Detailed Scale Ground Motion Maps with Guaranteed Accuracies and Web-GIS Application for the Local Communities

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SUMMARY:
The present paper discusses and proposes various types of countermeasures against earthquake disasters in a typical Japanese local city of Owari-asahi, equipped with the system to estimate strong ground motions with the highest and guaranteed accuracies. The estimations are objectively made, and the estimated values are always compared with the measured ones when earthquakes occur. Then the estimation algorisms are being statistically compensated to keep the highest accuracy.
The results of the estimations are exhibited in digital maps on the web-GIS together with other information such as refuge places, hospitals, and so on, to share and to utilize the information with the local government and its communities. As the ground motions are estimated at every building point, the digital maps contribute to stir up great public awareness, and can be utilized to take the optimum action plans, such as seismic capacity evaluations, seismic strengthening, furniture anchoring, evacuation planning and etc.

Keywords: earthquake ground motion, digital, hazard map, accuracy, web-GIS, Kriging, stochastic

1. INTRODUCTION

The first aim of the present paper is to provide a system to estimate seismic indexes such as strong ground motions with the accuracies of each building in the target areas for both of various type of scenario and of real earthquakes in one of the typical Japanese cities of Owari-asahi. As the motions are estimated at every building, the highest public awareness can be expected, and it leads the habitat to the optimum countermeasures with the quantitative and objective accuracies. The estimation accuracies of the system are guaranteed, and go on greater as the more real earthquake motions are observed and more ground investigation data are obtained. By the calibrations of estimated and observed ground motions, the highest accuracy can be kept with the minimum cost in the proposed system.
The second aim is to exhibit the distributions of the strong ground motions on the digital maps, so that the local government and the community can recognize many types of information such as vulnerabilities, functions, capacities etc. of buildings (individual houses, refuges, hospitals, and fire departments etc.), and take the best countermeasures.

2. METHOD OF ESTIMATIONS

2.1. General

To provide the hazard maps in the target area (i.e. Owari-asahi city), it is need to hypnoses some mechanical aspects of the epicentres, and to calculate earthquake waves that leach the surfaces of the bed grounds under the city before estimate the strong ground motions on the ground surfaces. The hypnoses or estimations of earthquake waves have, however, been discussed in the other studies or papers (e.g. Sugai at el), and thus are not in the objects of the present paper.

2.2. Calculation of Intensities at Boring Points

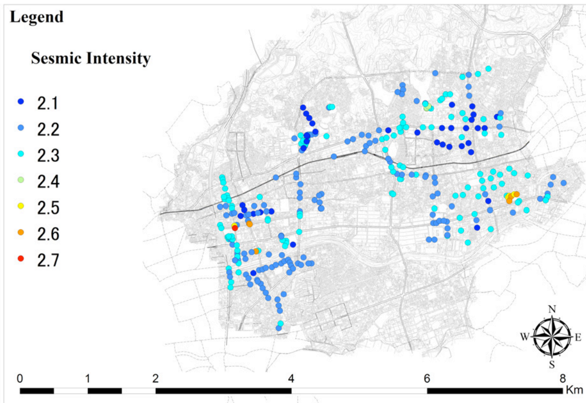


Figure 2.1. Distribution of boring points and their seismic intensities in Owari-asahi city by the East Japan Great Earthquake 11th March 2011

Once the earthquake waves under the surface layers (referred as “input waves” in this paper) are given, the strong ground motions on the ground surfaces (referred as “output waves” in this paper) can be calculated by already proposed analytical methods by utilizing boring investigation data in completely objective manners at each boring point. For example, **Figure 2.1.** shows the distribution of boring points and their seismic intensities calculated by one of the simplest methods with the input waves that were observed on the surfaces of the bed grounds nearby the Owari-asahi city in 11th March 2011 (when the East Japan Great Earthquake occurred). Although over 600 boring date are provided by the local government, locations of about 300 data could not be specified, and depth of few boring data are not enough to reach the bed rocks. Then about 300 data of the boring investigations data are utilized in the analysis. As the figure shows, the seismic intensities are lager along the trace of ancient river (just above the present river), and smaller in the other area, which seem to be accordant with the geographical aspects in the city.

