack of instrumental data, a comprehensive analysis of macroseismic data are required. To ensure equal treatment of all data, a local macroseismic intensity attenuation relationship is required. This requires the calibration of the effects of past and the present earthquakes, ultimately used in the development of a reliable historical earthquake catalogue as an additional input parameter for seismic hazard analysis. Previously many studies have found the usefulness of macroseismic data and demonstrate strong correlations with instrumental parameters. As an example, Johnston (1996) revealed that macroseismic and instrumental data holds the same order of uncertainty in the estimation of seismic moment when both high-quality macroseismic and instrumental data are available for a same event.

2. CHARACTERIZATION OF SINO-KOREAN CRATONIC ZONATION

2.1. Geological and tectonic setting

One of main criteria in the selection of data is the availability of both high-quality macroseismic and instrumental data for a same event. To overcome the absence of high intensity data in the Korean peninsula, the ergodic approach is carefully applied to the Sino-Korean craton (SKC) (Fenton et al., 2006; Johnston et al., 1994). The SKC was chosen because it has a similar geological history and seismotectonic character to the Korean peninsula. Due to uncertainty in the boundaries of deformation around the margin of the SKC, we decided to reduce cratonic boundaries by 100km (*cf.* Fenton et al., 2006). The remaining area of Sino-Korean cratonic zone (SKCZ) is used for this study (Fig. 1).

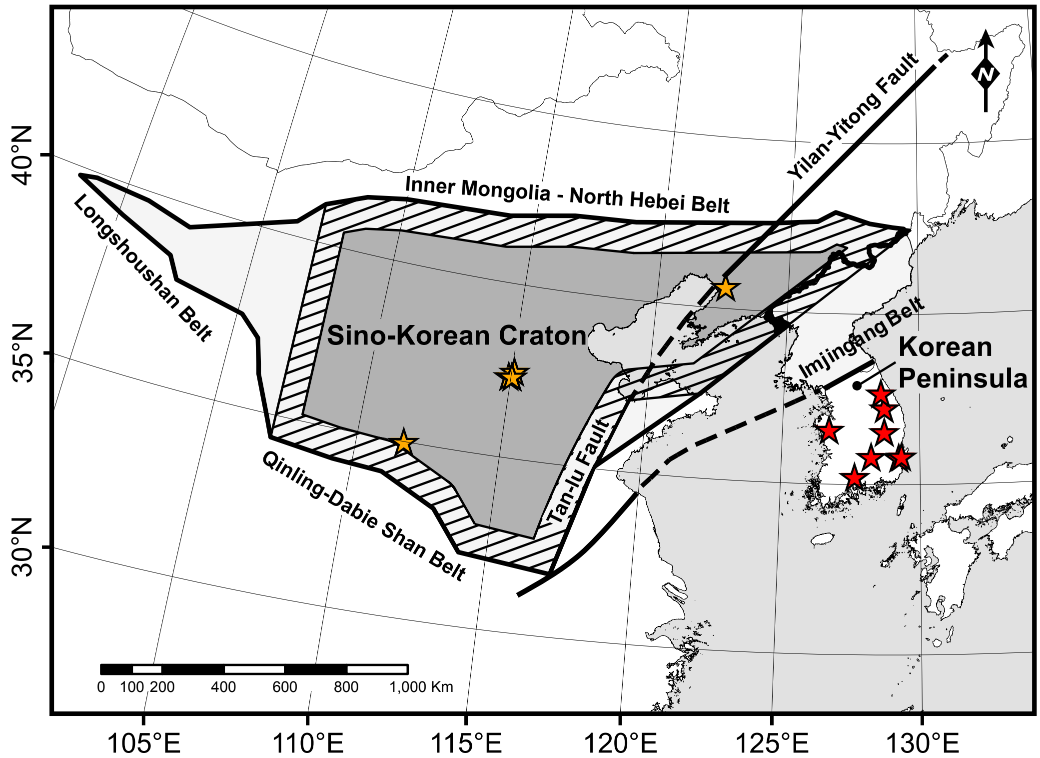

Figure 1. Map of the Sino-Korean craton as defined in this study. Light gray indicates entire SKC. Hatched area indicates marginal reduction of 100km from the cratonic boundaries. Dark gray is the SKCZ (see details in the text). Red Star: Korean earthquakes, Orange Star: SKC earthquake.

