SANACIJA NIVELMANSKE MREŽE MESTNE OBČINE LJUBLJANA

RENOVATION OF THE LEVELLING NETWORK OF THE MUNICIPALITY OF LJUBLJANA[1]

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UDK: 347.193:528.38(497.451.1)
Klasifikacija prispevka po COBISS.SI: 1.03
Prispelo: 17. 5. 2024
Sprejeto: 15. 7. 2024

DOI: 10.15292/geodetski-vestnik.2024.03.327-359
SHORT SCIENTIFIC ARTICLE
Received: 17. 5. 2024
Accepted: 15. 7. 2024

IZVLEČEK

V prispevku sta predstavljeni sanacija in nadgradnja nivelmanske mreže mestne občine Ljubljana. Predstavljene so stare izmere na območju mestne občine Ljubljana, projekt sanacije, oblika nove nivelmanske mreže in nivelmanska izmera. Opisana je predhodna obdelava podatkov. Na podlagi analize stabilnosti reperjev 1. reda nivelmanske mreže Slovenije so bili izbrani dani reperji za izravnavo nivelmanske mreže. Analizirana je natančnost na podlagi odstopanj obojestransko merjenih višinskih razlik, odstopanj pri zapiranju nivelmanskih zank in na podlagi popravkov merjenih višinskih razlik po izravnavi.

ABSTRACT

This article presents the renovation and improvement of the urban levelling network of the Municipality of Ljubljana. It presents the old measurements in the area of the Municipality of Ljubljana, the renovation project and the configuration of the new levelling network as well as the levelling measurement. The pre-processing of the data is described. Based on the analysis of the stability of the 1st order benchmarks of the levelling network of Slovenia, the predetermined benchmarks were selected for the adjustment of the levelling network. The accuracy is analysed based on the deviations of the height differences measured height, the deviations in the closure of levelling loops and the corrections of the measured height differences after the adjustment.

KLJUČNE BESEDE

nivelmanska mreža, izmera, izravnava, analiza natančnosti

KEY WORDS

levelling network, measurement, adjustment, accuracy analysis

[1] *The Englisch translation was made with the help of ChatGPT and Instatext*

1 INTRODUCTION

The Municipality of Ljubljana (ML) requires a standardised, high-quality geodetic basis for spatial planning, placement of objects in space, planning, construction, recording and maintenance of objects. When planning, building and maintaining objects that are connected to other objects, it is often necessary to determine their height with millimetre accuracy. In the Republic of Slovenia, in accordance with the provisions of the Law on the National Geodetic Reference System (UL RS, 2014) and the Regulation on the Determination of the Parameters of the Vertical Component of the National Spatial Coordinate System (UL RS, 2018), the new Slovenian Height System 2010 (SVS2010, datum Koper) is used, replacing the old Slovenian Height System 2000 (SVS2000, datum Trieste, Koler et al., 2019, Medved et al., 2020).

Due to increasing urbanisation and the ageing of municipal infrastructure, investments in the construction and renovation of municipal and other infrastructure have increased in recent years. Therefore, a well-established height network is extremely important for the infrastructure construction. Ljubljana's urban levelling network has become inadequate, unreliable and inhomogeneous due to destruction, subsidence and recalculation of benchmark's heights. This leads to cause difficulties in project preparation, construction and real estate registration.

The urban levelling network problem began to be reflected in ML projects as discrepancies in construction works and infrastructure registration became more frequent. The problem has only grown over the years as more and more problematic benchmarks have emerged. To solve this problem, ML launched the "Project for the renovation and modernisation of the levelling network of the city of Ljubljana" at the end of 2021 as part of a public tender. The project was carried out by a consortium of three companies LGB d.o.o. as the leading partner and Geodetska družba d.o.o. and Geodetski zavod Celje d.o.o. as partners. The contractual subcontractors included the University of Ljubljana, Faculty of Civil and Geodetic Engineering, Department of Geodesy, GEOFOTO d.o.o., Geograd d.o.o., LUZ d.d. and Aleš Breznikar s.p. Over 20 geodetic experts were involved in the project, including 9 licenced geodetic engineers. Together with the supporting staff, over 30 people worked on the project (LGB, 2023).