2.3 General Idea for Modelling of Stochastic Field of Seismic Intensities

Then, to estimate strong ground motions with the accuracies of each building in the city, Kriging analyses are employed in this study. The random fields of the seismic intensities are modeled, here, with normal Gaussian distributions, as follow.

$$p(\mathbf{z}|\boldsymbol{\theta}) = \left(\frac{1}{\sqrt{2\pi}}\right)^{\frac{n}{2}} \cdot |\mathbf{C}|^{-\frac{1}{2}} \cdot \exp\left\{-\frac{1}{2}(\mathbf{z}-\boldsymbol{\mu})^T \mathbf{C}^{-1} (\mathbf{z}-\boldsymbol{\mu})\right\}^2 \tag{2.1}$$

Here $\boldsymbol{z}$ is vector of the seismic intensities, and $\boldsymbol{C}$ is the covariance matrix, and $\boldsymbol{\mu}$ is the trend function of $\boldsymbol{z}$, which is determined by location (x, y), and is expressed, in the present paper, as n dimensional function as follows.

$$\boldsymbol{\mu} = \mu(x,y) = \sum_{i=0}^{n} \sum_{j=(i+1)\cdot i/2}^{(i+2)(i+1)/2-1} b_j x^{\frac{(i+3)\cdot i}{2}-j} y^{\frac{-(i+1)\cdot i}{2}+j} \tag{2.2}$$

The dimension n can be determined by minimizing AIC as follows (Akaike, H. 1973).

$$\mathrm{AIC} = -2 \times \mathrm{Max}\{\ln p(\mathbf{z}|\mathbf{b},\boldsymbol{\theta})\} + 2 \times (m) \tag{2.3}$$

Here m is number of coefficient parameters, and $\boldsymbol{b}$ is the vector of efficient b_i of the trend-function (Wackernagel, H. 2003). As in the equation, AIC is calculated with the number of parameters in covariance matrix $\boldsymbol{C}$, that in trend function and the most likelihood estimators. As in equation (2.1), the stochastic distributions of seismic intensities are modeled with the normal probabilistic distributions in the present study. This has been justified by quantitative analyses of comparisons between elementary probabilistic distributions based the AIC or maximum likelihood estimators.

2.4 "Observation error"

The "output waves" are accompanied by some errors, when calculated by proposed analytical methods even using the completely objective data of boring investigation in the surface layers at the each point. This is mainly because those methods assume one dimensional soil layers distributions in their analyses. Real surface soil layers, however, distribute in 3 dimensional manners, and vary from point to point. Thus the output waves are overestimated in some points, and underestimated near the points. The real strong ground motion on the ground surface smaller than the overestimated values due to the surrounding soils that do not amplify the input wave, and vice versa.

Therefore, these errors accompanied with the calculating "output wave" are referred, in the present paper, as "observation errors" σ'^2. It should be mentioned here that these "observation errors" σ'^2 are not observation errors in the viewpoint of physics of the earthquake ground motion monitors, but are called so in stochastic analyses of the Kriging analyses. Then covariance matrix ***C*** of Kriging analyses is expressed as follows.

$$\mathbf{C} = \begin{bmatrix} C(\mathbf{u}_1 - \mathbf{u}_1) & C(\mathbf{u}_1 - \mathbf{u}_2) & \cdots & C(\mathbf{u}_1 - \mathbf{u}_n) \\ C(\mathbf{u}_2 - \mathbf{u}_1) & C(\mathbf{u}_2 - \mathbf{u}_2) & \cdots & C(\mathbf{u}_2 - \mathbf{u}_n) \\ \vdots & \vdots & \ddots & \vdots \\ C(\mathbf{u}_n - \mathbf{u}_1) & C(\mathbf{u}_n - \mathbf{u}_2) & \cdots & C(\mathbf{u}_n - \mathbf{u}_n) \end{bmatrix} + \begin{bmatrix} \sigma'^2 & 0 & \cdots & 0 \\ 0 & \sigma'^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma'^2 \end{bmatrix} \tag{2.4}$$