3. DATA COLLECTION AND CALIBRATION

There are two primary types of macroseismic dataset used in the derivation of macroseismic data: intensity data points (IDP) and isoseismal data. The former approach is more commonly considered in modern macroseismic studies (*e.g.*, Bakun and Wenthworth, 1997) than the latter (*e.g.*, Ambraseys, 1985; Burton et al., 1985; Musson, 1996). In this study, it was decided to make use of both datasets for cross-validation. For the Korean peninsula, the quality of macroseismic data is variable, largely due to limitation in the geographic extent. Therefore cross-validation of estimates from each dataset is very useful. The use of a second dataset compensates for bias: the IDP data in the population distribution, macroseismic surveying method, source directivity and anomalous site effects, and the isoseismal data in the subjectivity and irreproducibility (*e.g.*, De Rubeis et al., 1992). Using two types of macroseismic data provides additional confidence and reliability in the estimation of macroseismic parameters.

The selection of earthquakes is made mainly based on the following criteria: 1) Earthquakes should have both macroseismic and instrumental data which are reliable, accurate, and sufficient (at least three observed intensity classes) to re-produce isoseismal maps and to identify intensity data points (IDPs) using damage descriptions. 2) Macroseismic or instrumental focal depth should be reasonably accurate. 3) Earthquakes should have similar focal mechanisms. A total of 1479 IDPs for 15 earthquakes with predominant strike-slip faulting were selected for both the Korean peninsula (442 IDP for 8 earthquakes) and SKC (1011 IDP for 6 earthquakes).

3.1 IDP data

For Korean earthquakes intensity assignment and reassessment are carried out using Modified Mercalli intensity (MMI) for each IDP. Whenever the original damage description is available, the MMI is directly assigned or at least taken into account with higher weighting. However, when either only a few summarised damage descriptions from newspapers or only IDP intensities without damage description from the governmental annual reports or professional bodies are available, the latter is considered more reliable with higher weighted in the intensity assignment. When either data source is not trustworthy, both are weighted equally. The large amount of historic information is retrieved from a variety of sources: newspaper archives (including national and regional newspapers), governmental reports, and academic journals. Available Chinese, Japanese and North Korean felt localities are also taken into account. For pre-2000 earthquakes, the JMA intensity scale (1956) is widely used in Korea. Since mid to low intensity ranges are the most frequent for intraplate regions, it should be noted that JMA scale is not ideal for low seismicity regions. Lower intensities, typically a range of JMA I to III, are difficult to differentiate to MMI and this is thought to be the primary source of uncertainty together with coarse conversion from JMA to MMI by conversion tables. In parallel with intensity assignment, data quality assessment is carried out by assigning three quality level codes for each IDP. These indicate the locational certainty, the reliability of damage description and the degree of clarification of information, respectively. These criteria are generally based on Leveret et al. (1994).

Sino-Korean earthquakes between 1900 and 1979 were selected from the ISC and NEIC databases. The temporal constraint was due to the availability of macroseismic data. The main sources of macroseismic data for SKC earthquakes are Gu et al. (1989) and Compilation Group of China Seismic Intensity Zoning Map (SSB) (1979). To assure the additional data quality, instrumental parameters for all the SKC earthquakes are adapted from the high-quality ISC EHB bulletin (2009), except for one SKC earthquake. SKC earthquakes are carefully selected by the following criteria: 1) Earthquakes should have both accurate isoseismal data with detailed damage descriptions and instrumental data. 2) The instrumentally recorded focal depth should have the reasonable level of accuracy. MMI II is included for most events unless the data is scarce or suspicious.

3.2 Isoseismal data

IDP data are used to construct isoseismals for selected events on the Korean peninsula. In order to minimise the subjectivity in drawing isoseismals, the isoseismals for all 17 earthquakes are re-constructed using raw IDPs (before calibration). Each isoseismal map is drawn using ESRI ArcGIS, based on general guidelines by Davison (1921) and Musson and Cecić (2002). The general process constructs polygons, followed by the smoothing using a Bezier interpolation algorithm (Farin, 1997). When events are located near the crust (often the case in Korea), a symmetric felt area is generally assumed (Fig. 2).

4. REGRESSION ANALYSIS

In this study, macroseismic parameters are estimated empirically using IDP dataset with instrumental focal depth for a given confidence level. Then the estimated macroseismic parameters are assumed in the macroseismic focal depth determination for isoseismal dataset. The estimated macroseismic depth can then be compared with instrumental depth. The attenuation model used in this study by Kövesligethy model (1906) is based on the isotropic radiation which has great advantages of integrating the focal depth determination (Musson and Jiménez, 2008).