2 MEASUREMENTS OF THE LEVELLING NETWORK IN THE LJUBLJANA AREA FROM 1895 TO 2002

The city levelling network of Ljubljana was first measured in 1895-1896, including 263 benchmarks. The levelling of the entire area of Ljubljana was carried out between 1940 and 1941. The first-order levelling network comprised 70 benchmarks. It consisted of 7 loops and 4 blind polygons. The accuracy of the entire network was poor, as no quality measurements could be carried out due to the blockades during the war. In 1941, the levelling network was initially set up in the Ljubljansko barje, but was soon destroyed. In 1949, the levelling network was stabilised and surveyed around and through the Ljubljansko barje. Most of the benchmarks were later destroyed (Koler, 1989, Hlebec, 2000).

Another survey followed between 1962 and 1963, which covered the entire area of Ljubljana and its suburbs. Due to the unstable ground, the Ljubljansko barje was not included in the measurements. The first-order levelling network comprised 493 benchmarks, consisting of 38 loops and 101 levelling polygons. Between 1964 and 1965, the area of Ljubljana began to expand. Therefore, 6 loops and 1 blind polygon on both sides of the Sava River and in the northern part of the Ljubljansko barje were added to the city levelling network. Three fundamental benchmarks were established, which formed the height reference and the basis for subsidence control. In 1970, 24 new benchmarks were added in the Medvode area, expanding the network with a new loope and consisting of 5 levelling polygons (Hlebec, 2000).

This was followed by systematic measurements to determine the vertical displacements of benchmarks in the Ljubljana area and in the Ljubljana barje. The first measurements were carried out between 1971 and 1976. New benchmarks were stabilised in new levelling loops, which also extended to the Barje area. 47 closed loops and 2 blind polygons were established. The levelling network was connected to 4 existing fundamental benchmarks (FR-1 to FR-4). Later, 4 additional fundamental benchmarks were stabilised in the Barje area (FR-5, FR-6, FR-7 and FR-8). The survey of new fundamental benchmarks took place in 1974 (Vodopivec, 1976).

In 1984, all levelling polygons of the first-order urban levelling network in the Ljubljansko barje were levelled. In that year, a proposal was also made to extend the network in the western part and to complete the eastern part of the Ljubljansko barje (Vodopivec, Kogoj, Goršič, 1985). Between 1987 and 1989, the levelling polygons in the western part of the Ljubljansko barje were also included in the measurement. This was a systematic survey of the entire Ljubljansko barje, which was connected to the fundamental benchmarks FR-5, FR-6 and FR-7 (Vodopivec et al., 1988, Vodopivec et al., 1990).

In 1991, two further fundamental benchmarks, FR-9 and FR-10, were stabilised in the western part of the Ljubljansko barje. It turned out that they had been placed on unstable ground and were sinking. Measurements followed in 1992 and 1994 covered the same levelling network as the 1987 measurement. The levelling network was connected to FR-3, FR-4, FR-6 and FR-7 and adjusted (Vodopivec et al., 1992, 1994).

In 1994, the levelling network improvement was conducted in two parts. The first part included 6 loops in the areas of Dolnice, Šiška, Savlje and Šentvid, and the network was connected to FR-2 and FR-4 (Breznikar, Koler, 1994). The second part included 3 existing loops and one new loop in the Kozarje and Brdo areas, and the network was connected to FR-2 (Hlebec, 2000).

The measurement in 1996 of the network of 6 loops in the Ljubljansko barje was connected to the fundamental benchmarks FR-3, FR-5, FR-6 and FR-7. Additionally, the urban levelling network of Ljubljana was integrated with the urban levelling network of the Municipality of Vrhnika (Vodopivec, Breznikar, Koler, 1997).

