Emergency Monitoring and Response Analysis of Horizontal Displacement in a Haidian Foundation Pit Under Heavy Rainfall Conditions

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Abstract: In response to a significant rainfall-induced risk encountered at an excavation site in Haidian District, Beijing, during the 2021 flood season, a zonal, multi-frequency emergency monitoring scheme was implemented. This scheme established a three-tiered monitoring network utilizing high-precision total stations. Monitoring was conducted according to the Second-Class Displacement Monitoring Standard and integrated a graded early warning system. A total of 458 observations over a 20-day period precisely delineated a three-stage characteristic deformation pattern triggered by rainfall: incipient deformation, accelerated development, and a critical state. The study conclusively identified the optimal window for manual monitoring as 13:00–17:00 local time, effectively mitigating data distortion caused by construction activities and nighttime visibility issues. Following the implementation of emergency control measures, the displacement growth rate markedly decreased to below 0.8 mm per day, validating the scheme's effectiveness. Recommendations for enhancing the system through automated upgrades and intelligent early warning optimization are presented.

Keywords: Excavation Engineering; Lateral Displacement; Emergency Monitoring; Heavy Rainfall; Early Warning System

1. Introduction

As a pivotal element in urban construction, the safety of excavation engineering directly impacts construction progress and the stability of the surrounding environment [1-3]. With the accelerating urbanization process, the scale of excavation projects continuously expands, leading to increasingly complex construction conditions. Particularly under extreme weather events, excavation safety faces severe challenges [4,5]. Research indicates that extreme weather phenomena, such as heavy downpours, reduce the effective stress of the soil mass, inducing strength degradation, and consequently increasing the risk of rising groundwater levels and deformation within the excavation [6,7]. Therefore, real-time monitoring of key parameters, such as lateral displacement, is of paramount importance for engineering safety and risk control.

The evolution of monitoring technologies provides robust support for excavation safety management. Traditional manual monitoring methods are gradually being superseded by automated monitoring systems. Applications of modern instruments including Global Position System (GPS), total stations, and inclinometers have significantly enhanced the precision and efficiency of data acquisition [8-10]. These technological advances enable more scientific and reliable monitoring under challenging conditions and extreme weather events, thereby emphasizing the critical need for developing specialized monitoring protocols tailored to such scenarios.

Addressing the potential threats posed by extreme weather to excavation safety, this study proposes an optimized real-time monitoring scheme. This scheme achieves efficient data acquisition and analysis by clearly defining critical monitoring parameters and optimizing sensor layout configurations and monitoring frequencies, thereby improving the capability to assess the excavation's actual state. Practical application of this scheme at an excavation site in Haidian District, Beijing, demonstrated its effectiveness in identifying potential risks and providing essential support for emergency management decisions. The implemented results

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not only validate the feasibility of the scheme but also establish a real-time monitoring feedback mechanism. This mechanism furnishes reliable data foundations for engineering management and construction optimization, consequently elevating the level of safety management for excavation projects facing extreme weather conditions.

2. Monitoring Horizontal Displacement in Excavations During Flood Season

2.1 Characteristics of Flood Season Excavations

The monitoring and management of excavations during flood seasons are critically important, primarily due to the impact of precipitation and variations in soil moisture. Flood season witnesses significantly increased rainfall, where water infiltration leads to soil saturation. This saturation alters the hydro-mechanical properties of the soil mass, subsequently impacting excavation stability. Precipitation accumulation and resultant groundwater fluctuations cause elevated pore-water pressure in the soil surrounding the excavation. This increases the effective stress in the soil, potentially triggering both settlement and horizontal displacement of the excavation structure. Consequently, excavations during flood season often exhibit distinct deformation characteristics, including accelerated deformation rates and complex deformation patterns. Therefore, monitoring specifically tailored to flood season conditions becomes imperative for the timely detection of dynamic deformation behavior.

2.2 Monitoring Methods for Horizontal Displacement in Flood Season

Effective monitoring of horizontal displacement during flood season necessitates the integration of multiple techniques and instruments. Common monitoring equipment includes automated total stations, GNSS (Global Navigation Satellite System) receivers, and inclinometers.