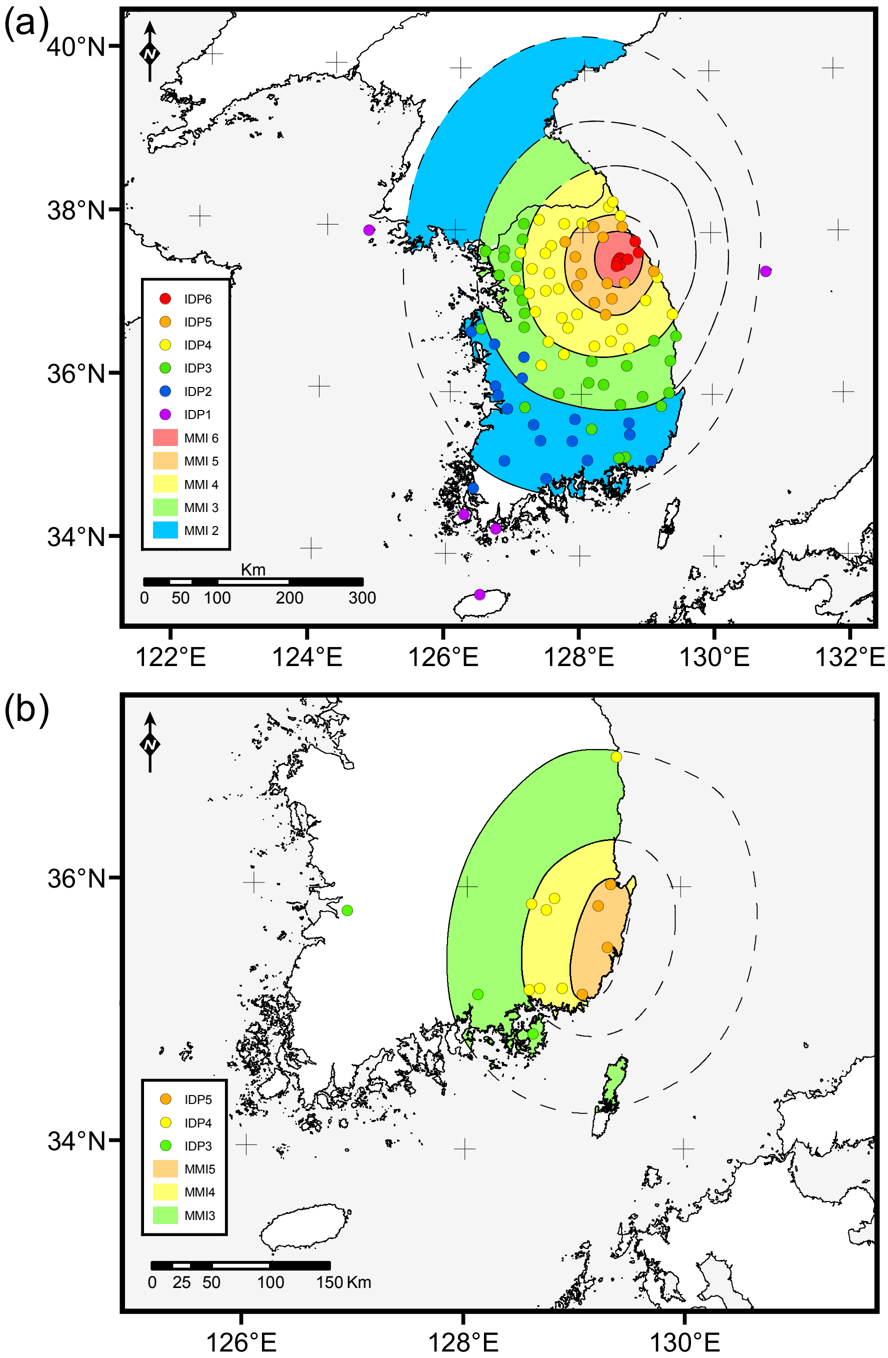

Figure 2. Examples of isoseismal maps for high-quality and poor-quality data. a) 2007 Odesan earthquake, b) 1999 Gyeongju earthquake.

The Kövesligethy model has the form:

$$I_{ij} = I_{0_i}{}^{*} - a\log\left(\frac{\sqrt{R_{ij}{}^2 + h_i{}^2}}{h_i}\right) - b\left(\sqrt{R_{ij}{}^2 + h_i{}^2} - h_i\right) \tag{1}$$

where R_{ij} is the epicentral distance and h_i is the focal depth for the i^{th} earthquake at j^{th} intensities. For simplicity of equation, a (= km) and b (= kγ·loge) are often used for the geometric spreading and an energy absorption coefficient term, where k is a geometric spreading coefficient, m is the seismic wave amplitude, γ is an energy absorption coefficient. Theoretically, I_0^* represents epicentral intensity however it must be used as a reference intensity in the regression analysis to be calculated for each earthquake to control the intercept in the ordinate. The epicentral intensity does not imply a true epicentral intensity at the source when R = 0km, but it corresponds to the average measure of ground shaking at the felt localities rather than at a point. Also the seismic intensity scale is a descriptive and non-uniform incremental parameter that is only known in whole or half intensity (Ambraseys, 1985; Musson, 1996).

