Abnormality Detection Algorithm of Horizontal Displacement Monitoring Data During Foundation Pit Excavation Based on Temporal-spatial Characteristics

HUI SU, JINFENG ZHANG, WEIHONG CHU, WEINAN CHEN, ZHIHUA LUO and SHIJI LU

ABSTRACT

Horizontal displacement of the enclosure structure or soil is one of the key indicators to evaluate the safety of deep foundation pit excavation. However, the monitoring data of horizontal displacement will have short- or long-term abnormal fluctuations due to the interference of various non-structural factors, which would directly affect the assessment and identification of the risk of deep foundation pit excavation. In order to avoid missing and misjudging the true large deformation of the foundation pit and consider the requirements for the accuracy and timeliness of the monitoring data, an abnormal data identification and correction algorithm was proposed in this paper considering the temporal-spatial characteristics of the horizontal displacement monitoring data. The algorithm builds a spatial distribution matrix according to the deployment position relationship of multiple sensors, records the historical measured values of sensors in a period of time, and calculates the estimated values of the measured values of sensors at the next time based on multidimensional Kalman filtering. After obtaining the latest horizontal displacement monitoring value at the current time, calculate the difference between the measured value and the estimated value based on the spatial matrix to correct the data, mark the sensor with the difference greater than the adaptive threshold, and finally update the historical measured value, adaptive threshold, Kalman filter parameters, etc. in the window, waiting for the input of the monitoring data at the next time. The abnormal data identification and correction algorithm described in this paper was successfully applied in a deep foundation pit excavation project in Shanghai. The anomaly identification and correction of single sensor data and the horizontal displacement curve were both given. In general, this method can simultaneously discriminate and correct the data of multiple sensors in real time, effectively eliminate the abnormal fluctuation of monitoring data, and has good engineering application value.

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INTRODUCTION

The construction of high-rise buildings, rail transit systems, etc., will inevitably bring about substantial deep foundation pit projects. The excavation of foundation pit will induce stress redistribution of the surrounding soil and generate displacement towards the direction of the pit [1]. Large horizontal displacement can cause structural instability or even collapse, which would pose a serious threat to human life and property safety [2]. As deep horizontal displacement monitoring of the enclosure structure or soil can reflect the foundation on the vertical profile of horizontal displacement with depth changes in the law, it is an important basis for determining whether the foundation pit is stable [3].

However, the sensors in the monitoring system inevitably produce a large number of abnormal data, including outlier, drift, and missing, due to the problems of power and network failure, etc., which will reduce the reliability of monitoring results and may trigger false alarming [4, 5]. Therefore, it is of great significance to accurately identify and then correct abnormal monitoring data to reduce false alarms or missing reports and correctly assess the stability of the foundation pit.

For horizontal displacement monitoring, the measurement values of adjacent sensors in space within the same time period should also be similar. The results of individual processing of single sensor ignore the spatial correlation between sensors, which will lead to the inconsistency of data processing results of different sensors and affect the accuracy of the results. In addition, when multiple adjacent sensors in space experience abnormal fluctuations in data, it may be due to a real large deformation of the foundation pit structure.

This paper focuses on the detection and correction of abnormal data during the deep horizontal displacement monitoring of the enclosure structure or surrounding soil, so as to accurately evaluate the safety state of the foundation pit excavation. The proposed algorithm based on Kalman filtering considered the temporal and spatial characteristics of the horizontal displacement monitoring data and was applied in a deep foundation pit project in Shanghai.

ABNORMALITY DETECTION ALGORITHM

In general, the abnormality detection algorithm consists of a data input module, data storage module, data processing module and data output module, as shown in Figure 1.

(1) The data input module is connected to the sensor group and can receive the configuration parameter data of the sensor group and the time series data obtained from real-time monitoring. The configuration parameters include sensor calibration data, sensor spatial distribution matrix, initial measurement values, and algorithm calculation parameters.