The renovation, carried out in the Bežigrad area in 2000, included 82 existing and 40 newly benchmarks (Hlebec, 2000). In 2002, the levelling network in the eastern part of the Ljubljansko barje was surveyed for the last time (Vodopivec et al., 2002, Ježovnik and Jakljič, 2003).

3 PROJECT FOR THE RENOVATION AND FORM OF THE LEVELLING NETWORK OF LJUBLJANA

3.1 Review of Benchmarks in the Field

For the preparation of the renovation of the levelling network of Ljubljana, a review of the benchmarks was carried out in 2021 as part of the project "Preparation of data for the project of the renovation and improvement of the levelling network of the Municipality of Ljubljana in the area of 45 cadastral municipalities". The basis for the verification of benchmarks was the database of state geodetic points managed by GURS, from which 1061 benchmarks marked as usable were taken.

During the on-site verification, it was found that the database of state geodetic points did not fully correspond to the actual situation on the ground. Consequently, new statuses of benchmarks were established (Table 1). The results of the review show that 51% of the benchmarks are usable, 25% are destroyed, 14% are of limited use, and 10% were not found in the field.

Table 1: Status of Benchmarks

Status	Description
Usable	Clearly recognisable and usable as a geodetic reference in geodetic services.
Limited use	Found in the field, but limited use due to insufficient space around it.
Destroyed	No longer usable for geodetic measurements.

The accessibility status of benchmarks was also determined (Table 2).

Table 2: Status Regarding Accessibility

Status	Description
Accessible	The object on which the benchmark is stabilised is freely accessible.
Inaccessible	The object on which the benchmark is stabilised is fenced or guarded, so it is not approachable.

In addition to the existence, accessibility and usability of existing benchmarks, the approximate locations for the installation of new benchmarks were also determined.

3.2 Shape of the levelling network of Ljubljana

In the past, several measurements of levelling polygons of different orders were carried out in the Ljubljana area (Table 3).

Table 3: Statistical indicators of Benchmarks in the levelling network survey of Ljubljana

Order and number of levelling polygon	Number of benchmarks
N1-5, N1-5/7, N1-6/7, N1-7/8, N1-8	41
N1-P26-8	3
N2-P22-1	1
N4-P266	1
NMN-P1 – old benchmarks	441
NMN-P1 – new benchmarks	269
Total	**756**

A total of 877 levelling lines were measured on both sides, with a total length of 707.07 km. Statistical indicators were also collected for the measured levelling lines (Table 4).

Table 4: Statistical indicators for levelling lines in the Ljubljana levelling network

Length of Levelling Line	d [*m*]	From - To
Minimum	7.44	NMN-P1 18/32 - NMN-P1 164
Maximum	2136.59	NMN-P1 39/76 - NMN-P1 39/99
Average	402.66	

Table 4 shows that there is a significant difference between the minimum and maximum length of the levelling line. The minimum lengths of the levelling lines are usually between benchmarks that were stabilised on the same object. In this case, we usually have a high benchmark or a benchmark with a hole and a so-called low benchmark nearby. The maximum length is between the benchmarks stabilised in the Rakova jelša area, as there are no suitable objects for stabilising other benchmarks in this area. The project documentation specified a criterion for determining the density of stabilisation of the new benchmarks. It is envisaged that the distance between benchmarks is 400 metres and about 7 benchmarks/km². Table 4 shows that the average length of the levelling lines corresponds to the criteria defined in the project documentation.

The Ljubljana levelling network consists of 121 levelling loops (Figure 1). When designing the levelling loops, it was ensured that the number of newly benchmarks did not exceed the number specified in the project documentation and that the lengths of the levelling lines did not exceed the planned lengths of the levelling lines. To a certain extent, the configurations of the old loops were also taken into account, but due to the conditions mentioned above and especially the stabilisation of new benchmarks in areas where height data is important for the development of the city, we redefined the levelling loops (Figure 1). The collected statistical indicators of the levelling network (Table 8) show that the differences between the lengths of the levelling loops are significant, which is to be expected for urban levelling networks, as they are shorter in the city centre (Figure 2) and longer on the city's periphery (Figure 1).