A typically assumed geometric spreading coefficient of 3 (Cancani, 1904; Kövesligethy, 1906) is applicable for European data (*e.g.*, Burton et al, 1985; Musson, 1996). However, it should be noted that the relationships between the physical earthquake process and the empirical findings in the macroseismic parameters are yet to be clearly understood (Kárník, 1969). Therefore it is not strictly correct to use a fixed geometric spreading coefficient for other regions. Theoretically, the geometric spreading coefficient should be derived empirically for individual regions to reflect physical correlation between the macroseismic intensity and ground motion amplitude. However, this is not practically straightforward, mainly due to considerable scattering and large uncertainty associated with the nature of macroseismic intensity (*e.g.*, Ambraseys, 1974; Murphy and O'Brien, 1977). For most intraplate regions, where strong ground motion data is scarce, the correlation between regional based macroseismic intensity and ground motion parameters is problematic.

4.1. Ordinary least-squares

Ordinary least-squares (OLS) regression is the most commonly applied to isoseismal radii datasets (*e.g.*, Ambraseys, 1985; Burton et al., 1985; Musson, 1996). To have sufficient observation data to control the solution at least three observed intensity radii are used in the analysis (Ambraseys, 1985). When both macroseismic and instrumental focal depth are unknown which is often the case for historical data, this requires at least four normal equations to solve Kövesligethy model (Eqn. 1) for the variables a, b, I_0 and h. However, decoupling four unknown variables becomes almost impossible to solve due to nonlinearity of the model and the considerable trade-off between parameters. As stated above, for European countries, it is typical to assume a=3 as scaling factor and find b individually for each event or using group optimization (*e.g.*, Musson, 1996). Alternatively, a and b are obtained directly from data fitting (Levret et al., 1994).

For the Korean Peninsula, there are several problems in using any of the above methods. One is that there is no definitive explanation or reason to assume a=3. Although this is empirically derived for Europe (Cancani, 1904), the quality of data used for the relationship are questionable. Also there is the lack of strong macroseismic intensity data to correlate with ground motion parameters. Therefore, two different approaches are considered: one is to constrain a=3 (Sponheuer, 1960) and the other without constraint. Then, b is estimated from the group optimization with unconstrained I_0^* using least-squares.

4.2. Weighted least-squares

Weighted least-squares (WLS) regression method proposed by Stromeyer and Grünthal (2009) is adapted for IDP dataset. Two of the main advantages for this technique are in the indication of uncertainty in the estimated parameters as well as the predicted intensities for the confidence level of interest based on the input parameters. Ultimately, this epistemic uncertainty can be incorporated into the probabilistic hazard calculation using a logic tree framework (Stromeyer and Grünthal, 2009). Stromeyer and Grünthal (2009) proposed a linear WLS method which is equivalent to the method of maximum likelihood or minimising goodness-of-fit in the context of finding optimum solutions by minimising its residuals. Since IDP is used as input data, disproportionate numbers of observations in the subclasses of both the highest and the lowest intensities are commonly encountered. To overcome such sampling bias, each of the IDP in one intensity class is equally weighted by the reciprocal of the total number of IDPs in that intensity class. This weighting scheme is particularly useful for Korean earthquakes where the lower intensity classes of MMI II and III are usually absent. For most intraplate regions, especially for the Korean peninsula with limited geographic extent and experiencing scarce events with large dispersion of the macroseismic data, it is difficult to assume for a single event of high quality IDP data to have a full control in the complicated near-field and far-field behaviour. Moreover, typical seismicity of low to moderate magnitude ranges for Korean earthquakes cause difficulties in the calibration for low intensity classes. For these reasons, the methods of Bakun and Wentworth (1997) and Levret et al. (1994) are not considered for this study. However, the disadvantage of this method is the need of the reliable macroseismic focal depth as input parameter which must be determined *a priori* usually from isoseismal data. Since there is no previously conducted macroseismic focal depth studies for the Korean peninsula, this study used the best available instrumental data.