- Total stations, valued for their high precision and real-time capabilities, are suitable for detecting subtle deformations within excavations.
- GPS receivers, leveraging satellite positioning technology, are ideal for monitoring deformation over large excavation areas and exhibit greater robustness against adverse environmental conditions.
- Inclinometers serve as effective tools for precisely measuring excavation tilt angles and deformation states.

Selecting appropriate monitoring indicators is paramount within the monitoring process. Horizontal displacement, as a primary monitoring metric, necessitates establishing a dense network of multiple monitoring points. Such a network not only ensures coverage of critical excavation zones but also provides a reliable basis for comprehensive data analysis.

The real-time transmission and analysis of monitoring data are fundamental for establishing robust early-warning mechanisms. This enables rapid implementation of mitigation measures upon detecting abnormal deformation trends. Furthermore, integrating meteorological data to perform detailed correlation analyses between precipitation intensity and excavation deformation behaviour serves as a vital reference for safety management.

For flood season excavation monitoring schemes, it is essential to design appropriate monitoring frequencies and implementation procedures based on site-specific conditions. Monitoring frequency should be dynamically adjusted according to rainfall intensity and historical meteorological data, with increased frequency during rainfall events to capture transient deformation responses. The implementation phase must adhere to a series of standardized procedures, encompassing:

a) Proper installation of monitoring instruments,
b) Accurate data acquisition,
c) Rigorous data quality control (QC).

These critical measures enhance monitoring efficacy, ensure the reliability of acquired data, and provide a robust foundation for the safe operation of excavation projects during flood months.

3. Emergency Monitoring and Analysis of Excavations

3.1 Design of Emergency Monitoring Schemes

3.1.1 Monitoring system layout

The case study excavation is situated on flat terrain within the Haidian District, Beijing. Designed as a temporary supporting structure with a one-year service life, the excavation reaches a depth of 17 meters. The Safety Grade of Excavation Support Structures (GB 50497 classification) was assessed as Grade I for the excavation sidewalls, based on its excavation

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depth, surrounding environment, and stratigraphic conditions. The primary retaining system employs a pile row wall, with pile depths ranging from 15.78 m (west side), 16.73 m (south side), 16.33 m (east side), and 15.73 m (north side).

During the 2021 flood season (June 1st to August 31st), the site experienced recorded precipitation of 627.4 mm, 70% more than the same period of the normal year, and the cumulative rainfall was a record high in the past 60 years. Reflecting the potential deformation dynamics of the excavation, a zoned, multi-frequency emergency monitoring scheme was implemented. The monitoring system adheres to a tiered layout principle, comprising a three-level network: reference points, working datum points, and monitoring points.

Reference points (providing the stable datum) were established in stable areas well beyond the influence zone of the excavation. Accounting for the anticipated deformation behaviour within the excavation and potential construction disturbance from adjacent activities, a total of nine (9) reference points (designated TT1 through TT9) were strategically placed, as illustrated in Figure 1.

For comprehensive monitoring of the supporting structure's deformation, twenty-seven (27) horizontal displacement monitoring points were uniformly installed along the top surface of the pile cap beam (capping beam). These points feature fixed L-shaped mini-prisms for targeted optical measurement.

3.1.2 Monitoring and early warning technical indicators

In accordance with the requirements of the Standard for Engineering Surveying (GB 50026-2020) and considering the building's nature and structural characteristics, second-order horizontal displacement monitoring was employed. As detailed in Table 1, the primary technical specifications for the reference network include:

1.Mean square error of point position between adjacent reference points ≤ 3.0 mm

2.Mean square error of angle measurement: 1.0″

3.Relative mean square error of distance measurement ≤ 1/200,000

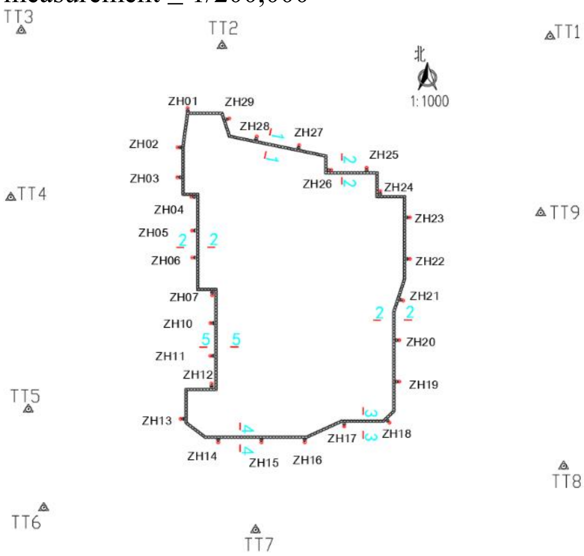

Figure 1. Layout Plan of the Excavation Site in Haidian District

The monitoring instrument selected is the Leica TM50 total station, which features a standard angular measurement accuracy of 1″and a standard distance measurement accuracy of 1.0mm+ 1.5ppm, meeting the specified requirements.