Table 5: Statistical indicators for the length of levelling loops in the Ljubljana levelling network

Length of levelling loope	d [*km*]	Levelling loop number
Minimum	0.526	88
Maximum	29.883	1
Average	4.926	

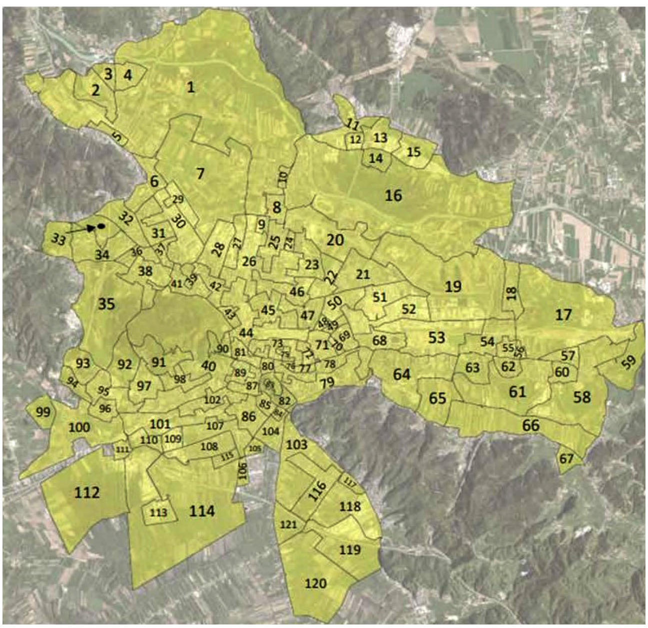

Figure 1: Markings of levelling loops in the Ljubljana levelling network (source: DOF2020)

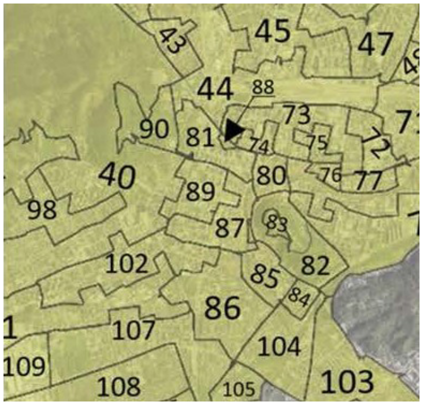

Figure 2: Levelling loops in the city center (source: DOF2020)

4 MEASUREMENT OF THE LJUBLJANA LEVELLING NETWORK

4.1 Division of the measurement area among the project partners

The Ljubljana levelling network was divided into 3 areas, each assigned to a specific partner for project implementation. When designing each area, we took into account the planned total length of the lines, as well as important characteristic features of the terrain and any circumstances that could complicate the measurements. The Ljubljana Municipality covers 275 km², including the historic city center, the Barje area, the Castle Hill, Rožnik, numerous bridgings and railway infrastructure, etc., all of which affect the course of the measurements. The division of the areas extended from the strict centre to the edges of the municipality. We followed the main traffic arteries of the city as far as possible, such as Celovška Street, Dunajska Street, Tržaška Street and Dolenjska Street. The areas were designated A, B and C (Figure 3). We consistently followed the intended designations when assigning line names to ensure an audit trail for project implementation.

