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Research Article

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Height Determination of Monitoring Points using Subsidence Plane Equation and Prediction Model

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Abstract In observation of building subsidence, monitoring points, in some cases may be affected by construction activities of different contractors on the site even monitoring points that are ruined in the process of building are unavoidable. This paper aims to solve a problem of determination of subsidence of these monitoring points in this case to ensure the continuity of monitoring process. In high rise building, monitoring points are major distributed within the area of foundation under the first floor or follow a certain main axis. Settlement of monitoring points is determined based on two subsidence models. Interpolated subsidence is compared with the real settlement from adjusted results. Data of this study are from a real subsidence monitoring project. The results allow surveyors to calculate subsidence of destroyed monitoring points and test suitability of used settlement models. Deviation between heights of monitoring points from subsidence plane equation or subsidence prediction model (polynomial) is equivalent to measurement error. This method can thus be applied in the real monitoring projects which have high level of subsidence and account for small area. It is necessary to impress that interpolated subsidence should be used for one measurement cycle. Destroyed monitoring points need to be additional drilled as soon as the detection of destruction.

Keywords Subsidence monitoring, subsidence prediction, polynomial, subsidence plane

1. Introduction

Subsidence monitoring is one of the sectors that has the highest level of accuracy with a very tight procedure of measurement, calculation and adjustment such as distance from station to leveling rod ranges from 3 to 30m or deviation of distance from station to two leveling rods is smaller than 0.5 to 1.0m for class I and II respectively, especially, settlement monitoring of high rise building. The most popular method for this service is using invar leveling rod and high precise leveling equipment. This is a conventional measure and thus to have accurate and absolute measures, monitoring networks have to connect with a system of vertical control points (benchmarks) [1]. Nowadays, many integrated methods can be used for land settlement monitoring. A combination amongst different modern techniques helps to improve coverage, accuracy and reliability of the monitoring results [2]. A three dimensional numerical model of land in Shanghai was built in the center area helps local government in controlling land subsidence and differential movement of the land surface [3]. Modern technologies including robotic total station combines with GNSS receivers, GPS technology were used to observed building fluctuation of high rise-building [4]. Besides, Laser scanning technology was used to determine deformation of high - capacity tank [5]. A three dimensional model of historical Mevlana museum was build using terrestrial laser scanner and time of flight camera. Level of accuracy for outdoor and indoor measurements is 2.3cm and 2.4cm respectively [6]. Also, a new application of terrestrial laser scanning for deformation monitoring of steel structure was mentioned. FARO Focus^{3D} laser scanner was used to monitoring displacement of the steel structure. Thus, the displacement of structure is about 40mm at the top and precision can be reached to mm level when distance is less than 25m [7]. It can be seen that applications of modern technologies are widely popular. However, almost applications are applied for completed structure or building or in process of using. In these types of building, it is convenient to set monitoring points. For instant, monitoring points are on the roof top of high-rise building or in a certain side of it. Another important thing is that monitoring points are not affected by construction activities. This is impossible to apply in the under construction sites. To solve this problem, some other modern methods were supposed. Wilczy & Ćmielewski [8] mentioned a method used the optoelectronic devices and Micro Electro-Mechanical Systems. These above methods and technologies are very modern and thus are exorbitant, difficult to apply in the actual projects in Vietnam. The fact indicated that the most well-known measure to detect subsidence of high building is geometrical technique using invar rod and high precise leveling devices. This method accounts for almost 100% in the real projects. In this method, monitoring points are drilled in the first underground floor. Monitoring program is carried out following a tight procedure and an accepted schedule by employer. Thus, monitoring task has to follow designated cycles based on loading level of building. Monitoring task is parallel to other tasks in the construction site. There are many constructors and hundreds even thousands of workers in an under construction site leading to destruction of several monitoring points in the process of building other items. In term of one or two monitoring points are ruined, a problem is that how to determine their subsidence to ensure the continuity of monitoring process. This paper aims to calculate subsidence of ruined monitoring points via subsidence prediction models.