(2) The data storage module includes parameter storage and data storage. The former stores the configuration parameters of the sensor group (including statistical indicators such as sensor measurement accuracy and calibration error, as well as numerical validity related parameters such as sensor measuring range and invalid values). The latter stores the original measurement values of the sensor group within a

full or fixed time window in a sequential manner, as well as the preprocessing and anomaly detection results of the original measurement values, and the corrected values.

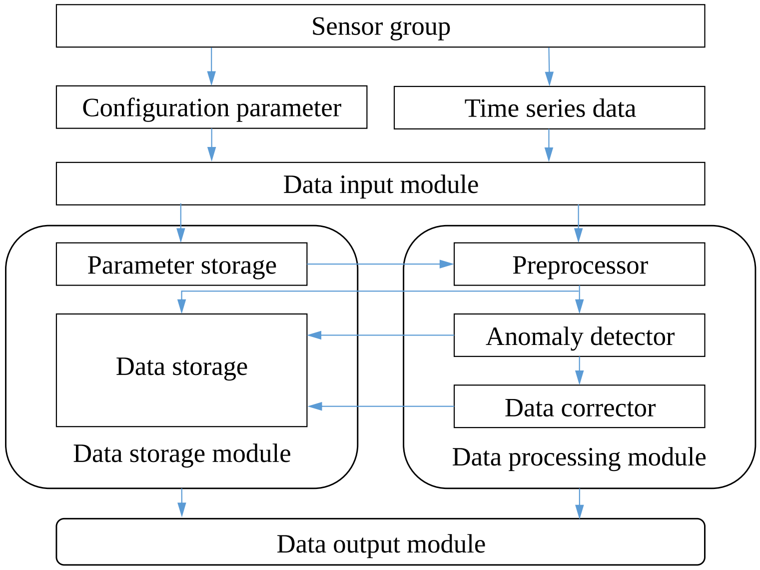

Figure 1. The structure of the abnormality detection algorithm.

(3) The data processing module includes a preprocessor, anomaly detector, and data corrector.

Preprocessing is based on the configuration parameters in the parameter storage (i.e. statistical indicators of monitoring data) to distinguish the monitoring data of the sensor group. Invalid measurement values that do not match the statistical distribution pattern with the configuration parameters or do not meet the numerical validity requirements are labeled and preprocessed. The preprocessing operations include but are not limited to replacing invalid measurements with measurements from the same sensor at the previous time, replacing them with the average value within a certain time window of the same sensor, and replacing them with measurements from neighboring sensors.

The anomaly detector performs temporal anomaly detection on the data processed by the preprocessor based on the historical data of the original measured and corrected values in the data storage. The anomaly detector is a multidimensional moving average filter that considers spatial distribution. It takes into account the similarity of measured values within a certain time window in terms of time sequence, and marks sensors according to the difference between the current measured values and the mean measured values within the time window that is greater than the threshold as suspected abnormal sensors. When initializing filtering, the sliding window size and outlier discrimination threshold should be configured in the anomaly detector.

The data corrector will consider the spatial distribution of abnormal sensors based on the judgment results of suspected abnormal sensors. If there are no other abnormal sensors adjacent to the location of the suspected abnormal sensor, the suspected abnormal sensor is considered to be a true outlier, and the measured values of adjacent sensors are used for Gaussian smoothing, and the measured values of the suspected abnormal sensor are replaced with the smoothed value.

If the adjacent sensors are also suspected abnormal sensors, it can be considered that the data fluctuation of theses sensors are caused by sudden changes in the state of the monitored structure. At the current time, risk identification should be performed on the sensors in this area.

Then, the preprocessed and corrected data will be added to the data storage in real time, and the time window of sliding average filtering will be moved forward.

(4) The data output module reads data from the data storage and outputs the data processing results of sensor group at each time through physical data lines or network API interfaces.

The implementation of the algorithm is presented in Figure 2.