Here covariance function C of $\boldsymbol{u}_i(x_i, y_i)$ and of $\boldsymbol{u}_j(x_j, y_j)$ is expressed here as following equation (2.5).

$$C(\mathbf{u}_i - \mathbf{u}_j) = \sigma^2 \exp\left\{-\frac{h}{l}\right\} \tag{2.5}$$

Here h is distance between $\boldsymbol{u}_i$ and $\boldsymbol{u}_j$, and σ^2 and ℓ are parameters called as sill and range respectively. Sill and range are determined based on the maximum likelihood method or minimizing the AIC in equation (2.3).

3. RESULTS OF EXAMPLE ESTIMATIONS

3.1 AIC, Sill, Range, the "Observation Error", and the Trend function

Table 3.1. shows AIC, sill, range, the "observation error", and the coefficient of the trend function, in equations (2.2) and (2.5). The optimum dimension of the trend function is estimated to be 0 due to the AIC, and the coefficient of b_0 is about 2.2. In this case, therefore, the method of stochastic interpolation is called as simple Kriging interpolation of the average seismic intensity is 2.2. As is shown in the table, the "observation error" is reasonably smaller than sill. Then it is inferred that the random field are estimated practically enough. As is also shown in the table, the range (i.e. auto-correlation coefficients) is estimated to be about 125 (m), which is well accordant with that of typical soil parameters in horizontal directions, as is well known in practical geotechnical engineering.

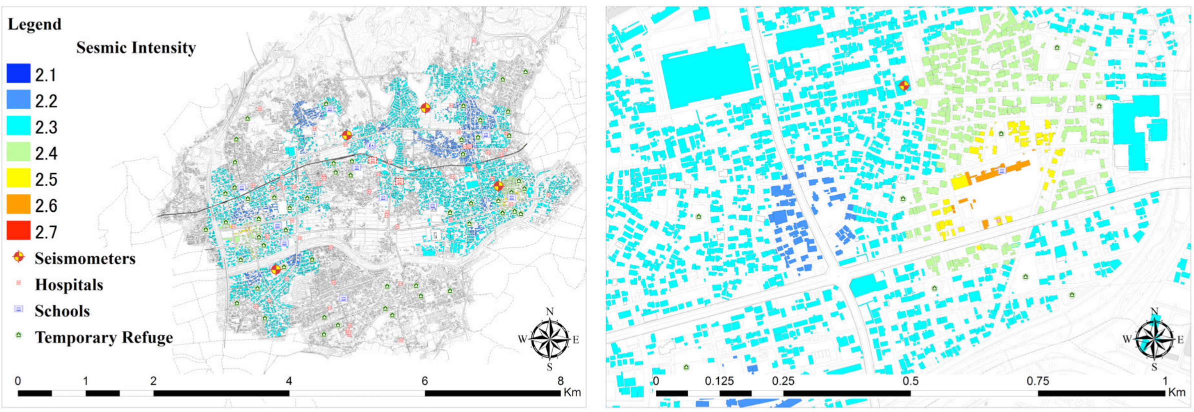
Table 3.1. Result of Kriging Analysis: AIC, Sill, Range, the "Observation Errors" and Coefficient of the Trend Function of seismic intensities in Owari-asahi city by the East Japan Great Earthquake 11th March 2011.

