APPLICATION OF ENSEMBLE KALMAN FILTER ONTO EARTH-FILL DAM THROUGH SURFACE WAVE

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1. INTRODUCTION

Almost maintenance and reinforcement of earth structures like earth-fill dam require in-situ investigation to confirm the property of it, especially strength. Exploration geophysics becomes widely used in investigation because of its convenience. For almost current analysis method, the solution of inverse problem is just a certain value. The reliability of it cannot be evaluated. Some data assimilation based on Monte Carlo method can combine a group of realization (numerical simulation) with realistic observation to estimate the distribution of model state. EnKF (Evensen,1994) and Particle filter (PF) are the typical method of them. In EnKF, the distributions are assumed to be Gaussian and only first and second moments are utilized. Thus, the EnKF can be applied with a small number of realizations. There are some studies used this method to estimate the permeability of ground (Yamamoto, 2014), few studies were made for parameters related to strength of earth structures. In this study, a method which can be used to estimate parameters about strength (young' modulus) of a earth-fill dam model through numerical simulation of elastic wave is presented.

2. ENSEMBLE KALMAN FILTER

The EnKF can adjusts parameters of model to an optimum state through combining the observation of realistic system and the "observation" of numerical model. In consider of depth of earth-fill dam which is not too large commonly and the convenience of in-situ investigation, the first arrival of surface wave which just propagates in near-surface ground as the observation data. The velocity of elastic wave like surface wave relates to elastic parameters like Young' modulus and Poisson's ratio of medium. The solution of inverse problem may be unstable while all related parameters are set to unknown. Thus, only Young' modulus which influence the velocity greatly is treated as parameter to be estimated and the others are determined by experience.

In EnKF the model of observation is given by

$$y_t = h_t(x_t, w_t) \tag{1}$$

where y_t is m-dimensional observation vector at time t, x_t is the n-dimensional state vector which should be estimated. The distribution of noise w_t with a mean of zero is Gaussian usually. EnKF cannot be used to deal with nonlinear observation directly. So, the h_t should be linear in most cases through follow equation.

$$y_t = H_t x_t + w_t \tag{2}$$

where H_t observation matrix. x_t in this equation includes both the parameters and observations. This is also named state variable vector. In this study, it is given by

$$x_t = \begin{bmatrix} \boldsymbol{E}_t \\ \boldsymbol{a}_t \end{bmatrix} \tag{3}$$

where vector $\boldsymbol{E}_t$ and $\boldsymbol{a}_t$ consist of all Young' moduli and observation of first arrival, respectively. For ensemble members, the first arrival $\boldsymbol{a}_t$ is characterized by numerical simulation (FEM), that is

$$\boldsymbol{a}_t = f(\boldsymbol{E}_t) \tag{4}$$

The adjustment of parameters in EnKF is called updated step and is given by

$$\hat{x}_{t|t}^{(i)} = \tilde{x}_{t|t-1}^{(i)} + \hat{K}_t \left(y_t^{(i)} - H_t \tilde{x}_{t|t-1}^{(i)} \right) \quad i = 1,2,\cdots,N \tag{5}$$

where $\{\tilde{x}_{t|t-1}^{(i)}\}_{i=1}^{N}$ are samples of state vector (i.e., ensemble).

The goal of this step is updating every prior model respectively to create the posterior ensemble. This requires computation of $n \times n$ covariance matrix, where n is dimension of state vector in the Kalman filter. It is difficult when n goes to a large number. EnKF can be interpreted as an approximate version through the covariance matrix based on the ensemble.

The other step of EnKF is forecast which describes the time evolution of system. Given model in this study, the parameters do not change with time, because the Young' modulus of dam can be treated as a time-invariant value. The position of wave source changes with time and the new observation of first arrivals is given by numerical simulation. The forecast step is represented by

$$\boldsymbol{E}_{t|t-1}^{(i)} = \boldsymbol{E}_{t-1|t-1}^{(i)} \tag{6}$$

$$\boldsymbol{a}_{t|t-1}^{(i)} = \hat{\boldsymbol{a}}_{t-1|t-1}^{(i)} \tag{7}$$

where $\hat{a}$ is the vector of first arrival given by simulation.

3. NUMERICAL SIMULATION

Finite element method (FEM) is used to simulate the transient propagation of surface waves with 2-dimensional model. This simulation is based on a finite element package so-called Quake3D (The Japanese Geotechnical Society, 2003). The accuracy of FEM analysis relates to the mesh dimension and boundary conditions (Zerwer, 2002). The surface waves which propagate in a vertically heterogeneous medium consist of waves with different frequency and phase velocity. For FEM high-frequency waves may be removed by Low-pass filtering of the mesh. An appropriate mesh size can be suggested by shortest wavelength to keep whole frequency, but the computational complexity is inacceptable for a large model. Considering the balance of accuracy and efficiency, an acceptable mesh size is suggested by trial and error at the present stage and some high-frequency waves are filtered out. The model and an example of simulated wave shot gathers are shown in Fig 1.