5. ESTIMATION OF MACROSEISMIC ATTENUATION PARAMETERS

Macroseismic parameters a and b are estimated using WLS technique using three types of regional datasets: Korean IDP data, SKC IDP data and combined data. These three datasets are considered to examine the problem of regionalisation. Those results are then compared with results from isoseismal radii data and with the values determined for other regions of similar tectonic character (Table 1). The mean macroseismic parameters and 1σ (68.3%) and 2σ (95.4%) joint confidence intervals are illustrated with error ellipsoids in Fig. 3. Estimation between macroseismic attenuation parameters between IDP and isoseismal radii data show small variation with energy absorption coefficient; b = 0.002–0.006 for Korea, b = 0.0005–0.0009 for SKC region and b = 0.0006–0.001 for combined region of the Northeast China and the Korean peninsula. These results are similar to other intraplate regions where the energy absorption term is relatively small (Table 5.1). However, the geometric spreading term showed significant variation between regions rather than the type of dataset. There are several possible reasons, including overestimation of isoseismal radii at the higher intensity and influence of anomalous site effects from IDP data. As much larger joint confidence intervals for Korean dataset shows (Fig. 3), the source of discrepancy in the geometric spreading is not from regional variation but mainly due to lack of data. Nevertheless, it is interesting to note that the macroseismic attenuation parameters from combined data are generally similar to other intraplate regions of Europe (Table 5.1).

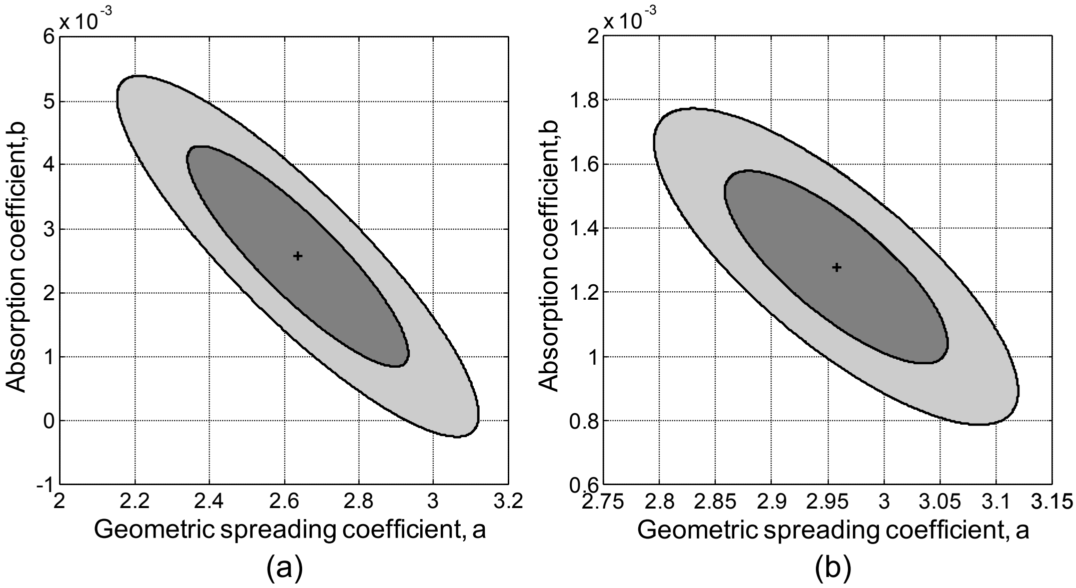

Figure 3. Error ellipsoid of the joint confidence regions for the estimated parameters a and b, Dark gray region indicates 1σ and light gray for 2σ from the mean. (a) Korean IDP data, (b) Combined (Korean peninsula plus SKC) data.

6. MACROSEISMIC EPICENTRE AND FOCAL DEPTH DETERMINATION

To date there has been very little research into macroseismic depth determination for the Korean peninsula. Globally, the majority of existing macroseismic depth studies are conducted in Europe and Russia (during the former Soviet Union) where the large amount of historical data are usually available. Two models are widely accepted for estimating macroseismic depth: Kövesligethy (1906) and Blake (1941). The Blake model is simple and effective for approximating depth but is less accurate than Kövesligethy model (Burton et al., 1985; Kárník, 1969). Therefore the Kövesligethy model is used in this study.

Table 5.1. Macroseismic parameters from different regions.