2. Materials and Methods

Different settlement prediction models were introduced. A new mathematical model was used to predict surface subsidence due to activities of mining exploitation [9] and a fusion model was used for subsidence prediction in Taiwan [10]. Most of them are used for subsidence prediction of land surface. In this study, building a subsidence plane is considered. Subsidences of ruined monitoring points are determined using this surface and a settlement prediction model will be established.

2.1. Settlement plane equation

In subsidence monitoring of high rise building, monitoring points are distributed in area of foundation. After the first cycle, a plane of subsidence can be written as follow.

$$S_i = a.x_i + b.y_i + c \qquad (1)$$

where: S_i, x_i, y_i are subsidence and coordinates or i monitoring point.

The number of equations depends on the number of monitoring points participating in establishing model of subsidence plane. Thus, the least square method will be used in case the number of monitoring points are more than three coefficients. Solution matrix is determined by following equation.

$$Z = \begin{bmatrix} a \\ b \\ c \end{bmatrix} = (R^T R)^{-1}.R^T S \qquad (2)$$

$$\text{where} \quad R = \begin{bmatrix} x_i & y_i & 1 \\ \ldots & \ldots & \ldots \\ x_n & y_n & 1 \end{bmatrix} \text{ and } S = \begin{bmatrix} s_1 \\ .. \\ s_n \end{bmatrix} \qquad (3)$$

Accuracy of model can be assessed using following equation

$$M_{MH} = \sqrt{\frac{v_i.v_i}{n-3}} \qquad (4)$$

Fisher testing should be used to assess reliability of model [11].

$$F = \frac{M_{MH}^2}{M_0^2} \qquad (5)$$

Quantity m_0 can be accepted as average error of subsidence of monitoring points which involve in building subsidence plane model.

2.2. Polynomial function for subsidence prediction

Polynomial is a general function and can be applied for any type of works [12]. Thus, subsidence (q) of a monitoring point at *t* time can be written following polynomial function as follow.

$$q_i = a_0 + a_1.t + a_2.t^2 + ... + a_k.t^k \quad (6)$$

Degree of polynomial will be determined to ensure two conditions including the smallest degree and error of settlement prediction model is equivalent to that of subsidence measurement. Like settlement plane model, collected subsidence prediction model need to be checked the suitability through Fisher testing.

3. Experiment data

This building is a small block in a complex of Luong Tai General Hospital, Bac Ninh Province and has five floors. Distributions of monitoring points are in *figure 1*