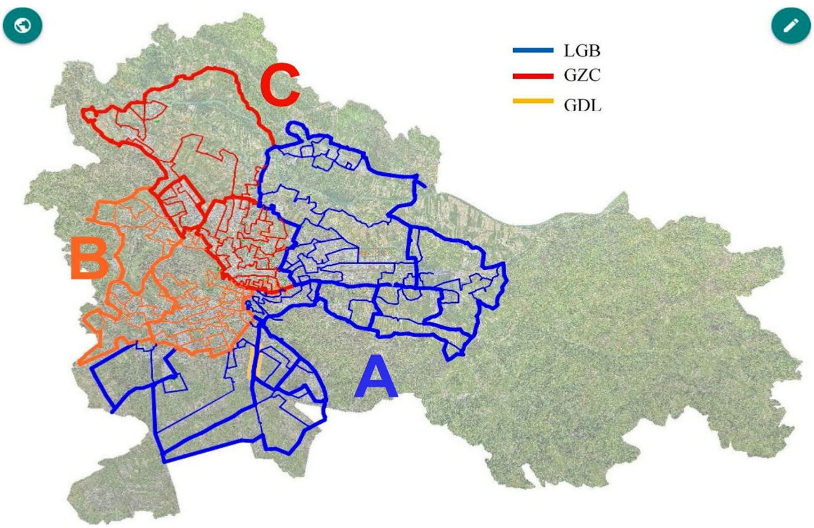

Figure 3: Division of the Ljubljana levelling network into three areas (source: DOF2020 D96).

4. 1 Web application for the organisation of contractor's work

Coordination between the project office and the teams on site is crucial for the successful realisation of the project. To this end, we developed a web application that enables a quick and easy flow of information (Figure 4). All stakeholders were given access to the application, which displays all data related to the measurements and project status on a web map.

Figure 4: Overview of the status of the levelling grid lines in the web application (source: DOF2020).

With the help of the web application, each contractor could organise their work independently without placing an additional burden on the project office. Furthermore, each contractor received feedback on the status of the levelling lines (line ready for measurement, line measured, edited or adjusted) via the web application.

4.2 Instrumentation, additional equipment and execution of the field work

The levelling lines were measured using precise digital levelling instruments (Leica Geosystems LS15, Leica Geosystems DNA03), which, according to the manufacturer, provide a levelling accuracy of up to 0.4 mm/km for double levelling measurements of height differences measured height (ISO 17123-2 standard), calibrated precise levelling rods with attached invar tape with coded graduation and support legs for vertical positioning of the rods. Auxiliary equipment includes tripods, footplates, commonly referred as "frogs" and digital or contact thermometers to measure the temperature of the invar tape. We kept records of the instruments and equipment used with certificates for each piece of equipment.

Before starting the measurements, the instruments were acclimated to the working temperature of the working environment. In accordance with the requirements of ISO 17123-2, we waited 2 minutes for each degree of temperature difference between the storage room and the working environment. We then set up the workstation and configured the device (Table 6).

Table 6: Device settings.

Data	Setting
Length of invar bar-code rod	Normally 3 m, in some cases 2 m.
Reading mode	Double-sided measurements (double levelling) – time-symmetrical readings "back-forward-forward-back" on the "BFFB" instrument ".
Measurement configuration	Setting: "Mean-S" (n min: 3; n max: 6); "sDevM/20m: 0.00010". From 3 to 6 measurements per rod to achieve a standard deviation of the reading at a distance of 20 m of at least 0.0001 m.
Deviation of double readings	Permitted deviation of double readings: 0.00015 m.
Sighting length	Up to 30 m. Deviation of the lengths "front-back" less than 1 m. Deviation of the sums of the lengths "front-back" less than 1 m.
Sighting height	Sighting height at least 0.6 m above the ground, minimum/maximum reading on the invar bar-code rod (0.2 m/2.8 m).

The surveyor leader entered into the instrument the name of the levelling line, the date and time of the measurement, the numbers of the invar bar-code rod, benchmark name of the reference point and the number of the invar bar-code rod used as well as the temperature of the invar tape at the benchmark and the intermediate temperatures in the event of significant changes. The surveyor also kept a levelling log in analogue form.

Daily (before starting the levelling) we conducted a test of the horizontality of the sighting axis of the levelling instrument using the "Förstner" method, which determines the non-horizontality of the sighting axis, which the instrument then takes into account in further measurements. The results of the daily test were entered into a prepared form.

4.3 Permitted deviation of the levelling lines measured on both sides

All levelling lines were measured as double levelling – "there" and "back" - in accordance with the rules for measuring high-precision levelling networks. The permissible deviation for double levelling lines measured on both sides is calculated for the levelling lines of the first-order urban levelling network (GURS, 2020) according to the equation:

$$\Delta_{per}^{line} = 4 \cdot \sqrt{d + 0,04 \cdot d^2} \tag{1}$$

where:

Δ_{per}^{line} ... the permissible deviation of the double measured height difference in mm,

d ... the average length of the levelling line in km.