Region	a	b	Data Type	Reference
Korea	2.64	0.003	IDP	Han and Fenton (this paper)
Korea	3 (constraint)	0.002	Isoseismal Radii	
	2.20	0.006		
SKC Region	3.15	0.0009	IDP	
SKC Region	3 (constraint)	0.0005	Isoseismal Radii	
	2.92	0.0007		
Combined	2.96	0.001	IDP	
Combined	3 (constraint)	0.0006	Isoseismal Radii	
	2.92	0.0008		
France	3.1	0.007	IDP	Levret et al. (1994)
SW Germany	3 (constraint)	0.001	Isoseismal Radii	Kárník (1969)
Central Europe	2.80	0.001	IDP	Stromeyer and Grünthal (2009)
U.K.	3 (constraint)	0.004	Isoseismal Radii	Musson (1996)

6.1 Comparison of macroseismic and instrumental focal depth

Macroseismic source parameters are estimated using the macroseismic attenuation parameters obtained for the Korean peninsula. The macroseismic focal depths are determined for eight Korean earthquakes of the period 1996-2010. A graphical assessment method of estimating focal depth was originally proposed by Sponheuer (1960) and subsequently developed by Burton et al. (1985) and Musson (1996). This method is one way of finding the optimum I_0 and h pair using root-mean-square (RMS) from the ranges of I_0 and h pairs. In this study, the range of 1 to 30km (approximated crustal thickness for the Korean peninsula) and the observed $I_0 - 1$ to $I_0 + 3$ are used, in increments of 0.1 intensity units (Fig. 4). Although the comparison is made between small samples, no systematic errors were evident; this is consistent with the findings of Musson (1996). The mean, median and standard deviation of residuals between observed and calculated depth were about 1.9km, 1km and 3.6km for a=2.64 and b=0.003 (Korean IDP data) and about 1.3km, 1km and 6.2km for a=2.96 and b=0.001 (combined IDP data). Since the standard deviation of the latter is greater than the former by a factor of 2, it should be examined further with the larger samples.

7. INTENSITY PREDICTION MODEL

The usefulness of intensity prediction models has been frequently emphasized, yet the majority of intensity prediction studies are limitedly to Europe and U.S.A. Since macroseismic intensity is a damage-related, semi-physical parameter it is extremely useful in the prediction of the earthquake impact and the probable losses to the built environment. Thus, such models are particularly useful in the earthquake loss estimation and intensity-based hazard assessments, performed for disaster response planning and insurance loss estimation. Using estimated macroseismic attenuation parameters, the performance of intensity prediction equation (IPE) is examined with recent Korean earthquake and compared with existing intensity prediction models in other intraplate regions (Fig. 5 and Fig. 6).
The Kövesligethy model has great advantages in estimating both depth determination and intensity attenuation. However, to better characterize the intensity attenuation, some physical parameter such as magnitude is also needed. It is important to note that there is no systematic difference between IDP and isoseismal data at depths of 10km and 20km (Fig. 6b and 6c). The overall trend for isoseismal data shows a slightly lower attenuation rate than IDP data in the near-field and a greater attenuation in the

far-field. No systematic differences are evident for both regions and types of datasets (Fig 6). However, at shallow depths, below 10km, the discrepancy between IDP and isoseismal data begins to increase (Fig. 6a). Since in a shallow focus event, the R/h ratio becomes larger so that it is greatly affected by the geometric spreading coefficient (a). In addition the IDP and isoseismal datasets for Korea alone seem to be insufficient to capture near-field effects for high intensity earthquakes (Fig. 6a), although this is not a significant problem for depth determination.