Furthermore, based on the characteristics of the support structure and its safety grade, a zoned and tiered warning threshold system was established. The control limit for pile top horizontal displacement ranges between 31–33 mm, the alarm threshold ranges between 25–27 mm, and the warning threshold for displacement rate is 3 mm/d. Specific early warning indicators are detailed in Table 2.

Table 1. Key Technical Specifications for Horizontal Displacement Reference Network Measurements

Order	Mean Square Error of Point Position Between Adjacent Ref. Points (mm)	Average Side Length L (m)	Mean Square Error of Angle Measurement (″)	Relative Mean Square Error of Distance Measurement	Required Number of Observation Sets		
					Instrument with Std. Dev. ≤ 0.5″	Inst. with Std. Dev. ≤ 1″	Inst. with Std. Dev. ≤ 2″
2nd	≤ 3.0	≤400	1.0	≤1/200000	6	9	--
		≤200	1.8	≤1/100000	4	6	9

Table 2. Alarm Thresholds and Control Limits for Horizontal Displacement of Pile Cap Beam

Excavation Support Safety Grade	Support Section ID	Depth to Pile Cap Beam (m)	Horizontal Displacement Control Limit (mm)	Horizontal Displacement Alarm Threshold (mm)	Maximum Allowable Displacement Rate (mm/d)
I	1-1	15.78	31	25	3

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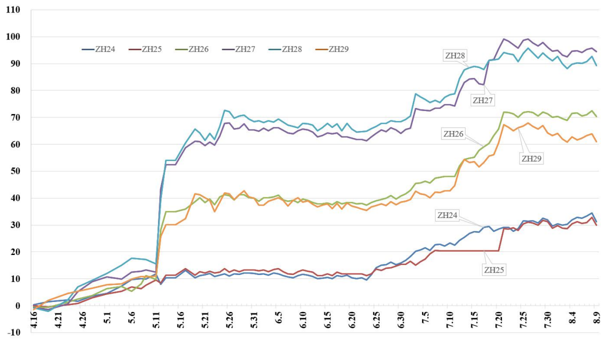
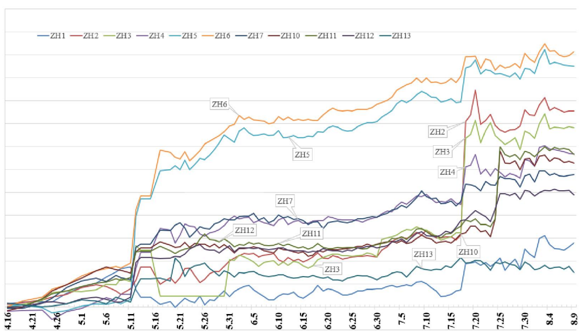
	2-2	16.73	33	27	3
	3-3	16.33	32	26	3
	4-4	15.73	31	25	3
	5-5	16.23	32	26	3

3.2 Rainfall-Induced Deformation Response Characteristics of the Excavation

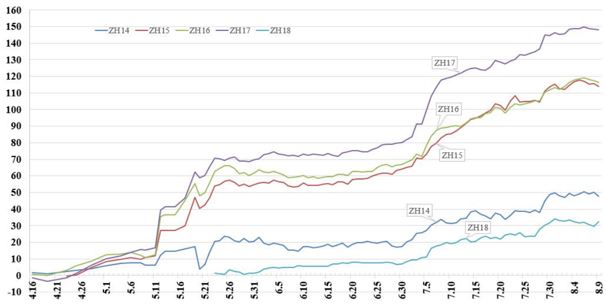
As illustrated in Figure 2, analysis of the initial pile cap beam horizontal displacement monitoring data reveals a distinct phased evolutionary deformation pattern under sustained precipitation:



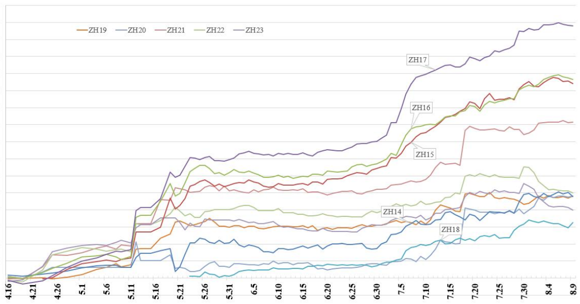
(a) Variation Curve of Cumulative Horizontal Displacement of Pile Cap Beam - North Side



(b) Variation Curve of Cumulative Horizontal Displacement of Pile Cap Beam - West Side



(c) Variation Curve of Cumulative Horizontal Displacement of Pile Cap Beam - South Side



(d) Variation Curve of Cumulative Horizontal Displacement of Pile Cap Beam - East Side

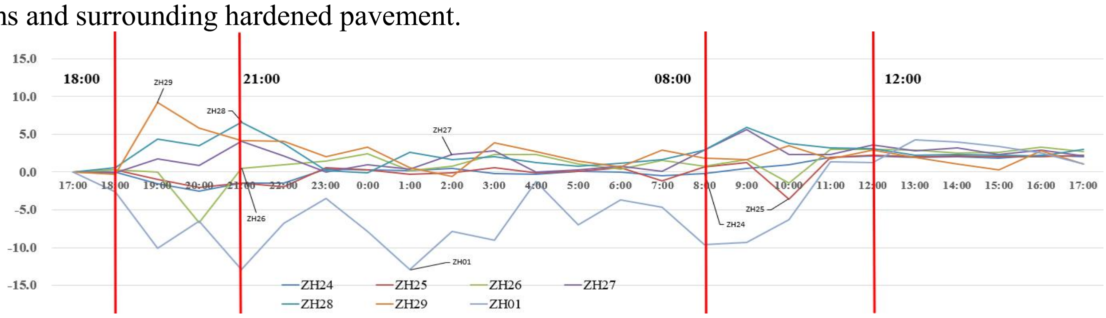
Figure 2. Cumulative Horizontal Displacement Curve for Pile Cap Beam

(1) Initial Deformation Phase (May 13-19): Horizontal displacements at 13 monitoring points (e.g., ZH4-ZH10 on the western side) exceeded alarm thresholds, with a maximum cumulative displacement of 67.5 mm.

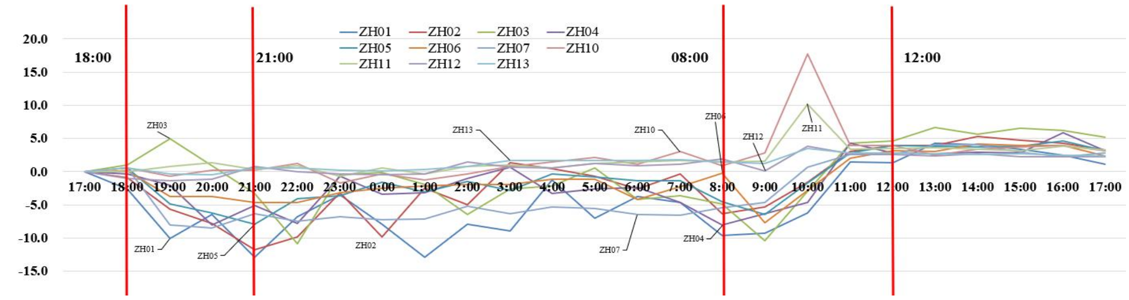
(2) Rapid Development Phase (June 30-July 15): Intensified rainfall led to increased excavation deformation. Displacements at 21 monitoring points surpassed alarm thresholds, reaching a peak deformation rate of 8.2 mm/day. Concurrently, cracks appeared in the capping beams and surrounding hardened pavement.

(3) Critical State Phase (July 17-18): Deformation rates at 14 monitoring points exceeded the warning threshold (3.0 mm/day), escalating to a maximum rate of 49.7 mm/day. Localized crack widths reached 50 mm, accompanied by water seepage through the support structure and gushing water from anchor rod boreholes.