AIC	-654.5
Sill σ_i^2	0.00596
Range（m）	124.8
Observation Error σ_i^2	0.00251
Coefficient b_0	2.24

3.2 Stochastic Interpolation of the Seismic Intensities estimated at the each building point in the Owari-asahi city.

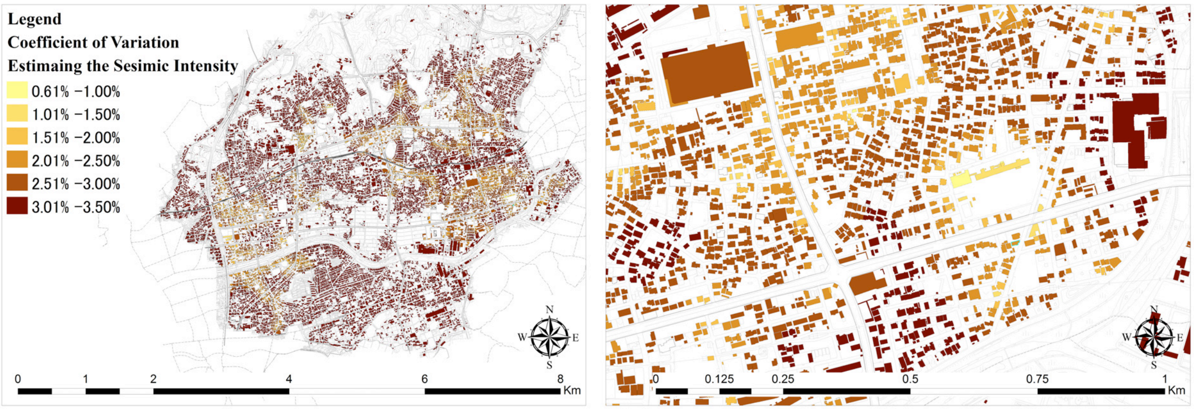
Figure 3.1. shows distribution of seismic intensity estimated at centroid of every building in Owari-asahi city by Kriging method based on calculated intensities at boring points shown in **Figure 2.1.**, and stochastic parameters shown in **Table 3.1**. **Figure 3.1.** also shows the locations of temporary refuge place, schools, hospitals that are essential institutes to be utilized at earthquake disasters occurrences. Although the temporary refuge places occasionally change place, and some hospitals are abolished or newly founded, the digital map of web-GIS can deal with such changes immediately and easily. The figures also show the locations of seismometers settled by the authors to investigate the accuracies of the estimation system of digital hazard maps, to study the seismology, and update the accuracies in the highest level. **Figure 3.1. (a)** shows the distribution of around most of the city. The northern part of the city is occupied by the public forested park, and there are few residential buildings in the area. **Figure 3.1. (b)** shows the distribution of a part of the city in a large scale. The authors were delightfully surprised at exceedingly strong public awareness much more than expected from the habitats in the city, when the present system was introduced to the audiences of a symposium organized by the scientific society of the Environment, Information and Business at Nagoya Sangyo University in 18th February 2011. Though it was uncertain whether all of the citizens well understood about the errors accompanied with the estimators, the estimated seismic intensities at their own houses surely interested the habitats. It was confirmed that the proposed system can attract the public awareness that lead citizens to take countermeasures against earthquake disasters when maps in detail such in **Figure 3.1.** are provided.

As is shown in **Figure 3.1. (a)**, the seismic intensities of the buildings are not exhibited in some zones of the city, and shown coated with gray shadow. These are the buildings around where no boring investigations are founded. As **Figure 2.1.** shows, only about 300 of 600 points of boing data can be preciously located in the present paper, and there are good chances to find the point of the other 300 boring investigation due to the cooperation of the local government because the address of the other investigation are recorded. The authors presume that other boring investigations should have been performed in the gray zones of the city shown in **Figure 3.1. (a)**, firstly because such in-situ investigations are necessary in the gray zones as there are many building constructed in the zones, and secondly because the addresses recorded on the boring investigation sheets pointed into the gray zone. In this paper, however, the authors dare to remain the gray zones on the maps in the figures, to insist that the Kriging system can provide the accuracies to interpolate and to estimate the seismic intensities in every building. The accuracies are higher in areas nearer the boring points, and lower in farer the points.



