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Construction Surveying for Setting Out Complex Structures in Mountainous Terrain

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SUMMARY

This paper examines construction surveying for a structure with a complex curvilinear configuration in mountainous terrain. The sequence of establishing the geodetic control network, aligning topographic and design data, developing a local coordinate system, and executing total station layout operations is analyzed. The research object is the new construction of a multifunctional recreational complex with a commercial infrastructure network in Polianytsia village, Vyshni area, Nadvirna district, Ivano-Frankivsk region (Phase I of a 9-story building on a 1 ha site). Attention is paid to selecting the total station setup method, monitoring baseline reference point stability, and staking out curvilinear elements on-site. Analysis of the resulting control network RMSE values demonstrates that errors do not exceed 1.98 mm vertically and 1.79 mm horizontally, satisfying precision requirements for this surveying work category. To determine total station positions under challenging mountainous conditions, combining different techniques is advisable to improve data quality. At this project site, a resection approach (incorporating distance and angular-distance methods) based on several stable control stations was deployed, allowing for systematic quality control. Furthermore, a methodology is presented wherein control points are distributed across multiple levels relative to the instrument position for continuous use as structural erection progresses. Systematic network readjustment of these multi-level benchmarks represents the only reliable method to guarantee optimal resection geometry and eliminate measurement error accumulation. Integrating geodetic measurement techniques for a non-standard facility in rugged mountainous terrain enables the optimization of surveying control workflows across the entire construction site.

Keywords: Construction surveying; Geodetic control network; Total station resection; Curvilinear structure; Mountainous terrain.

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Introduction

Construction surveying critically ensures that as-built structural positions comply with design data. However, mountainous terrain complicates field operations due to elevation changes, terrain complexity, limited line-of-sight, and network stability issues, demanding continuous quality control. Recent research highlights that engineering survey reliability heavily depends on geodetic control quality, station setup methods, and independent verification. Varbla et al. (2024) applied the resection method for total station georeferencing, noting that positioning accuracy relies on reference point quantity and precision while emphasizing independent data validation. For horizontal positioning and spatial localization, Chetverikov et al. (2022) established a methodological framework to monitor structural positions during surveying tasks.

High-precision geodesy in rugged terrain requires accounting for specific environmental factors. In the Tatras, Strugarek et al. (2026) demonstrated that GNSS heighting accuracy depends significantly on the geoid model, processing strategies, and tropospheric delay modeling. For complex geological settings, Savchyn et al. (2025) designed a stable geodetic network to monitor the Dniester Hydroelectric Complex, proving that integrated terrestrial and remote sensing methods are essential for tracking structural stability. Similarly, Gera et al. (2025) confirmed the vital role of a stable survey control base during foundation settlement monitoring. Consequently, prior literature provides the foundation for this study by validating reliable control network monitoring (Savchyn et al., 2025), mountainous height determination challenges (Strugarek et al., 2026), and resection verification (Varbla et al., 2024). Building on these frameworks, this paper analyzes the construction surveying sequence for setting out a complex curvilinear structure in mountainous terrain. The study aims to enhance layout workflows by optimizing both geodetic measurement accuracy and the point density defining the design contour under challenging topographic conditions.

Method and Theory

The object of research is the new construction of a multifunctional recreational complex with a commercial infrastructure network in Polianytsia village, Vyshni area, Nadvirna district, Ivano-Frankivsk region (Phase I of a 9-story building on a 1 ha site) (Fig. 1). According to the design specifications, the entire hotel complex comprises 8 buildings of various complex configurations.

Figure 1. *Design project for Phase I of the 9-story hotel complex building*

Prior to the commencement of construction, a 1:500 scale topographic survey was conducted using the MSK-63 local coordinate system. Once the architects integrated the structural design solutions onto this survey base, the task emerged to set out the object on-site within the construction area. To verify the compliance of the archival topographic data with the actual site conditions, a follow-up total station survey of the existing fence perimeters and adjacent structures was executed. Additionally, observations were captured for the pre-anchored special geodetic targets, which serve as the baseline horizontal and vertical control network for subsequent surveying operations.

To enhance measurement precision and reliability, at least five readings were taken per geodetic target, verifying their convergence. Given the mountainous terrain, target stability was prioritized.

Located in Polianytsia village's popular Vyshnia area, the site features elevations from 860 m to 930 m and moderate to steep slopes, though construction pads exhibit terraced or artificially leveled topography. Targets were mounted exclusively on cleared, stable, rigid foundations—such as structural components or monolithic concrete elements—minimizing deformations and potential displacements during observations (Fig. 2).

