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Reliable land subsidence mapping by a geostatistical spatial interpolation procedure

Cartographie fiable pour les tassements de terre utilisant interpellation geostatistique spatiale

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ABSTRACT
Land subsidence is an important environmental issue, particularly in extensive plain regions. Settlements at many locations have been observed using a bench mark survey to establish the present situation and forecast future trends. A land subsidence map is very useful for disaster mitigation and environmental preservation in the objective region. It is important for sustainable development of the region to evaluate the reliability of the map developed from limited information. A reliable land subsidence mapping by a geostatistical spatial procedure has been proposed and the method has been successful in expressing the accuracy of maps of the present stuations and future trends of land subsidence to evaluate the reliability of hazard maps of this kind.

RÉSUMÉ
L'affaissement de la terre est une issue environnementale importante en particulier en plaines étendues. On a observé des tassements à beaucoup d'endroits en utilisant un enquête de reference pour établir la situation actuelle et tendances de prévision futures. Une carte d'affaissement de terre est très utile pour la réduction de désastre et conservation de l'environnement dan la zone sous consideration. Il est important pour le développement soutenable de la région d'évaluer la fiabilité de la carte développée à partir de l'information limitée. On a proposé une procedure de cartographie fiable pour les tassements de terre utilisant une procedure geostatistique spatiale. La méthode a été réussie pour déterminer l'exactitude des cartes pour des tendances présentes et futures et évaluer de ce fait la fiabilité des cartes de risque de cette sorte.

1 INTRODUCTION

Land subsidence is an important environmental issue, particularly in extensive plains regions such as the northern Kanto Plain, Niigata Plain, or Saga Plain in Japan. Settlement at many locations has been revealed using a bench mark survey to establish the present situation and forecast future trends. In Japan, more than 1,000 such locations are on the Nobi Plain (Kunieda, 2002) and the northern Kanto Plain (Murakami et al., 1998). In southeast Asian countries, about 500 locations exist in and near Bangkok, Thailand (Ramnarong & Baupeng, 1992; Teparaksa, 2002) and 43 locations in and near Hanoi, Vietnam (Giao, 2000).

A land subsidence map is very useful for disaster mitigation and environmental preservation in the objective region (Murakami et al., 2000, 2002; Yasuhara and Murakami, 2001). Settlement distribution has been estimated using observations in the region to investigate the present situation or to forecast future land subsidence trends. However, accuracy of the estimated distribution has not been clarified. It is important for sustainable development of the region to evaluate the reliability of the estimated results in use as a hazard map for disaster mitigation and environmental preservation. In addition, the role that geotechnical engineering plays in its contribution to risk management and asset management is large in development of spatial geo-information technology that can specify the accuracy of estimations.

This paper describes a land subsidence mapping method for representing estimations' reliability by a geostatistical spatial interpolation. That interpolation uses observation locations for monitoring settlements in the northern Kanto Plain, Japan, where settlement has been measured at approximately 1,300 locations, as shown in Fig. 1. First the spatial variability of settlements using a semivariogram was investigated in detail to achieve this. Subsequently, a spatial interpolation method based on the Kriging method being used in geostatistics was applied to land subsidence mapping for representing the present situation. The land subsidence map produced in this way indicates not only the estimator distributions, but also the estimations' standard deviation (ESD). Therefore, the land subsidence map is reliable because it is capable of simultaneously presenting the expected value and accuracy. Furthermore, spatial interpolation was applied in consideration of the prediction error that used the subsidence prediction method; reliability was evaluated, and the land subsidence forecast map was produced reliably.

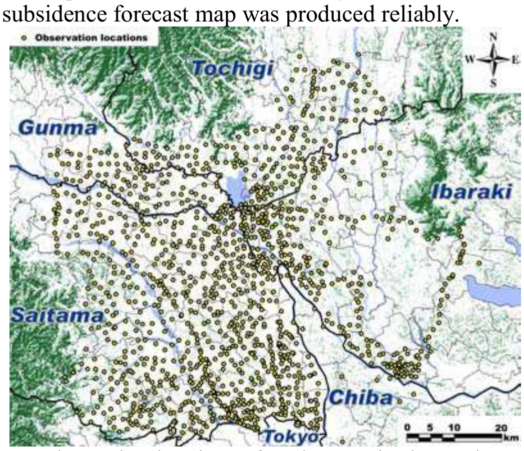


Figure 1 Observation locations of settlements in the northern Kanto Plain, Japan.

