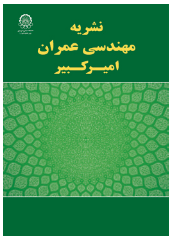

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Presentation of an Extended Surface Finite Element Method to Model the Deformation of Structures Continually; Case Study: Karkhe Earth dam

M. Jafari

Department of Geodesy and Surveying Engineering, Tafresh University, Tafresh, Iran

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ABSTRACT: A deformation modeling method for structures based on a new adaptive methodology by implementation of inter-element continuity constraints is presented in this paper. Estimating the proper relative weight of each sensor observation. Developing an extended surface finite element method (ESFEM), the differential equations of deformation with inter-element continuity constraints are solved. Furthermore, this method provides the possibility of fusion of non-synchronized repetitious geotechnical and geodetic observations as the boundary data to model the deformation with respect to an inertial reference frame. Also the proper weight of multi-sensor's observations would be estimated.

1- Introduction

The importance of the deformation analysis of the structures based on the monitoring measurements due to the numerous contributions is obvious [1-14]. In the absence of potential effective loads or their inaccurate measurements, kinematic analysis of deformation monitoring data is preferable. In this work, the kinematic post-construction behavior of structures is investigated and consequently a method based on a new development in finite element method to model the surface deformations of the structures is presented. In this work, the studied surface deformation of structures is continuously and the performed equation system of each element is enriched by adding inter-element deformation continuity constraints. In other words, an extended surface finite element method (ESFEM) to deformation model is presented and consequently the equation systems of whole elements are solved altogether. Besides, the most reliable control systems are those built on multi-sensors data fusion [15]. In order to develop a reliable deformation modelling methodology which can be embedded in the monitoring system of structures, a deformation study method based on the fusion of two main sources of the monitoring measurements (via the geodetic and geotechnical instruments) is proposed.

2- Methodology

Considering the scope of this paper which is the deformation study of structures based on the fusion of geodetic and geotechnical observations in terms of finite elements, that is done with motivations including: 1) To use surface elements instead of volume elements with three nodes on the surface of the structure or on the cross-section plane, 2) To establish an inertial reference frame based on the outside stable points using the main factors of the structure such as the bed-rock and the specific directions then transfer the position of two data types to the reference frame, 3) To develop surface elements using e.g. Delaunay triangulation method. The time series of the geodetic and geotechnical displacements based on the logged repeated observations is developed with respect to the selected reference epoch which can be the first epoch of monitoring observations and is submitted into the data fusion machinery.

For mathematical setup of presented method to deformation study of structures, we start with 3-D displacement vector after linearization by Taylor series expansion in each station are considered, that in shorthand matrix notations is as follows:

$$\mathbf{d} := \mathbf{A}\mathbf{x} \tag{1}$$

By developing the surface finite elements, an equation system can be derived associated with each surface element. In the case of fraction within the body of the structure, the deformation is non-continuous. Otherwise, it is necessary to develop a continuous deformation model on the surface of the structure. Therefore, it is proposed that the differential equations of whole elements have to be come in one equation system altogether, as well as the inter-element continuity

Corresponding author, E-mail:

constraints which ensure the continuity of the surface deformation model. Having enriched the equation system of elements by continuity constraints an extended surface finite element method (ESFEM). Based on the inter-element continuity constraints, following equation in shorthand matrix notations by definition of the constraint matrix , can be derived.

$$\mathbf{D}\mathbf{x}_{all} = \mathbf{0} \tag{2}$$

Which results in an equation system based on the multi-sensor observations by considering a pseudo-observation category l_c with the known weight matrix as follows:

$$\begin{cases} \mathbf{d}_i + \mathbf{v}_i = \mathbf{A}_i\mathbf{x}_{all}, & \mathbf{C}_i = \sigma_i^2\mathbf{P}_i^{-1} \quad i = 1,2,3,4 \\ \mathbf{l}_c + \mathbf{v}_c = \mathbf{D}\mathbf{x}_{all}, & \mathbf{C}_{\mathrm{l}_c} = \sigma_{\mathrm{l}_c}^2\mathbf{P}_{\mathrm{l}_c}^{-1}, \quad \mathbf{l}_c = \mathbf{0} \end{cases} \tag{3}$$

The unknown variance factors (σ_i^2 and $\sigma_{\mathrm{l}_c}^2$) are estimable with other unknown parameters ($\mathrm{X}_{\mathrm{all}}$) in an iterative reweighting least square procedure to the improvement of weight matrices scale as follows:

$$\hat{\mathbf{x}}_{all} = (\mathbf{A}_i^T\mathbf{P}_i\mathbf{A}_i + \mathbf{D}^T\mathbf{P}_{\mathrm{l}_c}\mathbf{D})^{-1}(\mathbf{A}_i^T\mathbf{P}_i\mathbf{d}_i + \mathbf{D}^T\mathbf{P}_{\mathrm{l}_c}\mathbf{l}_c) \tag{4}$$

The approximate values are introduced for the variance components such that their values are close to one and one iterates until at the convergence [15].

3- Results and Discussion

Practical applicability of the method was assessed by determination of the surface settlement variations of the Karkhe earth-dam continuously based on the fusion of geodetic leveling and geotechnical settlement observations. Figure 1 shows the modeled settlement of the Karkhe earth-dam after 76 months, due to the reference epoch (22 Feb. 2000) with respect to the reference frame. Regarding this figure one can see that during nearly 6 years, the settlement is reached to more than one meter over the crest along the main axis of the dam and close to the abutments reduced to a few centimeters.

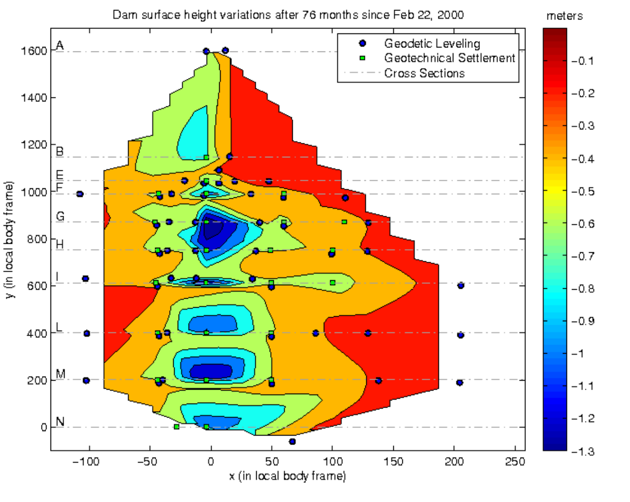

Figure 1. Settlements of the dam surface during 76 months

The difference between the observed and modelled settlement on the check points has been calculated and related statistical results are presented in Table 1. Also the results of other experimented methods by author in other researches are presented for comparison.

Table 1. Statistical results of the settlement model validation

Method	The settlement differences		
	Mean (mm)	STD (mm)	RMS (mm)
Only Geotechnical data	−1.4	1.6	3.8
Fusion without continuity constrains	−0.4	1.3	1.4
Fusion with continuity constrains	−0. 2	0.9	1.0

Regarding the estimated RMS of difference between the test data and the prediction which was about one millimeter and the accuracy and precision improvement of the modelling respectively by the amount of 89% and 73%, the presented method was more successful related to the deformation modeling based on single-sensor data also the multi-sensor data fusion without inter-element continuity constraints.

4- Conclusions

The results imply the success of inter-element continuity conditions to present a continuous deformation model based on the developed finite element method to study of structure. Generally, indicate that the derived settlements are changing in time since reference epoch to reach to its final stable state.

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