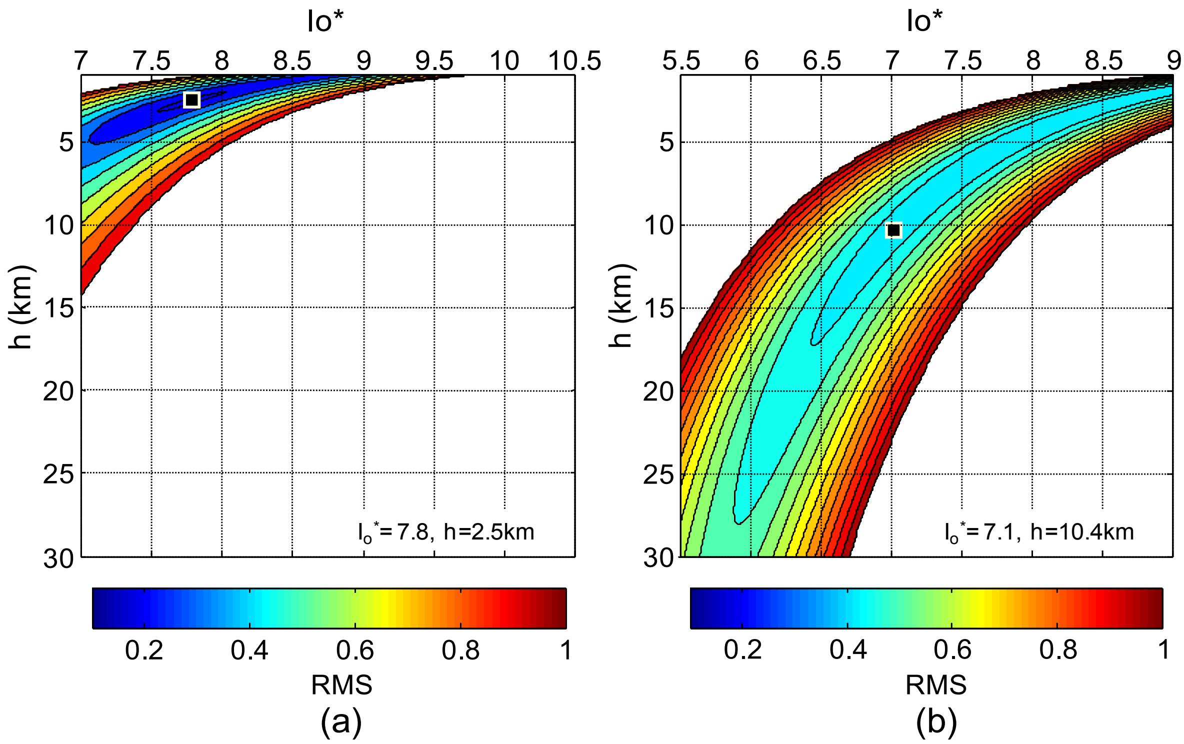

Figure 4. Macroseismic depth determination. a) 1978 Hongsung earthquake, b) 2007 Odesan earthquake.

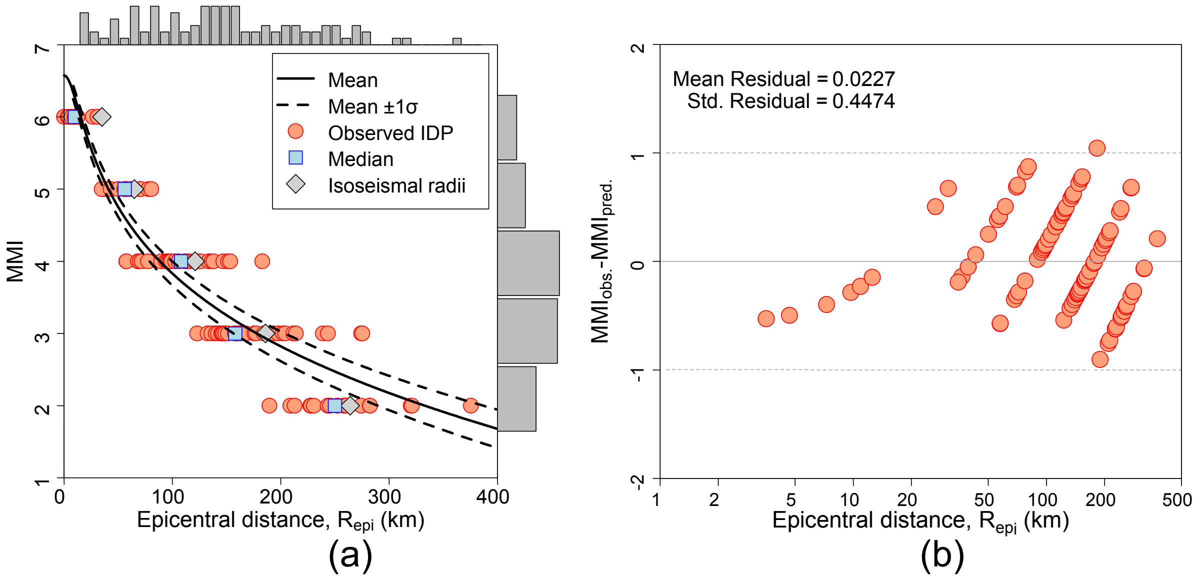

Figure 5. Comparison between intensity prediction model and observed intensities for 2007 Odesan earthquake. a) mean and 1σ attenuation parameters, b) mean and standard deviation of residuals.

