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"Research Note"

MODELING OF VERTICAL MOVEMENTS OF BUILDINGS WITH MAT FOUNDATION*

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Abstract– A developed model was applied to displacement vectors acquired from a project that monitored the vertical movements of a building in the main campus of Nigde University. The estimated subsidence and its corresponding standard deviation errors by the model are -4.89 mm ± 0.53 mm for block 1, -1.23 mm ± 0.35 mm for block 2, and -3.65 mm ± 0.54 mm for block 3, respectively. The tilt angle is estimated and its corresponding standard errors are 16".61 ± 2".39, -18".93 ± 1".95, and -13".87 ± 4".64 arc second for Block 1, Block 2, and Block 3 respectively over a period of one year. Results showed that the model produced in this paper can be used to estimate the vertical movements of a building with a Mat foundation.

Keywords– Vertical deformation monitoring, building settlement, modeling, least square adjustment

1. INTRODUCTION

Deformation monitoring by geodetic surveying methods is a powerful technique for both natural and man-made features. Particularly, monitoring deformations of engineering structures such as dams, bridges, plants, and buildings where large human activities take place can be a critical issue for the prediction of possible hazardous events.

Monitoring deformation by geodetic methods consists of four stages: specification, design, implementation, and analysis [1]. In the specification stage a number of issues need to be posed concerning the magnitude and confidence level of the movement, selection of constant or variable accuracy for points, and requirements for direction of the movement.

In the second stage, four sub stages of the design are distinguished [2]**.** Under the specifications made, an optimum configuration of stations and a measurement plan are sought [3], [4]. Measurement techniques are mainly divided into two groups; geodetic and non-geodetic techniques [5]**.** Geodetic measurements can be analyzed by various methods. Two-epoch and multi-epoch analysis need to be distinguished. One method of multi-epoch analysis is performed based on two-epoch analysis. It is carried out between the first epoch and the current one [6]. Several researchers have developed analysis methods including Bonn, Delft, Fredericton, Haifa-Tel Aviv, Hanover, Karlsruhe, Munich I-II, Stuttgart, and Warsaw I approaches. A summary of these methods was given by [7], [8]. Absolute or relative networks can be chosen according to the feature of the movement under question. In monitoring natural features such as faults, a relative movement is required; in man-made structures such as dams, bridges, and buildings, an absolute network is preferable to a relative one. The Global Congruency Test [3] is applied to both networks to verify if the absolute network has maintained its shape and to search for a reference network consisting of points that have a minimum configuration defect in relative networks [1]. After determining the reference points, a

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combined adjustment is required to compare the estimated parameters. This is done by applying one set of parameters for the reference points and two sets of parameters for the rest of the points in the network. From the result of the combined adjustment, a displacement vector whose significance is to be tested is obtained. Significant movements are then formulated to fit a deformation model. A number of models have been imposed on monitored structures such as dams, bridges etc. Skal'nyi [9] studied to monitor the foundation of the Arkierejskie Palaty building of the Suzdal Kremlin. However, few studies have been done on modeling vertical movements of buildings with Mat foundations.

The aim of this paper is to develop a model for the estimation of vertical movements of a building with a Mat foundation. A displacement vector from the project has been used in modeling and the results presented. This paper develops a model to estimate overall mode of deformation, in addition to individual point deformation given by the displacement vector from the project below.

2. PROJECT: MONITORING VERTICAL MOVEMENTS OF BUILDINGS ON THE CAMPUS OF NIGDE UNIVERSITY

The main aim of this project was to determine the vertical movements of the buildings on the campus. A reference network with 5 stations was used to serve absolute reference points, nine points were set to the Presidential Building, and 17 points set to the Faculty of Arts and Science Building as object points whose movements were to be monitored (Fig. 1).