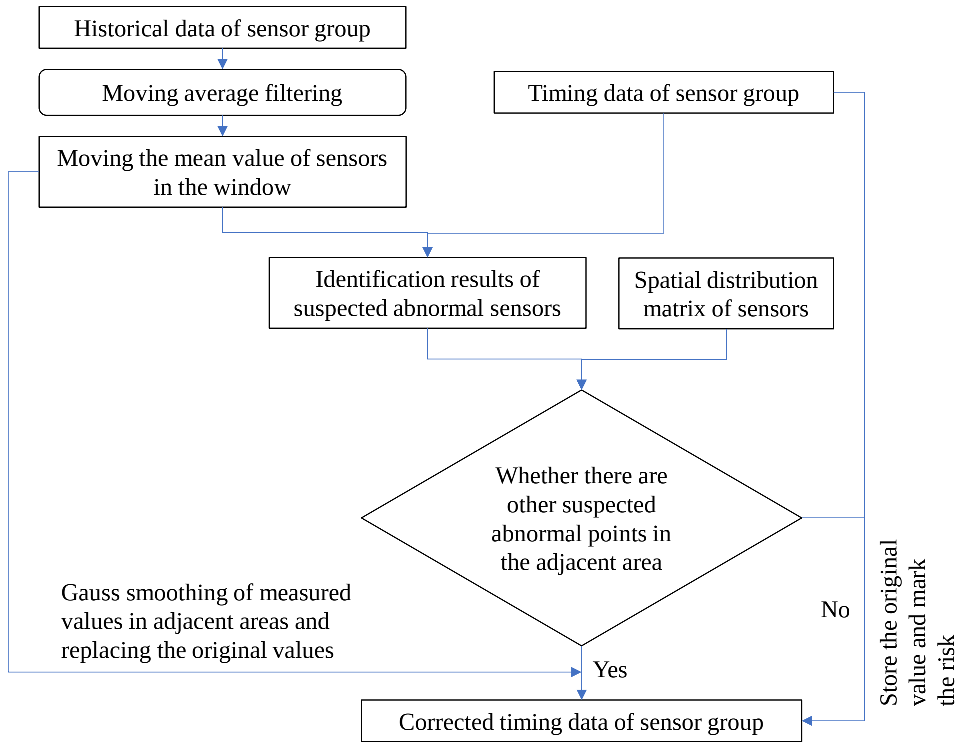

Figure 2. Implementation flowchart of the algorithm.

For an inclinometer hole containing *n* sensors, the sensor group and configuration parameters at the initial moment, including the spatial position matrix and sensor calibration matrix, are passed into the data input module. And the time series data $\left[v_1^t, v_2^t, \cdots, v_n^t\right]$ obtained at time *t* are passed into the data processing module. The preprocessor preprocesses the original measured values based on the parameters in the parameter storage, removes invalid values such as over-range values and zero values, and transmits the results to the anomaly detector.

The anomaly detector assumes that the values in the inclinometer hole are slowly changing, constructs a multidimensional sliding average filter, takes 12 hours before the current time as the time window, and calculates the mean value of historical measurements in the data storage within the window.

If the difference between the measured value of a sensor and the mean is greater than the preset threshold, the sensor will be marked as a suspected abnormal sensor, then obtain the anomaly detection results at time *t*.

The data corrector distinguishes the detection results based on the anomaly detection results and the spatial position matrix of the sensor group. If there are no other suspected abnormal sensors in the adjacent area of the suspected abnormal sensor, the measured data of this sensor is identified as abnormal data, and Gaussian smoothing is performed on the measured values of the sensors in the area to replace the true value of this point. If there are other suspected abnormal points in the adjacent area, it will be judged as a change in structural state, and the original measurement value will not be corrected.

ALGORITHM APPLICATIONS

An expansion project of a sewage treatment plant is located in Jiading District, Shanghai, and the plan view of the foundation pit is shown in Figure 3. The foundation pit enclosure structure adopts an underground continuous wall with three layers of concrete support. The excavation depth of the foundation pit was about 15 m, and the monitoring depth of deep horizontal displacement was about 25 m. Figure 3 also dipicts the layout of the automatic horizontal displacement monitoring points.