2 SPATIAL INTERPOLATION METHOD BASED ON GEOSTATICS

A method for expressing the precision of spatial information in geotechnical engineering is to perform spatial interpolation of observations obtained at various points in the objective area. A method for geostatistics spatial interpolation is called Kriging (Deutsch & Journel, 1998). Kriging is a spatial interpolation method based on an assumption that the estimation at an arbitrary point in an objective area is expressed with a linear weighting that is a combination of all observations. Applicability of Kriging to estimate spatial distributions of geo-technical information at construction sites has been reported, e.g. for residual settlements (Ueda et al., 1986), N-values (Matsui et al., 1991), unconfined compressive strength (Honjo & Kuroda, 1991), thickness of layers, resistivities in layered sediments (Ohnishi et al., 1992), and pile tip levels (Honda et al., 1997).

Estimation $\hat{S}$ of S at an arbitrary location in the space $\boldsymbol{r}$ is expressed as follows.

$$\hat{S}(r_0) = \boldsymbol{\lambda}^T \boldsymbol{S}(\boldsymbol{r}) \tag{1}$$

In that equation, $\boldsymbol{r}_0$ is the position vector at the estimated location, $\boldsymbol{S}(\boldsymbol{r}) = \{S(r_1), S(r_2), \cdots, S(r_N)\}^T$ is an observation vector containing the components of N observations, where N is the number of observations, $\boldsymbol{r}_i$ is the position vector at the i-th observation location $(i = 1, 2, \cdots, N)$, and λ_i is a weighting coefficient for the i-th observation. It is determined by the following formula.

$$\boldsymbol{\lambda}^T \boldsymbol{i} = 1, \quad \boldsymbol{i} = \{1 \quad 1 \quad \cdots \quad 1\}^T, \ \boldsymbol{\lambda} \geq 0 \tag{2}$$

Kriging is classified according to determination methods of the weighting parameters, into Simple Kriging, Ordinary Kriging, Universal Kriging, Co-Kriging, etc. (Deutsch & Journel, 1998). On the basis of Ordinary Kriging, the best estimation is given when the squared estimation error,

$$\hat{\sigma}^2(r_0) = -\boldsymbol{\lambda}^T (\boldsymbol{\Gamma} - I_\varepsilon)\boldsymbol{\lambda} + 2\boldsymbol{\lambda}^T \gamma_0 + Var[S(r_0)] \tag{3}$$

is minimized subject to Eq. (2). Components of $\boldsymbol{\lambda}$ are obtainable from the solution of the following simultaneous equations.

$$\begin{bmatrix} \boldsymbol{\Gamma} - I_\varepsilon & \boldsymbol{1}^T \\ \boldsymbol{1} & 0 \end{bmatrix} \begin{Bmatrix} \boldsymbol{\lambda} \\ \mu \end{Bmatrix} = \begin{Bmatrix} \gamma_0 \\ 1 \end{Bmatrix} \tag{4}$$

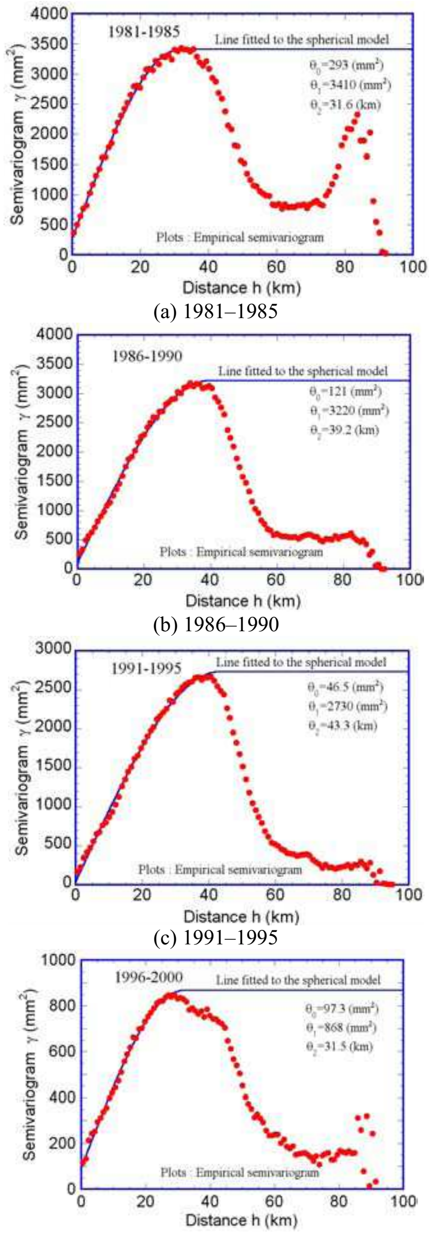
where $\boldsymbol{\Gamma}$ is the matrix that expresses the spatial correlation with each observation location, $\boldsymbol{I}_\varepsilon$ is the diagonal matrix that expresses the autocorrelation at each location, γ_0 is the vector that expresses the spatial correlation between the estimate and observation location, and μ is the Lagrange multiplier. The spatial correlation is modeled as a function of the distance after investigating the following semivariogram, which is calculated using all observations.