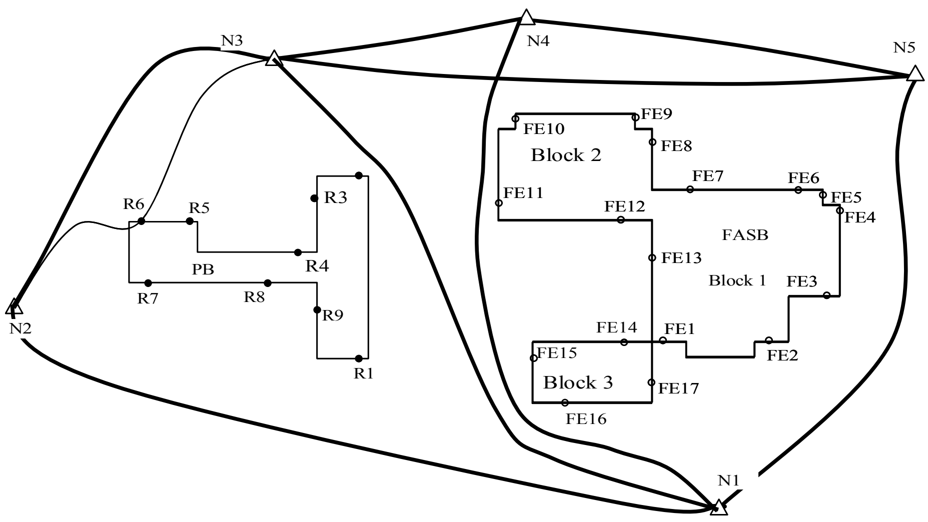

Fig. 1. Location of reference (N_i) and object points (R_i, and FE_i) installed in the campus

Precise leveling was applied to perform measurements using a Pentax AFL-320 level with an SM5 parallel glass plate and 2m invar staff. Two measurement campaigns on 26 July, 2003 and on 24 July, 2004 were performed.

3. MODELING VERTICAL MOVEMENTS OF A BUILDING WITH MAT FOUNDATION

A model to estimate the overall mode of deformation of the body under question has been developed in this section. A section of a building at a given time t_1 can be assumed as a 2-D plane surface considering its basement. A 2-D plane surface was assumed since the building was constructed with a Mat foundation. The section may be tilted and subsidized by some magnitude due to settlement within the period of two epochs. To obtain the tilt angle α and the magnitude of subsidence ‘a’, a model can be set up as follows (Fig. 2)

$$d_i + v_{di} = a + S_{i'j'}\sin(\alpha), \quad d_i = h_{i'} - h_i, \quad C_d = \sigma h_i^2 + \sigma h_{i'}^2 \tag{1}$$

where h_i and $h_{i'}$ are the heights of points *i* and *i'*. $S_{i'j'}$ is the distance between *i* and *j*. σ_{h_i} and $\sigma_{h_{i'}}$ are standard deviations of h_i and $h_{i'}$. The relationship between the angle α and the displacement difference can be formulated from Figs. 1a, 1b, 1c, and Eq. (1) can be linearized by Taylor's expansion. $S_{i'j'}$ is assumed to be a constant, therefore, Eq. (1) can be rewritten as

$$v_d = a_0 + S_{i'j'}\sin(\alpha_0) + da + S_{i'j'}\cos(\alpha_0)d\alpha - d_i \tag{2}$$

Where

$$\alpha = \alpha_0 + d\alpha, \quad a = a_0 + da, \quad \mathbf{dx} = \begin{bmatrix} da \\ d\alpha \end{bmatrix}$$

$$-b = a_0 + S_{i'j'}\sin(\alpha_0) - d_i, \quad \mathbf{A} = \begin{bmatrix} 1 & S_{i'j'}\cos(\alpha_0) \\ \vdots & \vdots \end{bmatrix}, \quad \mathbf{v}_d = \mathbf{Adx} - \mathbf{b}, \quad \mathbf{P} = \mathbf{C}_d^{-1} \tag{3}$$

The linearized form is now obtained. The solution to Eq. (3) is a well-known least square adjustment problem [10].

$$\mathbf{dx} = \left(\mathbf{A}^T\mathbf{PA}\right)^{-1}\mathbf{A}^T\mathbf{Pb}, \quad \mathbf{C}_{dx} = (\mathbf{A}^T\mathbf{PA})^{-1} \tag{4}$$