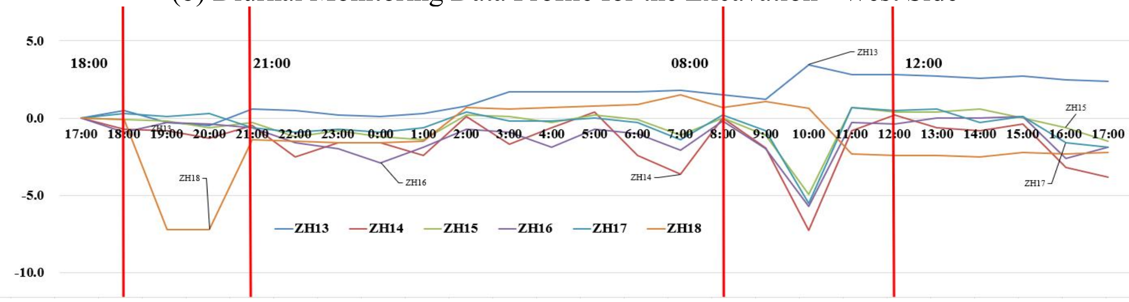
3.3 Monitoring Implementation and Data Analysis



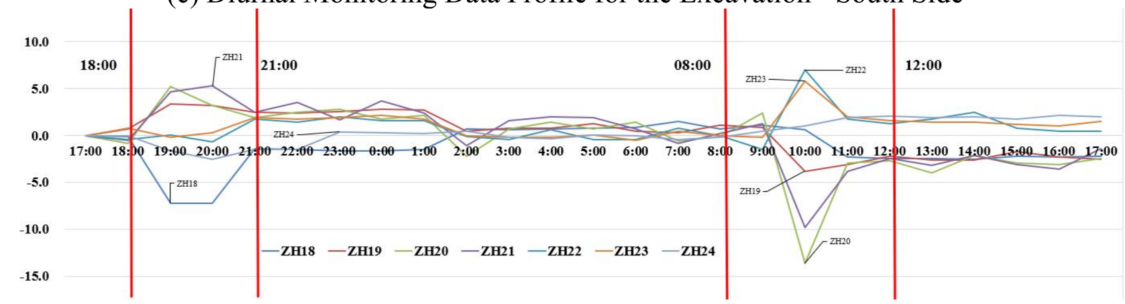
(a) Diurnal Monitoring Data Profile for the Excavation - North Side



(b) Diurnal Monitoring Data Profile for the Excavation - West Side



(c) Diurnal Monitoring Data Profile for the Excavation - South Side



(d) Diurnal Monitoring Data Profile for the Excavation - East Side

Figure 3. Diurnal Monitoring Data Profile for the Excavation (22 July, 17:00–23 July, 17:00)

To address the deformation risk triggered by persistent heavy rainfall during flood season, emergency monitoring was initiated at 17:00 on July 20, 2021 and lasted for 20 days. This effort comprised 458 observation sessions, yielding 120,006 field measurements with full coverage of all critical locations across the excavation site. Utilizing 24-hour monitoring data from 17:00 July 22 to 17:00 July 23 (Figure 3) as a representative case, analysis of real-time monitoring data revealed the following:

1. Pronounced Environmental Influence: During 08:00–12:00 and 18:00–21:00, significant variations in solar radiation intensity, ambient temperature, and nighttime construction activities induced abnormal increases in deformation rates (peak instantaneous rate: 49.7 mm/day). Concurrently, optical limitations of manual total station observations and reduced visibility for survey crews at night degraded data quality, resulting in low data yield efficiency.

2. Optimal Observation Window: The 13:00–17:00 period demonstrated stable solar conditions and minimal thermal fluctuations, delivering optimal measurement data quality. This timeframe was established as the reference period for reliability analysis.

3. Deformation During Remediation Works: After excluding anomalous periods, pile cap beam displacement during emergency stabilization (July 20–28) exhibited an "initial reduction followed by rebound" trend, with values approaching convergence after short-term fluctuations. Post-August 3, deformation rates decreased significantly and cumulative displacement stabilized, confirming the progressive efficacy of remediation measures.