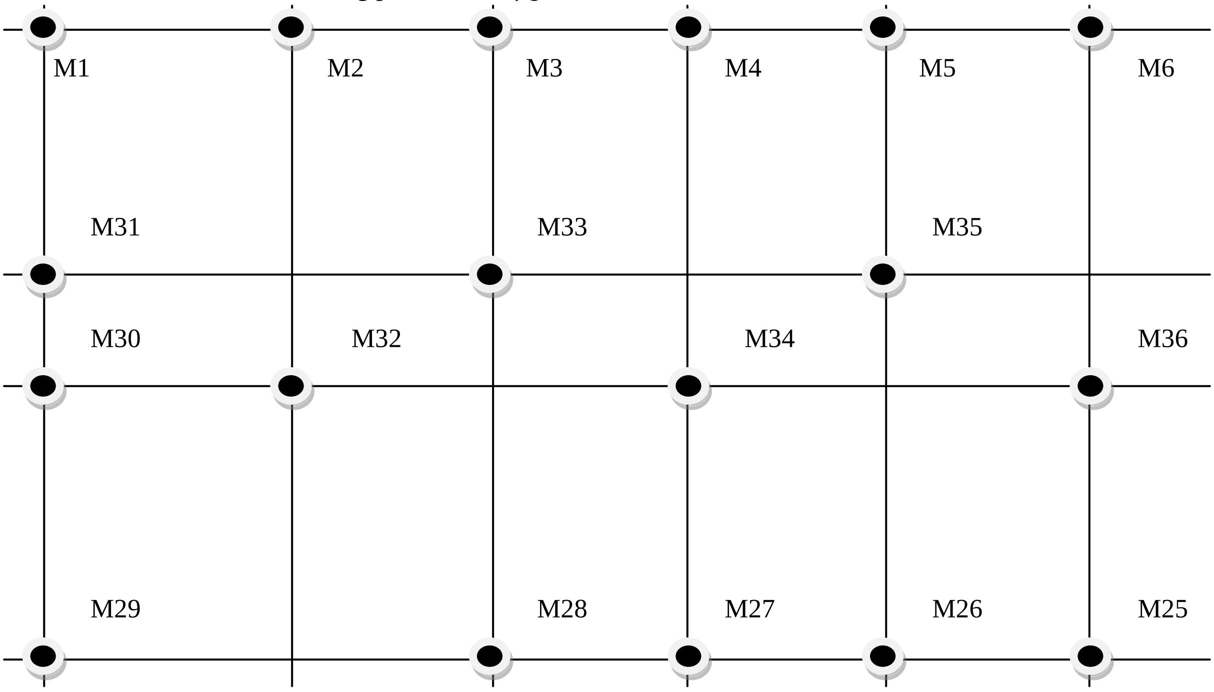

Figure 1: Monitoring points on the ground floor

The number of monitoring points is 40 and is numbered from M1 to M40. Is this study, 18 monitoring points on left side will be collected to build subsidence plane and settlement prediction model.

Using coordinates of 17 points and their settlement to build subsidence plane equation of this block. X, Y coordinates of point M34 are used to calculate its subsidence base on subsidence plane equation. Coordinates and subsidence of 18 monitoring points in the cycle 10 are in *table 1*.

Table 1: Coordinates and subsidence of 18 monitoring points

Order	Point's name	X (m)	Y(m)	Subsidence (mm) Cycle 10	Error (mm)
1	M1	39.99	2788.59	-43.58	0.86
2	M2	39.99	2793.24	-44.64	0.88
3	M3	39.99	2796.99	-45.25	0.90
4	M4	39.99	2800.73	-46.01	0.93
5	M5	39.99	2804.47	-46.11	0.90
6	M6	39.99	2808.22	-47.07	0.87

7	M36	30.61	2808.22	-41.80	0.61
8	M25	24.39	2808.22	-40.40	0.67
9	M26	24.38	2804.47	-40.41	0.71
10	M27	24.38	2800.73	-41.11	0.72
11	M28	24.38	2796.99	-39.02	0.72
12	M29	24.39	2788.56	-40.37	0.78
13	M30	30.61	2788.56	-41.13	0.82
14	M31	33.69	2788.56	-41.10	0.78
15	M32	30.61	2793.24	-42.54	0.85
16	M35	33.69	2804.47	-43.18	0.82
17	M33	33.69	2796.99	-41.95	0.82
18	M34	30.61	2800.73	-41.79	0.85

To build subsidence prediction model, time of 10 monitoring cycles and subsidence of point M34 will be used. Data of time and subsidence of point M34 from cycle 0 to cycle 07 are used to build settlement prediction model using polynomial equation. Subsidence of this point in cycle 8, 9, 10 will be calculated using this model. The heights from prediction model are then compared to the real subsidence from adjusted results. Time of monitoring and subsidence are in table 2.

Table 2: Time and subsidence of point M34

Cycle	Time of monitoring (MM/DD/YY)	Number of days	Subsidence (mm)	Error (mm)
Cycle 0	12/21/2010	0	0.00	-
Cycle 1	12/31/2010	10	-4.12	0.92
Cycle 2	01/10/2011	20	-10.74	0.89
Cycle 3	01/19/2011	29	-14.04	0.66
Cycle 4	01/29/2011	39	-18.11	0.84
Cycle 5	02/08/2011	49	-22.85	0.99
Cycle 6	02/18/2011	59	-27.83	0.75
Cycle 7	02/28/2011	69	-32.47	0.97
Cycle 8	03/11/2011	80	-37.10	0.93
Cycle 9	03/24/2011	93	-41.79	0.92
Cycle 10	05/08/2011	138	-60.91	0.81

4. Results and analysis

Three parameters of subsidence plane are determined using coordinates and subsidence of 17 points. The least square method was used to calculate these parameters (a, b, C) and assess the accuracy of model. An equation of subsidence plane is determined as below.

$$S_i = -0.000336.X_i - 0.000090.Y_i + 0.220591$$

Parameters of subsidence plane equation are in table 3.