$$\gamma(h) = \frac{1}{2|N_k|} \sum_{N_k} \{S(\boldsymbol{r}_i) - S(\boldsymbol{r}_j)\}^2 \tag{5}$$

In that equation, N_k is number of unique pairs of observation locations separated by distance h. Generally speaking, the value of a semivariogram increases with increasing distance because the spatial correlation of a pair of observations decreases with the distance. Therefore, the semivariogram value decreases with increasing spatial correlation.

3 AN APPLICATION OF LAND SUBSIDENCE MAPPING USING OBSERVATIONS

The spatial variability of settlements in a land subsidence area has been investigated using the semivariogram defined by Eq. (5) to investigate the applicability to land subsidence mapping of the spatial interpolation method based on Kriging. The objective is the northern Kanto Plain in Japan. About 1,300 settlement observation locations are in this region. Annual settlement at those locations has been measured through a bench mark survey for 25 years from 1981. These data were partitioned quinquennially and the accumulated settlement data for five years were used for analysis. These data are used for investigating the settlements' spatial variability.



(a) 1981–1985

(b) 1986–1990

(c) 1991–1995

(d) 1996–2000

Figure 2 Relationships between semivariograms and distance

Figure 3 shows semivariogram graphs for each quinquennial period. For a short distance, the semivariograms of settlements initially increase. Nevertheless, after the maximum value at about 35 km the semivariogram decreases with increasing distance. The reason is that a pair of observations across a severe settlement zone, a pair of observations over different land subsidence areas, and a pair of observations near the border of the region have similar settlement values. Such combinations appear more with greater distance. Therefore, the semivariogram is only used up to the maximum value for investigating the spatial variability of settlements in a land subsidence area.

Solid lines fitted by a semivariogram model known as a spherical model are shown in Fig. 2. The function of the semivariogram model is defined as

$$\gamma(h) = \begin{cases} 0 & h = 0 \\ \theta_0 + (\theta_1 - \theta_0) \cdot \left\{ \dfrac{3}{2}\dfrac{h}{\theta_2} - \dfrac{1}{2}\left(\dfrac{h}{\theta_2}\right)^3 \right\} & 0 < h \leq \theta_2 \\ \theta_1 & h > \theta_2 \end{cases} \tag{6}$$

where θ_0, θ_1 and θ_2 are parameters called the nugget, range and sill, which respectively characterize the semivariogram. The parameters for the semivariogram model are determined using least-squares approximation. Estimated values of the parameters are also indicated in Fig. 2. The fitted line is in good agreement with empirical semivariograms.

Estimations and observations were compared to confirm the applicability of the spatial interpolation procedure. Verification of the method was carried out by removing one location from the set of observations and then estimating the removed observation. Estimations and estimation variances were calculated for all locations using the proposed procedure. The errors between estimations and observations are plotted with the ESDs in Fig. 3.

Solid lines in Fig. 3 represent the 1σ, 2σ, and 3σ estimation error lines. About 10 locations are over the 3σ estimation error line in the figure. Figure 7 shows three locations of these points. Those locations are scattered over the region. For that reason, the locations have no spatial correlation with each other. The observations include the component of local settlements caused by construction, except for the component of wide land subsidence. Percentages of the prediction errors under the σ-line, 2σ-line, and 3σ-line are about 70%, 90%, and 99%, respectively. The percentages correspond approximately to values from probability theory. Thus, the proposed procedure is applicable to spatial interpolation of settlements in a wide land subsidence area.