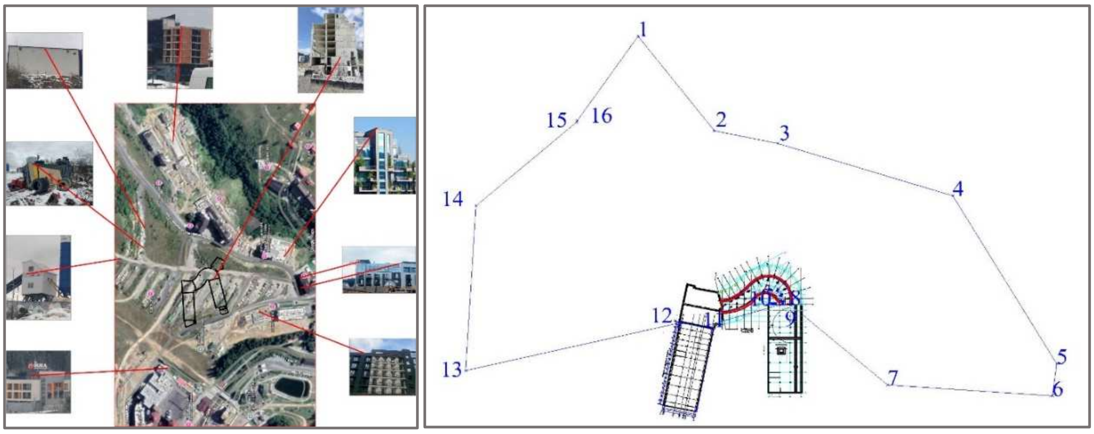

Figure 2. *Layout scheme of the site construction control network*

When establishing a geodetic control network, its geometric configuration is critical. Ideally, reference control points should sit near a single horizon, approximately at the total station's instrument height. This approach avoids excessively acute angles during resections, ensuring favorable measurement geometry for angular and linear measurements. Conversely, significantly differing point elevations cause unfavorable targeting angles, degrading resection accuracy. Therefore, control network design should position stations roughly level with the total station to guarantee optimal resection geometry. In practice, establishing a single-horizon geodetic control network for high-rise buildings is challenging due to elevation differences and intervisibility requirements. Designing such networks demands a compromise between vertical positioning, mutual visibility, operational ease, and resection geometry. Consequently, control points are distributed across different horizons (e.g., the first, fifth, and tenth floors). As structural erection progresses, new points are established, periodically remeasured, and the network readjusted to monitor coordinate transfer accuracy and prevent error accumulation.

The subsequent stage involves adjusting the geodetic control network mathematically or graphically. During data processing, observations containing gross errors or outliers are excluded, and averaged coordinate values are determined to serve as reference points with unique identifiers for future geodetic computations. Once obtained, the adjusted control base and total station survey results are integrated with the 1:500 scale topographic plan, generating a unified spatial coordinate model that aligns field measurements with design data. The next phase transforms data from the SK-63 state coordinate system to an arbitrary local coordinate system to simplify field stakeout. Design point coordinates are prepared in AutoCAD and uploaded directly into the electronic total station. The origin of this local construction grid is defined as X = 1000 and Y = 2000, facilitating subsequent data reduction and as-built documentation management. Finally, all distinctive features scheduled for on-site stakeout inside the excavation pit or at relevant structural levels are generated in AutoCAD. Simultaneously, a layout diagram is prepared in hardcopy or digital format for real-time monitoring before executing direct fieldwork. During fieldwork directly on the construction site, the coordinates of the electronic total station setup are determined by solving a resection problem (either distance or angular-distance resection). Utilizing multiple reference points enables verification of the acquired station position and enhances the reliability of the subsequent stakeout. Once the instrument coordinates are established, the total station is oriented, and the field layout of the design points is performed. Since the building features a curvilinear (semi-circular) configuration, a higher density of layout points is adopted—with a step size of approximately 0.5 m or less, depending on the precision requirements and the geometry of the structural element. This approach ensures the correct reproduction of the curvilinear contour on-site.