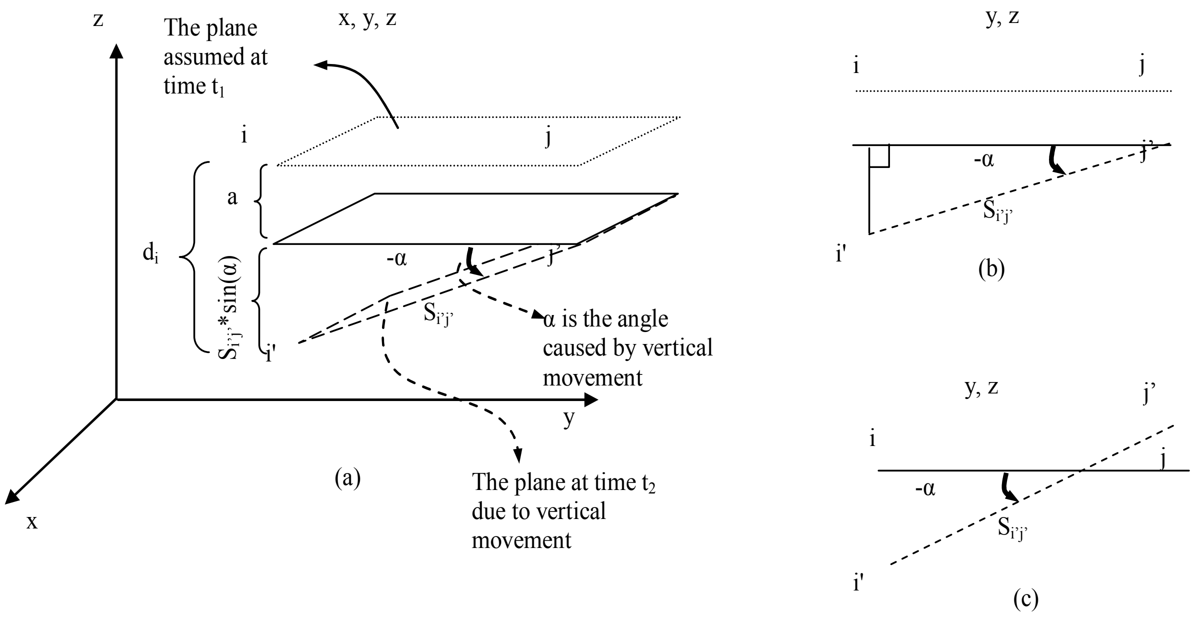

Fig. 2. A model of vertical movement of a building with mat foundation

This model was set up for the data acquired from the project. The Faculty of Arts and Science Building consists of three blocks constructed at different times. FE1, FE2, FE3, FE4, FE5, FE6, FE7, and FE13 points are from Block1, FE8, FE9, FE10, FE11, and FE12 points are from Block 2, and finally FE14, FE15, FE16, and FE17 points are from Block 3 (Fig. 1).

Displacement vectors for the three blocks, and distances between points i and j, were taken from the project as inputs to the given model (Table 1).

Table 1. Displacement vector dh_i and its standard deviation error from the combined adjustment and distances

Blocks number	*i*	$dh_i=h_{i'}-h_i$ (mm)	S_{dhi} (mm)	*i to j*	$S_{ij}(m)$
1	FE1	-3.1	0.6	FE1-FE1	0.000
	FE3	-2.9	0.6	FE1-FE3	38.950
	FE4	2.4	0.5	FE1-FE4	55.192
	FE5	1.4	0.5	FE1-FE5	56.515
	FE6	-0.4	0.5	FE1-FE6	47.710
	FE7	-3.1	0.5	FE1-FE7	52.742
	FE13	-4.9	0.5	FE1-FE13	33.166
2	FE8	-1.3	0.5	FE8-FE8	0.000
	FE9	-2	0.4	FE8-FE9	10.839
	FE10	-5.2	0.5	FE8-FE10	44.582
	FE11	-6.5	0.5	FE8-FE11	59.571
	FE12	-5.8	0.5	FE8-FE12	43.806
3	FE14	-3.9	0.6	FE14-FE14	0.000
	FE15	-3.8	0.6	FE14-FE15	20.243
	FE16	-6.1	0.6	FE14-FE16	35.682
	FE17	-6.2	0.6	FE14-FE17	25.953

The outputs are the subsidence ‘a’ and tilt angle α

4. RESULTS & CONCLUSIONS

Displacement vector, its associated variance-covariance matrix from a combined-adjustment, and distances between the base point and another point in each block were used in the model to estimate overall mode of deformation (Table 1). Figure 3 illustrates the vertical movements estimated for the three blocks of the Faculty of Arts and Science Building in the campus, and the estimated magnitude of subsidence, tilt angles and their corresponding standard deviation errors are tabulated in Table 2.