(a) Around Most of the City (A Small Scale) **(b) A Part of the City (A Large Scale)**

Figure 3.1. Distribution of seismic intensities in Owari-asahi city by the East Japan Great Earthquake 11th March 2011 (M_{JMA} = 9.0, Epicentre : Sanriu Oki, Depth = 24km)

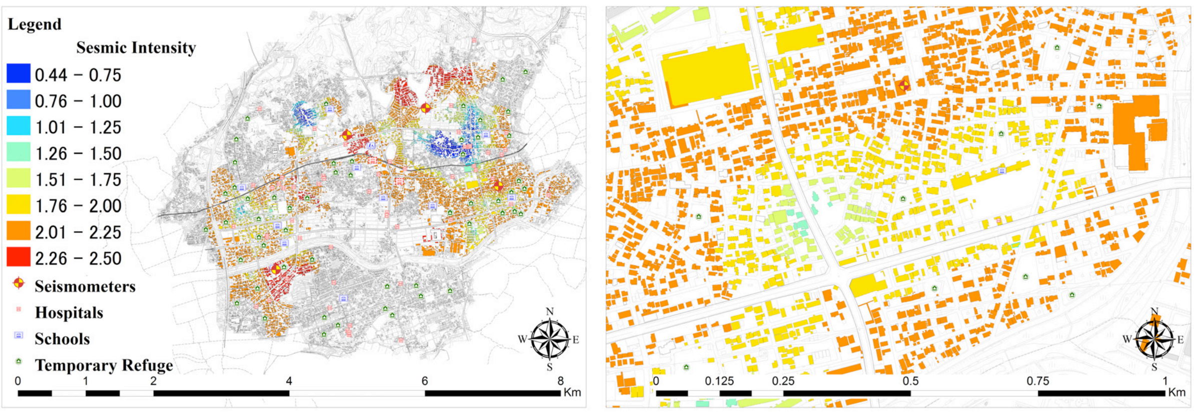


(a) Around Most of the City (A Small Scale) **(b) A Part of the City (A Large Scale)**

Figure 3.2. Distribution of error (Coefficient of Variation) Estimating the Seismic Intensities in Owari-asahi city by the East Japan Great Earthquake 11th March 2011 (M_{JMA} = 9.0, Epicentre : Sanriu Oki, Depth = 24km)

Figure 3.2. shows the accuracies of the Kriging analyses in terms of coefficients of variations. By comparing between **Figure 2.1.** and **Figure 3.2. (a)**, it is clear that coefficients of variations are smaller around the boring points and larger in distance from the points. **Figure 3.2. (b)** shows the difference of or special variations of the accuracies more clearly and in detail. The hazard of earthquake ground motions should be recognized with not only their magnitudes but also the accuracies of the estimations. It should be mentioned here, that the proposed system can quantitatively and objectively provide both the magnitudes and the accuracies. The other methods cannot estimate any earthquake indexes (e.g. seismic intensities, peak ground accelerations, velocities) with their accuracies, neither in quantitative nor in objective manners, because the other methods evaluate the indexes not at points, but for meshes in which model ground layers systems are assumed based on so called “engineering judgments”. When the earthquake indexes are estimated for a mesh, the estimators cannot be compared with those observed by seismometer at a point. “Engineering judgments” may lead to human errors that cannot be quantitatively assessed. Accordingly it must be emphasized that estimation system need to a logic built right in to assess the estimation accuracies quantitatively and objectively. In addition, the cost for establishing the proposed system is quite low, because any other methods consume the most of the costs in assuming the model ground layers systems.

Figure 3.3 shows the distribution of seismic intensities in Owari-asahi city, by an earthquake occurred



(a) Around Most of the City (A Small Scale) **(b) A Part of the City (A Large Scale)**

Figure 3.3. Distribution of seismic intensities in Owari-asahi city by an Earthquake 10th November 2011 (M_{JMA} = 3.9, Epicentre : in Ama City, Depth = 10km)