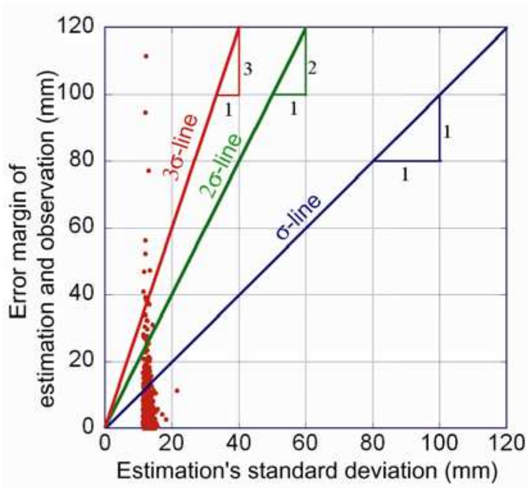


Figure 3 Comparisons with ESDs and estimation errors

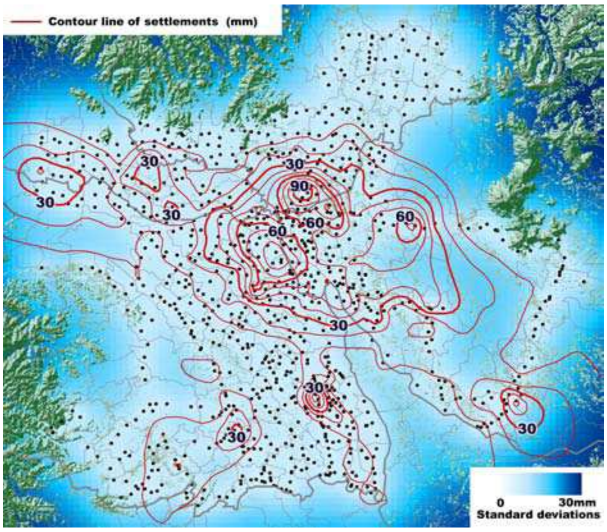


Figure 4 Land subsidence map (1996–2000)

The distribution of settlements for five years from 1996 to 2000 has been estimated using the proposed procedure of spatial interpolation based on ordinary Kriging. Figure 4 shows the distributions of estimations and ESDs of settlements. The land subsidence map simultaneously represents both distributions of estimations as contour lines and ESDs as raster data. Representing both estimations and ESDs on a map allows users to consider ESDs. Thereby, they can visualize the precision of the interpolated settlement and reduce the possibility of mistaken judgment of countermeasures against land subsidence. The map also facilitates improvement of the precision of the interpolated settlement data by location of new observation points for which ESD is large.

4 OBSERVATIONAL PREDICTION METHOD OF LAND SUBSIDENCE AND ITS PREDICTION ERRORS

It is necessary to understand the future situation of land subsidence in a region for sustainable development together with disaster mitigation and environmental preservation. A map representing a likely future situation should be reliable. Therefore, we infer that it is useful for sustainable development to show map accuracy. The expected value of future settlement at observation locations can be calculated using a proposed method (Murakami et al., 2002).

$$S(t; S_{p0}, C_R) = S_{p0}\{1 - \exp(-C_R \cdot t)\} \quad (7)$$

where S_{p0} is the residual settlement expected from the present until the termination of subsidence under the assumption that groundwater variation is maintained as observed at the present, and that C_R is the parameter corresponding to the settlement strain rate.

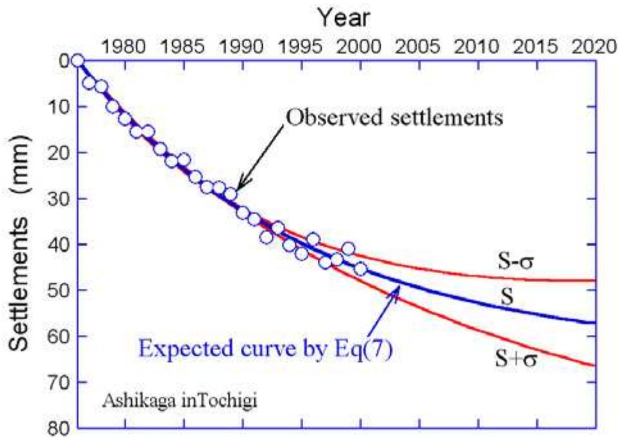


Figure 5 Application of the prediction model

The propagation rule of errors was applied in this study for evaluating prediction errors.