Table 2. Estimated subsidence, tilt angle and corresponding standard deviation errors

Block number	Subsidance (mm)	Standard error(Subs) (mm)	Estimated angle (Second of arc)	Standard deviation error (Second of Arc)
1	-4.89	0.53	16.61	2.39
2	-1.23	0.35	-18.93	1.95
3	-3.65	0.54	-13.87	4.64

These estimated subsidence and tilt angles are based on the base point FE1, FE8, and FE14 for Block 1, Block 2, and Block 3 respectively. A positive tilt angle represents anticlockwise rotation from a horizontal level (from the assumed 2-D plane) and a negative one represents the clockwise rotation of the plane. The tilt angle 16.61 arc second for Block 1 is positive due to the base point. From Fig. 3, it seems that all the estimated tilt angles are consistent with one another.

A comparison of displacements between the model-based subsidence and tilt angles and those from the combined-adjustment were tabulated in Table 3. For Block 1, Block 2 and Block 3, the model can precisely represent the overall mode of deformation with standard deviation errors ±0.3 and ±0.6 mm respectively.

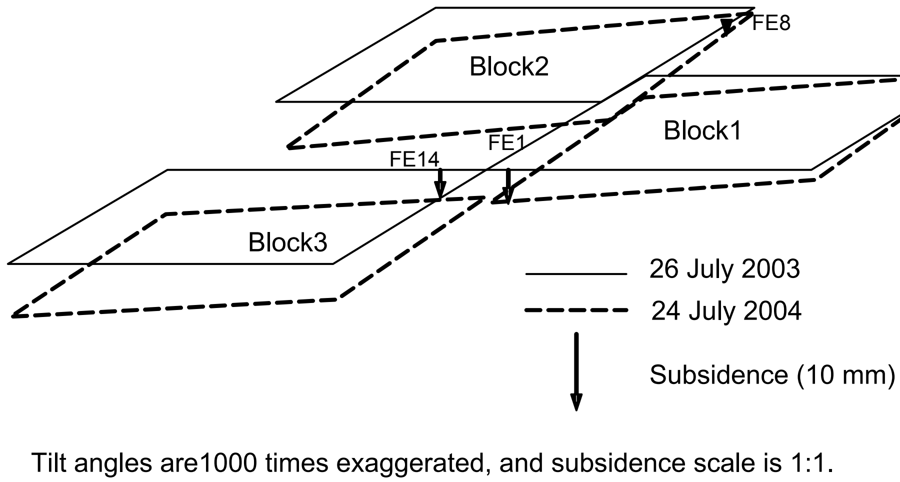

Fig. 3. Vertical movements of the faculty of arts and science building

Table 3. Model errors

Block Number	Point ID	di(m) from model (mm)	di(m) from displacement (mm)	Error (mm)	Standard deviation error of the model (mm)
1	FE1	-4.9	-3.1	1.8	2.2
	FE3	-1.7	-2.9	-1.2	
	FE4	-0.4	2.5	2.9	
	FE5	-0.3	1.4	1.7	
	FE6	-1.0	-0.4	0.6	
	FE7	-0.6	-3.1	-2.5	
	FE13	-2.2	-4.9	-2.7	
2	FE8	-1.2	-1.3	-0.1	0.3
	FE9	-2.2	-2.0	0.2	
	FE10	-5.3	-5.2	0.1	
	FE11	-6.7	-6.5	0.2	
	FE12	-5.2	-5.8	-0.5	
3	FE14	-3.6	-3.9	-0.3	0.6
	FE15	-5.0	-3.8	1.2	
	FE16	-6.0	-6.1	0.0	
	FE17	-5.4	-6.2	-0.8	

For Block 1, ±2.2 mm standard deviation error may suggest that Mat foundation of Block 1 was not moving rigidly. The Block 1 building is the oldest among others constructed in 1998. Since then it has been settling. Little or no movement was anticipated for Block 1. However, -4.89 mm subsidence indicates that the settlement is still in progress. The Block 2 construction is relatively new in comparison with Block 1 and old in comparison with Block 3. Therefore, it is expected that a larger magnitude of subsidence occurs to Block 3. It is demonstrated that the model produced in this paper can accurately reflect vertical movements of a building with Mat foundation only, and so this model may be used for buildings with MAT foundation.

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