If the deviation of the double measured height difference was greater than the permissible deviation, the levelling line was remeasured.

5 PRELIMINARY PROCESSING OF THE MEASUREMENTS

5.1 Checking the raw measurements

The field teams exported the measurements daily and uploaded them to the agreed website. The measurement control programme developed by the lead partner checked all raw measurements daily and sent a report on the suitability of the measurements and any errors to the project office (Table 7).

Table 7: Types of errors found when checking the raw data with the programme

Errors in the raw data of the levelling measurement	
Errors when reading the file	Insufficient number of Benchmarks (only 2 expected)
Incorrectly entered attributes (date, time, temperature, etc.)	Insufficient entry of the initial or final invar bar-code rod according to the number of levelling device levels
Exceeding the maximum length at a single stand	Exceeding the difference of double readings on the invar bar-code rod (back or forward)
Exceeding the sum of the length differences of the rear and front measuring rod on the levelling line	

The project office checked the report daily and corrected logical errors where possible. If the errors could not be corrected, the measurements were rejected and the levelling line was sent back for re-measurement. If the measurements were confirmed, the project office marked the levelling line as accepted, which was also shown graphically in the web application. In this way, the contractors received feedback that the measurements had been successfully checked.

5.2 Processing raw data

We used calibrated invar bar-code rods and measured the temperature of the invar tape during the measurement. Based on the calibration data of the invar bar-code rods and the measured temperature, we calculate the correction of the metre of the invar bar-code rod, the temperature correction and the foot correction of the rod according to the equation:

$$L = l_0 + L' \cdot \{1 + [m_0 + \alpha \cdot (T - T_0)]\} \cdot 10^{-6} \qquad (2)$$

where:

L ... corrected reading on the invar bar-code rod,

L' ... reading on the invar bar-code rod,

m_0 ... correction of the division of the invar bar-code rod,

T ... temperature of the invar bar-code rod at the time of measurement,

T_0 ... temperature of the invar bar-code rod at the time of calibration,

α ... temperature expansion coefficient of the graduation.

All accepted measurements were processed daily using a specially adapted programme for processing and adjusting the levelling network. The outcome of the daily check was processed measurements and adjustment of the levelling network. In this way, we were able to continuously check the network and recognise possible gross errors.

5.3 Calculation of Deviations in Closing Levelling Loops

Based on the corrected measured height differences, we calculate the average value of the corrected height differences, which we connect to form closed levelling loops that form the Ljubljana levelling network (Figure 1). The sum of the corrected average values of the measured height differences in the loop of the urban levelling network (Δ_{loop}) must be zero or less than the permissible deviation (GURS, 2020), which we calculate according to the equation:

$$\Delta_{perm}^{loop} = 2 \cdot \sqrt{d + 0,04 \cdot d^2} \quad (3)$$

where:

Δ_{perm}^{loop} ... permitted deviation when closing the levelling loop in mm,

d ... average length of the levelling loop in km.

Table 8 contains a statistical evaluation of the closure of levelling loops.

Table 8: Statistical evaluation of the closure of levelling loops

	Loop number	**d** [*km*]	Δ_{loop} [*mm*]	Δ_{perm}^{loop} [*mm*]
Minimum	112	8,11	– 6,55	± 6,56
Maximum	121	3,88	0,00	± 4,23

41 benchmarks were included in the levelling measurement, the heights of which were determined as part of the new first-order levelling network of Slovenia (Koler et al., 2019, Medved et al., 2020). In order to determine stable benchmarks of the first-order levelling network, which should be used for the connection of the urban first-order levelling network, we carried out the adjustment of the Ljubljana levelling network in several steps.