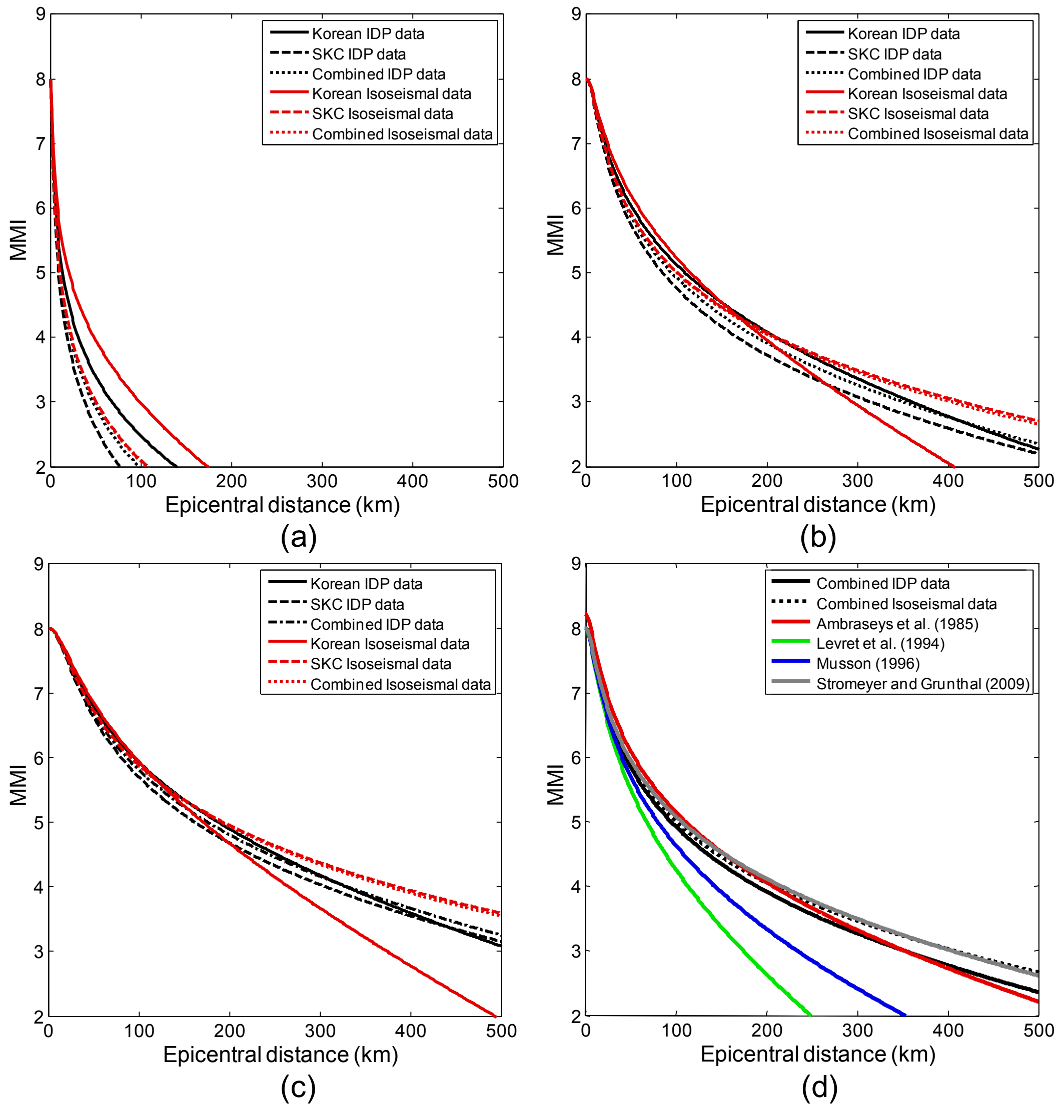

Figure 6. Comparison of derived intensity prediction relationships among different dataset for the Korean peninsula at focal depth a) h=1km, b) h=10km, (c) h=20km and (d) other intraplate regions at h=10km. Assumed $I_0^*=8$ for all cases.

Comparison of existing intensity attenuation relations for other intraplate regions, at depth of 10km, (Fig. 6b) shows significant difference and this becomes dramatic at 1km and 20km (Fig. 6b and 6c). This is because all existing attenuation relationships for Korea assumed a fixed depth of h=10km.

8. CONCLUSION

Various aspects of both the types and regionalisation of datasets and related-issues in the use of macroseismic data for intraplate regions are investigated. The comprehensive framework used in this study is helpful for intraplate regions, particularly in the development of an intensity attenuation model. One of the most interesting findings is in the comparison of datasets. No systematic differences in the macroseismic parameters are evident between regional data but the scarcity of high intensity data is thought to be the main factor for the variation of geometric spreading coefficient. The intensity attenuation model for both Korean and SKC regions from the combined data shows good agreement with other intraplate regions of Europe, particularly with Stable Continental Regions.

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