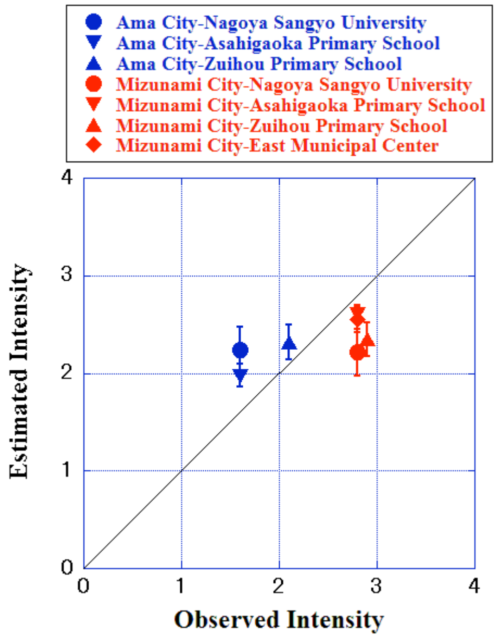


Figure 3.5. A Comparison between
Observed and Estimated Intensities
at the Seismometers in Owari-asahi city

The error = 19.9%

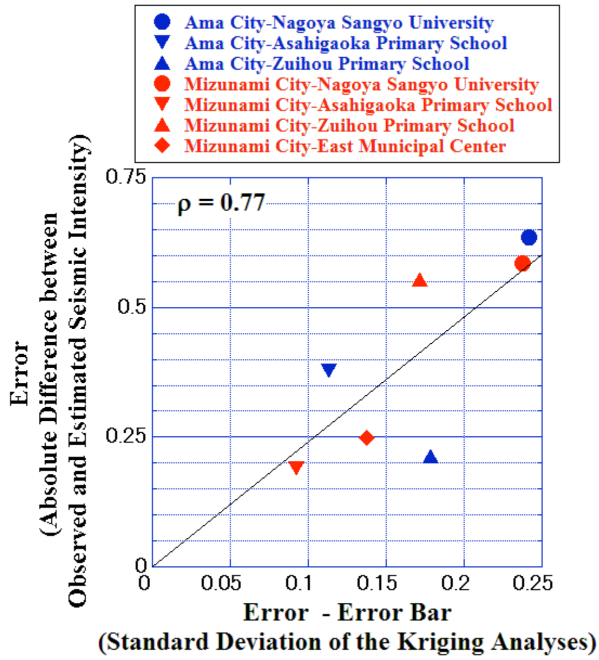


Figure 3.6. A Comparison between
Error Bars in **Figure 3.5.** and Absolute Differences of
the Observed and Estimated Intensities
at the seismometers in Owari-asahi city
The correlation Efficient = 0.77

in 10th November 2011, estimated based on by Kriging analyses. **Figure 3.3 (a)** shows the distribution of around most of the city, and **Figure 3.3 (b)** a part of the city in a large scale. Although the epicenter was much nearer than that in **Figure 3.1**, the Japan Methodological Agency local scale magnitude (M_{JMA}) of the earthquakes was much smaller. Accordingly the seismic intensities are estimated to be smaller. The spatial variation of intensities, however, is clearly exhibited in the **Figure 3.3**. **Figure 3.4** shows the distribution of seismic intensities in the city, by and earthquake occurred in 14th December 2011, in the same way. As is same in **Figure 3.3**, **Figure 3.4 (a)** shows the distribution of around most of the city, and **Figure 3.1 (b)** a part of the city in a large scale. Although the epicenter was in deeper than that in **Figure 3.3**, it was slightly nearer than that in **Figure 3.3,** and the M_{JMA} of the earthquakes was larger than that in **Figure 3.3**. Accordingly the seismic intensities are estimated to be slightly larger. The spatial variation of intensities, however, is clearly exhibited in the **Figure 3.4** as in **Figure 3.3**.

Figure 3.5. shows the comparison of estimated and observed seismic intensities at seismometers located at 6 points shown in **Figures 3.1.**, **3.2.** and **3.4.**. The seismometers had been set and started working after the East Japan Great Earthquake occurred. Therefore, the seismometers did not record the seismic waves in the East Japan Great Earthquake. Although 6 seismometers were set up, some of them did not work and recorded no seismic waves. Then 3 seismic intensities could be calculated for the earthquake in 10th November 2011, and 4 in 14th December 2011. In the figure, the errors of estimations in Kriging analyses are also shown as the error bar in terms of standard deviations.