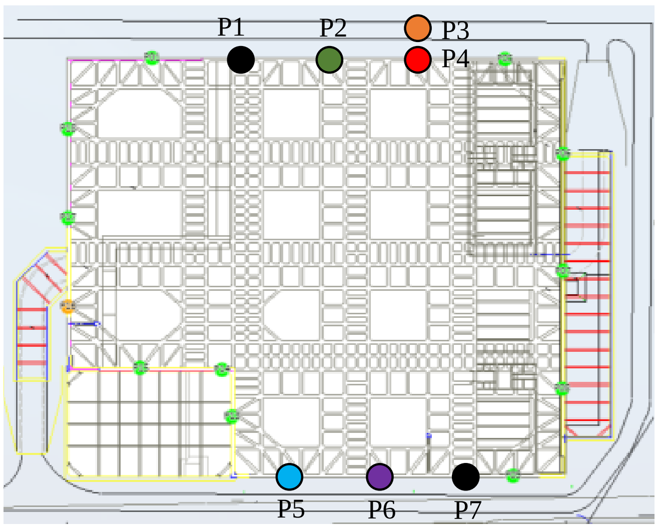

Figure 3. Plan view of the foundation pit.

The monitoring data of horizontal displacement sometimes have abnormal fluctuations due to the interference of various non-structural factors, such as electromagnetic interference and mechanical vibration. The anomaly identification and correction of single sensor data and the horizontal displacement curve are shown in Figure 4 and 5, respectively. It can be seen that the abnormal data in single sensor data is detected and corrected, and the low-frequency data change trend is retained. In the curve of horizontal displacement changing with depth, the abnormal fluctuations caused by abnormal data have also been detected and corrected.

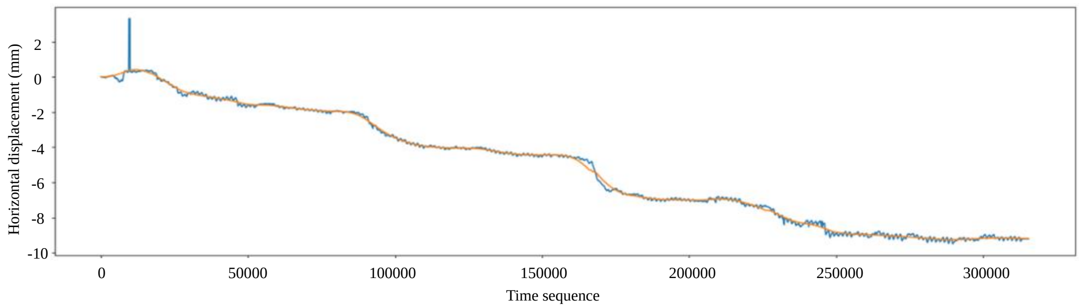

Figure 4. Anomaly identification and correction of single sensor data.

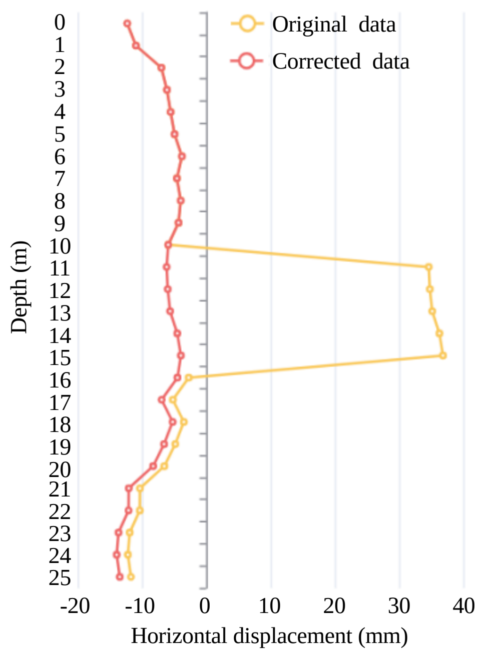

Figure 5. Anomaly identification and correction of the horizontal displacement curve.

CONCLUSIONS

To identify and correct the abnormal data of deep horizontal displacement monitoring, an abnormal data detection and correction algorithm based on Kalman filtering was proposed in this paper, with the consideration of the temporal-spatial characteristics of the horizontal displacement monitoring data. Moreover, the application of this method in a deep foundation pit project verified its feasibility and effectiveness.

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