Table 3: Parameters of subsidence plane equation

M_{MH}	M_0	$F = \frac{M_{MH}^2}{M_0^2}$	$F_{0.05}(14,17)$ From Fisher Distribution Table
(1)	*(2)*	*(3)*	*(4)*
0.85	0.89	0.91	2.31

In table 3, quantity M_0 is average error of standard deviations of subsidence. From those results, quantity F in column 3 is smaller than quantity F_{gh} in column 4. Two quantities F and F_{gh} have the same accuracy and this block has no deformation.

Settlement of point M34 in cycle 10 is calculated using above subsidence plane equation and then compared to the real subsidence *table 4*.

Table 4: Deviation of subsidence

Point's name	Real subsidence	Interpolated subsidence	Deviation (mm)
M34	-41.79	-42.23	0.44

Data of time and subsidence of monitoring point M34 from cycle 0 to cycle 07 are used to build subsidence prediction model using polynomial. Degree of polynomial ranges from degree 0 to degree 3. Parameters of polynomial are determined using the least square method. The results are in *table 5*.

Table 5: Confidence assessment of model

Order	Degree of polynomial	Error of model	Average error of subsidence	F	F_{gh}
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
1	0	9.90	0.87	129.91	$F_{gh} = F_{0.05}(6,7) = 4.21$
2	1	0.67	0.87	0.59	$F_{gh} = F_{0.05}(5,7) = 3.97$
3	2	**0.73**	**0.87**	0.71	$F_{gh} = F_{0.05}(4,7) = 4.12$
4	3	0.62	0.87	0.52	$F_{gh} = F_{0.05}(3,7) = 4.35$

Referring to the results in table 5, quantity F of polynomial degree 0 is bigger than quantity F_{gh}. Polynomial degree 0 cannot be applied to build subsidence prediction model. Referring to polynomial degree 1 to degree 3, quantities F are all smaller than quantity F_{gh}. However, polynomial degree 2 has the smallest model error and model error is equivalent to error of subsidence measurement. Polynomial degree 2 is thus accepted to establish subsidence prediction model. Three parameters a_0, a_1, a_2 are calculated using the least square method. Settlement prediction equation can be written as below.

$$q_i = 0.068532 - 0.490358.t + 0.000311.t^2$$

Subsidence of point M34 from cycle 8 to cycle 11 will be calculated using this prediction model. The results are in *table 6*.

Table 6: Predicted and real subsidence of point M34

Cycle	Predicted subsidence (mm)	Real subsidence (mm)	Deviation (mm)
(1)	*(2)*	*(3)*	*(4)*
Cycle 8	-37.17	-37.10	-0.07
Cycle 9	-42.84	-41.79	-1.05
Cycle 10	-61.67	-60.91	-0.76
Cycle 11	-71.58	-66.94	-4.64

The results indicate that predicted subsidence in cycle 8 has the smallest deviation. This cycle is the closest cycle to the last cycle *(cycle 7)* that participated in building of subsidence prediction model. Deviations of cycle 9, 10, 11 are increasing follow the time interval of cycle monitoring. Predicted subsidence from cycle 9 to cycle 11 has huge deviation and cannot be used.

5. Conclusions

This study is not a representative for all high-rise building monitoring but referring to the calculated results, some outlines can be made

Subsidence plane equation can be used to determine subsidence of monitoring point in case this monitoring point is destroyed or impacted by other construction activities of contractors in the construction site to ensure the continuity of monitoring procedure.

Polynomial degree 2 is the most suitable subsidence prediction model for high-rise building monitoring. Prediction model should be only used for the cycle that next to the last cycle.

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