As it clear in the figure, the seismic intensities are overestimated for the earthquake whose epicenter was in Ama city in 10th November 2011, and underestimated in Mizunami city in 14th December 2011. Accordingly, the seismic intensities would be overestimated in **Figure 3.3.**, and underestimated in **Figure 3.4**.

The precious amount of or characteristics of the errors could not have been studied well at this moment, and the errors are only roughly estimated to be 19.9%. This is because the number of observation is not enough for statistical analyses in detail. As is shown in **Figure 3.5.**, however, the error bars are larger when the absolute differences are larger between the observed and estimated seismic intensities. **Figure 3.6.** shows this comparison between error bars (standard deviation of the

Kriging analyses) in **Figure 3.5.** and the absolute difference of the observed and the estimated intensities. The correlation coefficient is calculated to be 0.77. Then statistical analyses in detail will show the precious error to be smaller than 19.9%. The precious statistical analyses, however, are not discussed in the present paper, because the number of observations is judged to be too few at this moment.

The errors of the 19.9% or smaller could be due to the hypothesis of the "input wave", of share wave velocities (Vs) in the surface ground layered systems, to calculation methods of "output wave" from the "input wave", to the frequencies of the seismic waves, or to another reasons. The authors intend to investigate and to minimize this error of 19.9% as smaller as possible, with more observation data, studies of the mechanics of earthquake wave propagations, and so on.

Anyway, the total errors to estimate the seismic intensities at each building is the summation of the variation of this error of 19.9% (or smaller value) and that of the Kriging analyses such as shown in **Figure 3.2.**, since these errors of two types are independent.

The point that should be emphasized here is that the quantitative errors can be estimated in the system, and that, when they are minimized, the result can be directly reflected in the same system.

4. SHARING OF MAPS BY USING WEB-GIS

The authors plan these generated maps will be shared by web-GIS system. The server system has constructed by FOSS4G (Free and Open Source Software for Geospatial). The authors have the plan introducing **e**-Community Platform 2.0 which is the integrated server software and developed by National Research Institute for Earth Science and Disaster Prevention (NIED), Japan (Sunaga el.al. 2009). The system will be applied to two targets; one is for local people, other is for local governments.

The users can recognize and overlay many types of information such as vulnerabilities, functions, capacities etc. of buildings (individual houses, refuges, hospitals, and fire departments etc.) on the web-GIS. The local people want to know such detail risk information on the daily living space.

The authors will use the system as the risk communication tools and discusses the way to share the information with the local government and the community on the web-GIS. The new type of risk communication is needed which all the estimated data contain the errors and The authors should recognize it and have to make evacuation plan taking account of the existing errors. Especially, The accuracy of the hazard maps is huge problem in Japanese society because of the 3.11 Tsunami or earthquake hazard map have a lot of errors and sometimes it lead the unsafe evacuation.

Although the effective disaster action plans against the future earthquake should be discussed based on the recognition of the errors, the local government and the community cannot easily understand such data and find the way for the preparation before the hazardous earthquakes. The authors will develop the suitable map symbol/notation for the data including errors within the web-GIS, the new learning tools for the data including errors, and the risk communication method in the local government and the community.

5. CONCLUSION

The present paper proposed an estimation system of seismic indexes, in which has following distinguish features or functions built right in.

1) The system can estimate seismic indexes such as the intensities objectively and quantitatively.
2) The system can estimate the accuracies of the estimation also objectively and quantitatively.
3) The system can estimate seismic indexes at every building in the target area immediately.
4) The system can works with minimum costs
5) The system can keep on increasing the accuracies greater and greater with more observation data of strong ground motions of more various types of epicentres, and/or more soil investigation data.

It was also confirmed that the proposed system could attract great public awareness due to the result of presentation of the maps at a public symposium organized in the city.

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