Results

Operations yielded a harmonized horizontal and vertical geodetic control network for the construction site, fully aligning field measurements with topographic and design data. Implementing a local coordinate system further streamlined design coordinate preparation and total station stakeout works.
Utilizing the resection method across multiple reference stations enabled precise electronic total station positioning and quality control. Given the rugged mountainous terrain and complex structure configuration, robust positioning control is critical; thus, at least 4 target control points were selected. Continuous horizontal and vertical monitoring was maintained during layout, producing as-built coordinates for subsequent surveys and design compliance evaluation.

For curvilinear contours, implementing a higher density of layout points enables a more precise reproduction of the design geometry on-site. The final selection of the stakeout step size is determined by the curve geometry, the required accuracy, and the actual field conditions. The results of the adjusted coordinates, along with their horizontal and vertical RMSE values, are presented below (Table 1).

Table 1. *Adjusted network coordinates with horizontal and vertical root-mean-square errors (RMSE)*

№	X (m)	Y (m)	H (m)	Height RMSE H (mm)	Plane RMSE XY (mm)
1	2183.252	944.952	953.562	1.09	1.79
2	2120.006	994.538	924.365	0.52	0.18
3	2111.687	1036.042	929.125	0.38	0.72
4	2076.78	1150.34	927.852	1.46	1.29
5	1964.714	1218.149	921.125	1.94	1.42
6	1943.346	1215.342	921.456	1.27	1.09
7	1950.621	1107.698	918.167	1.83	1.77
8	2004.011	1044.264	928.123	0.14	0.51
9	2004.131	1044.417	931.365	0.71	0.72
10	2004.002	1037.272	931.548	0.62	0.57
11	1989.577	987.056	924.652	0.29	0.57
12	1992.363	973.369	926.852	0.55	0.44
13	1960.139	832.37	911.025	1.98	1.78
14	2070.07	839.074	940.456	1.21	1.28
15	2125.994	904.788	942.123	0.14	0.9
16	2126.99	905.041	942.354	1.83	1.6

To establish and assess geodetic control network accuracy, a multiple-measurement method was applied using an electronic total station and two tripods positioned up to 10 m apart to form a baseline. Following initial instrument setup, baseline parameters were determined, and subsequent angle and distance measurements were captured for the control points. To increase precision and ensure independent measurement verification, the total station was transferred to the second tripod. The baseline was then remeasured, a repeat series of observations executed, and each point defined by five independent readings per station. The acquired measurement results were processed and jointly adjusted using the method of least squares. The network adjustment was performed within the Microsoft Excel environment utilizing the Solver add-in by minimizing the sum of squared residuals between the results of individual observations. Based on the adjustment results, the most probable coordinate values were determined for each point, and a quality assessment of their precision was conducted.

The distance resection is executed using an electronic total station with an accuracy not exceeding 2 mm along both the X and Y axes. Points on the slab are staked out with an accuracy of not more than one millimeter in distance and 2” in angle. The primary regulatory document governing the layout of points and axes on-site is DBN V.1.3-2:2010 'Geodetic Works in Construction', according to which the RMSE is specified as 5 mm for angular and linear stakeout of detailed axes, and 3 mm for vertical profiling (plumbing). For large-scale capital structures (covering areas up to 10–100 ha), the root-mean-square error for linear measurements is established at not more than 1:10,000 (1 cm per 100 meters of baseline), with angular measurement errors not exceeding 5". Based on the observation results, the maximum vertical RMSE values are 1.98 mm at point 13, and 1.94 mm and 1.83 mm at points 5 and 16, respectively. In all cases, the maximum error values are caused by the remoteness of these stations from the observation setup, which is a consistent and expected phenomenon. All results comply with the regulatory requirements established for this type of surveying work.

Conclusions

Construction surveying in rugged terrain demands strict geodetic network stability and continuous horizontal and vertical positioning control. Implementing the developed multilevel point distribution scheme, coupled with a local coordinate system instead of national grids, ensures optimal resection geometry, simplifies design data preparation, and eliminates error accumulation as structural erection progresses.

Utilizing a two-tripod configuration with redundant observations significantly increases coordinate determination accuracy compared to single-session measurements. Subsequent simultaneous least-squares adjustment within the Excel solver environment effectively mitigates random measurement errors, thereby enhancing baseline data reliability for all setting-out works.

Follow-up total station surveys and multi-epoch checking of anchored geodetic targets provide stable network geometry. In challenging topography, combining distance and angular-distance resections linked to multiple stable control stations offers robust setup verification and superior data quality.

Staking out curvilinear infrastructure requires critically balancing geodetic accuracy with layout point density to accurately transfer the complex architectural geometry on-site.

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