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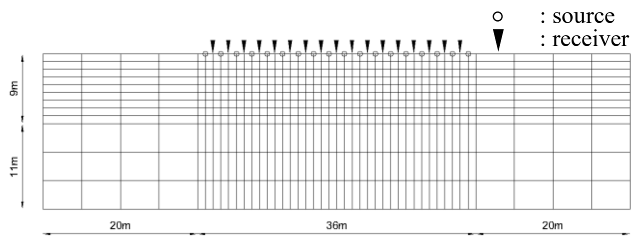


Fig. 1 FEM model

4. INITIAL DISTRIBUTION

For EnKF, the ensemble of initial states $\{x_{0|0}^{(i)}\}_{i=1}^{N}$ should be determined appropriately. Quite often, the initial states for all grid points are interpolated by observations at time point 0. in this section, the initial states are generated from the data of N-value of Swedish weight sounding test(SWS), which was taken on an earth-fill dam, by sequential Gaussian simulation(sGs). The realizations of sGs are treated as the samples of EnKF. The statistic model for sGs consist of a mean function and a covariance function suggested by MAIC (Nishimura, 2011) and semi-variogram (Journel and Huijbregts, 1978), respectively. The mean function tells the trend of spatial distribution and the covariance function tells the correlation. One of the initial ensemble members is shown in Fig.1.

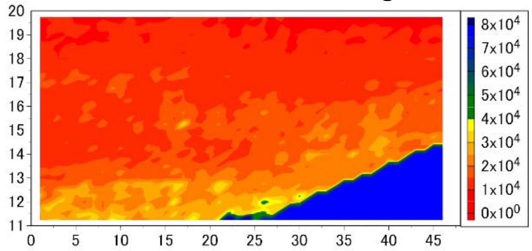


Fig.1 An initial distribution

5. NUMERICAL EXPERIMENTS

To verify the influence of noise of the true observations over the estimation, a noise $R_t \sim N(0, s^2)$ is applied onto the true observations. The standard deviation $\boldsymbol{s}$ is chosen with respect to the value of first arrival (i.e., the vector $\boldsymbol{a}$)

$$\boldsymbol{s} = \alpha \boldsymbol{a}\ (\alpha = 0, 10\%, 20\%, 30\%) \tag{8}$$

Residual sum of squares (RSS) is utilized to evaluate the error between true observations and estimate observations, that is the difference of first arrivals. Fig.3 shows the convergence of RSS with state updating in the numerical experiments with the different degrees of noise.

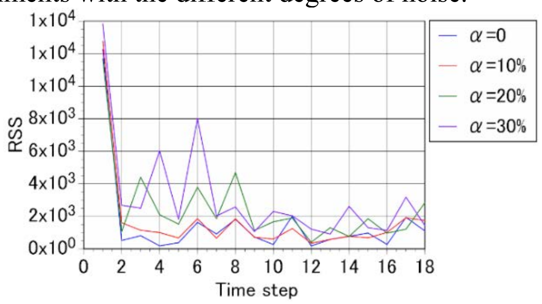


Fig.3 RSS of observations

6. APPLICATION ON EARTH-FILL DAM

This section addresses the application of proposed method with in-situ investigation data taken on identical earth-fill dam with the SWS test in Okayama. The data acquisition of waves is same as Multi-channel Analysis of Surface Waves (MASW) and the first arrivals are determined manually, and the space of geophone and wave source are both 2m. The area that under the maximal depth of SWS test is treated as bedrock and its parameter is subject to the mean of the others.

One of the estimations through EnKF (i.e., the mean of ensemble) is shown in Fig.4. The spatial distributions of coefficient of variation before and after the updating are shown in Fig.5. This method is shown to be effective in reducing the variance of distribution.

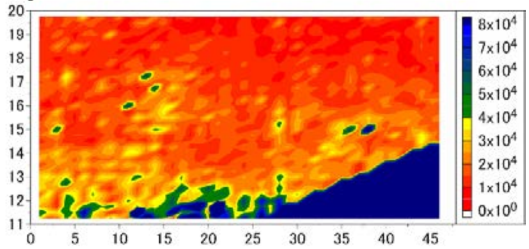
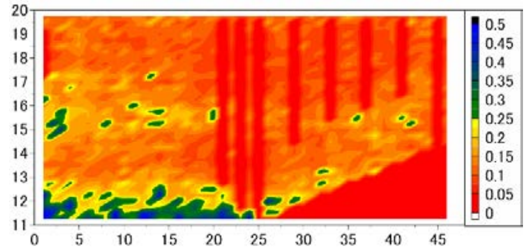
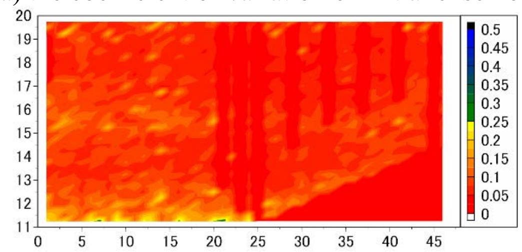


Fig.4 An estimate spatial distribution of Young's modulus (mean of ensemble)



(a) the coefficient of variation of initial ensemble



(b) the coefficient of variation of estimate ensemble

Fig.5 The spatial distribution of coefficient of variation

7. CONCLUSIONS

An analysis method of inverse problem which aims to obtain the probability distributions of the parameters of earth-fill dam model is presented. The effectiveness of EnKF within this model is verified by numerical experiments. The application of this method with in-situ investigation data is presented.

REFERENCES

1) G. Evensen: Journal of Geophysical Research, Vol.99, No.C5, pp.143-162, 1994.
2) Yamamoto, S.,etc., ISRM International Symposium - 8th Asian Rock Mechanics Symposium, 2014.
3) The Japanese Geotechnical Society, Using Elastoplastic FEM, Maruzen,2003
4) A. Zerwer, etc., Journal of Geotechnical and Geoenvironmental Engineering, March 2002
5) Shin-ichi NISHIMURA, etc., Journal of Japan Society of Civil Engineers, Ser. C (Geosphere Engineering) 2011 Volume 67 Issue 2 Pages 252-263
6) Journel, A.G. and Huijbregts, C.J. (1978), Mining Geostatistics, Academic Press, 117-195.