Upon concluding real-time monitoring on August 9, cumulative displacement magnitudes were: West Section: 111.5 mm, South Section: 148.0 mm (most affected by heavy rainfall), East Section: 91.4 mm, North Section: 94.5 mm.

Considering both the stabilizing displacement trend (Figure 2) and assessment by the expert panel, the excavation was confirmed to have reached a globally safe and stable state. Monitoring frequency was subsequently reduced to the routine schedule (1 session/day).

4. Conclusion

This study established an efficient monitoring and early-warning system through a 20-day emergency campaign at a rainfall-affected excavation site in Beijing's Haidian District, accumulating 458 real-time surveys and over 120,000 data points. Monitoring data quantitatively characterized rainfall-induced deformation:

1. The south section incurred the most severe rainfall impact, with cumulative displacement reaching 148.0 mm (vs. 91.4–111.5 mm in other sections).
2. During critical July rainfall, peak deformation rate peaked at 49.7 mm/d, triggering staged alerts (thresholds: cumulative displacement ≥25–27 mm; rate ≥3 mm/d) to support emergency decision-making.
3. Optimal manual monitoring occurred during 13:00–17:00, effectively minimizing data distortion from construction interference (08:00–12:00) and nighttime obstructions (post-18:00).

Post-implementation of emergency measures (initiated 3 August), displacement growth rate reduced to <0.8 mm/d, with cumulative displacements converging within safe thresholds.

To enhance extreme-weather resilience, the following research directions are proposed:

1.Deploying automated systems (robotic total stations and fiber-optic sensors) for continuous millimeter-level data acquisition,

2.Building cloud platforms integrating real-time meteorological/hydrological data with AI predictive models,

3.Advancing fundamental research on coupling mechanisms of rainfall-soil degradation-structural response to optimize resilient design theories.

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References

[1] Zhang, L.W. (2013) Existing Problems and Countermeasures in Deep Foundation Pit Construction of Building Engineering. Urban Constr. Theor. Res. (Electron. Ed.), 2013(18). doi:10.3969/j.issn.2095-2104.2013.18.496.

[2] Su, C. & Chen, T.L. (2021) Brief Discussion on Quality and Safety Hazards in Foundation Pit Construction. China Sci. J. Database Ind. A, 2021(11), Art. 3.

[3] Cao, D.D. (2024) Research on Key Construction Technologies of Deep Foundation Pit Support in Building Engineering. Chin. Sci. J. Database (Abst. Ed.) Eng. Technol., 2024(002), Art. 000.

[4] Wang, W.C. (2025) Construction Technology of Deep Foundation Pit Support in Building Engineering. Urban Constr. Theor. Res. (Electron. Ed.), 2025(16), pp. 129–131. doi:10.19569/j.cnki.cn119313/tu.202516043.

[5] Gui, S.P. (2025) Application Research of Deep Foundation Pit Support Technology in Building Engineering. Mod. Eng. Technol., 4(07), pp. 81–84. doi:10.26929/j.cnki.issn.2097-1672.2025.07.021.

[6] Tian, R.D., Xiao, J.H. & Wang, X.R. (2024) Deformation Analysis and Dewatering Treatment of Deep Foundation Pit Caused by Heavy Rainstorm. J. Water Res. Archit. Eng., 22(05), pp. 38–45.

[7] Duan, J.R. (2024) Study on the Influence of Precipitation Rate on the Stability of Water-filled Foundation Pit After Extreme Rainstorm. North China Univ. Water Resour. Electr. Power. doi:10.27144/d.cnki.ghbsc.2024.000013.

[8] Zhang, H. & Gu, J.S. (2003) Deformation Monitoring and Data Analysis of Municipal Foundation Pit. J. Zhejiang Univ. Technol., 31(5), pp. 512–515. doi:10.3969/j.issn.1006-4303.2003.05.022.

[9] Liu, P. (2011) Application of Automated Total Station in Deformation Monitoring of High-Rise Building Foundation Pit. Geomat. Spat. Inf. Technol., 34(3), pp. 180–182. doi:10.3969/j.issn.1672-5867.2011.03.080.

[10] Li, W.Q. (2018) Comparative Analysis of Common Automated Measurement Methods in Foundation Pit Monitoring. Urban Surv., 2018(2), pp. 149–153. doi:CNKI:SUN:CSKC.0.2018-02-049.