$$\hat{\sigma}_\varepsilon^2 = \hat{\sigma}_m^2 \left\{ \boldsymbol{a}^T \left(\boldsymbol{A}^T \boldsymbol{A} \right)^{-1} \boldsymbol{a} \right\} \quad (8)$$

$$a_j = \partial S(t_p)/\partial x_j \;\mid\; A_{ij} = \partial S(t_i)/\partial x_j \;\mid\; \boldsymbol{x} = \left(S_{p0} \quad C_R \right)^T \quad (9)$$

Therein, $\hat{\sigma}_m^2$ is the value of decentralization obtained after application of least squares method; t_p is the elapsed time at the predicted time, t_i is the elapsed time of i-th observation. Therefore, not only are future settlements at the observation locations predictable: the prediction errors can be evaluated. Figure 5 shows an example of application to an observation location. That figure shows that prediction error increases with increasing elapsed time. Reliability of predicted settlement can be evaluated because the prediction errors can be estimated.

5 RELIABLE LAND SUBSIDENCE FORECAST MAP USING THE PREDICTED RESULTS

A future prediction map of land subsidence was represented using spatial interpolation based on ordinary Kriging using the predicted results of settlements in the objective region. The semivariogram parameters were determined using the predicted settlements, which are the expected values. On the other hand, spatial correlations of the prediction errors were not admitted from results of investigating the relationships between the semivariogram and distance. For that reason, the applicability of the prediction model to the region dose not have locality. Figure 6 shows a future land subsidence map. The accuracy of the settlement distributions, which have both spatial interpolated errors and future prediction errors, is indicated on the map. Using the map aids planning of the maintenance of infrastructure facilities in the land subsidence area. It is possible to find improvement of the map if sufficient precision is not obtained. Improvement of map precision is also carried out efficiently by installing new observations in locations where the ESD is largest. Moreover, in cases where the future predicted error is much larger than the spatial interpolated errors, it is possible to point out improvement of the prediction model.

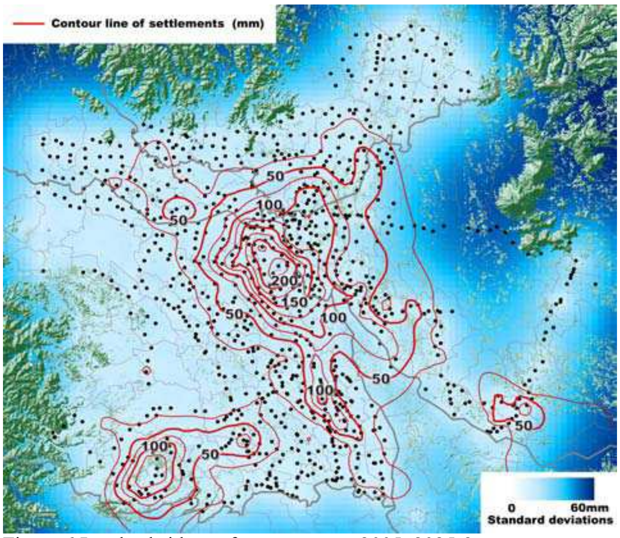


Figure 6 Land subsidence forecast map ¢ 2005–2025 £

6 CONCLUSIONS

This paper describes a spatial interpolation procedure of settlement to represent the reliability of land subsidence mapping. Applicability of a spatial interpolation method based on the ordinary Kriging method to a land subsidence area in the northern Kanto plain was investigated herein.

The following are the main conclusions obtained from the present study:

1) For a short distance, the semivariogram of settlements increases. However, after the maximum value at about 35 km, the semivariogram decreases with increasing distance. This trend exists because, in a pair of observations across a severe settlement zone, over different land subsidence areas and near a regional border, each has similar settlement values. Such combinations appear at more than about 35 km with greater distance. Therefore, the semivariogram is only used up to the maximum value for investigating spatial variability of settlements in a land subsidence area.
2) A spatial interpolation procedure based on ordinary Kriging has been proposed. The procedure applicability is confirmed by comparing estimations with observations.
3) A land subsidence map was produced by including both estimations and standard estimation errors. Consideration of ESDs allows us to estimate the precision of the interpolated settlement.
4) Applying spatial interpolation method with expected values and predicted errors objectively indicated that accuracy of the land subsidence map made using predicted values is smaller than that of a map using observations.
5) The proposed procedure that can express the estimated accuracy of map is effective because the accuracy affects reliability of the represented map.

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