6 ADJUSTMENT OF THE LEVELLING NETWORK OF LJUBLJANA AND ACCURACY ASSESMENT

6.1 Adjustment of the levelling network connected to benchmark N1-8 FR1014

We first adjusted the levelling network with a connection to the fundamental benchmark of the state levelling network N1-8 FR1014, which is stabilised in Črnuče (Figure 5). The measured height differences were adjusted using the computer programme VimWin ver. 5.1, which was developed at UL FGG (Ambrožič, 2016).

Figure 5: Fundamental Benchmark N1-8 FR1014

By adjusting the levelling network with a connection to benchmark N1-8 FR1014, we obtained data on the reference standard deviation (σ_0) and the accuracy of determining the normal heights of benchmarks (σ_H), which were included in the measurement of the levelling network (Table 9).

Table 9: Accuracy assessment of the adjustment of the levelling network connected to benchmark N1-8 FR1014

Accuracy assessment		
	σ_H [mm]	Benchmark
Minimum	1,68	NMN-P1 R1
Maximum	0,17	N1-8 OP-194
Average	1,12	
	$\hat{\sigma}_0$ [mm]	
A posteriori	0,65	

From Table 9 we can see that the measurement of Ljubljana's levelling network was carried out with quality and, depending on the measurement method used, within the expected accuracy.

6.2 Height displacements and stability analysis of 1st order benchmarks

Height displacements are calculated from the height differences of benchmarks between the new and the old measurement of the levelling network according to the following equation:

$$\Delta H_i = H_i^{Lj} - H_i^{1st.} \tag{4}$$

where:

ΔH_i ... height displacements of the benchmark "i" in *mm*,

H_i^{Lj} ... height of the benchmark "i" determined in the levelling network of Ljubljana,

$H_i^{1st.}$ ... height of benchmark "i" determined in the new 1st order levelling network in Slovenia.

The accuracy estimate of the height displacement of the benchmark is calculated according to the equation (Table 10):

$$\sigma_{\Delta H_i} = \sqrt{\sigma^2_{H_i^{Lj}} + \sigma^2_{H_i^{1st.}}} \tag{5}$$

where are:

$\sigma_{\Delta H_i}$ ... accuracy estimate of the difference in heights of benchmarks "i",

$\sigma_{H_i^{Lj}}$ ... accuracy estimation of the height of benchmark "i" when measuring the levelling network of Ljubljana,

$\sigma_{H_i^{1st.}}$ . . . accuracy estimate of the height of benchmark "i" when measuring the1st order levelling network in Slovenia.

We consider benchmarks to be stable if (Savšek-Safić et al., 2008):

$$\Delta H_i \leq 3 \cdot \sigma_{\Delta H_i} \tag{6}$$

The criterion in equation 6 actually represents the limit value that characterises the change in height of the benchmark as a statistically significant height displacement. It is a statistical test in which we test the null hypothesis that there has been no height displacement. In this case, the test statistic is the ratio between the height change and the corresponding accuracy ($T = {}^{\Delta H}/_{\sigma_{\Delta H}}$), which is normally distributed according to the linear relationship with the compared heights in Equation 4 and is compared with the critical value at the selected risk level α. If the value of the test statistic T exceeds the calculated critical value, we reject the null hypothesis and can use the selected risk level to claim that there was a height displacement or that this displacement is statistically significant. With the usually selected risk level $\alpha = 1\%$, the critical value is 2.57. In our case, we have set this limit to 3, which means that if we reject the null hypothesis and thus claim that there was a height displacement, we are taking a risk of significantly less than 1% (Marjetič et al., 2012).

Table 10: Stability analysis of the 1st order Benchmarks of the Slovenian levelling network

Benchmark	1st. order		Levelling network of Ljubljana		ΔH_i [mm]	$\sigma_{\Delta H_i}$ [mm]	Stab.
	$H_i^{1st.}$ [m]	$\sigma_{H_i^{1st.}}$ [mm]	H_i^{Lj} [m]	$\sigma_{H_i^{Lj}}$ [mm]			
N1-8 PNI-210	294.69940	4.07	294.69817	0.45	-1.23	1.21	Yes
N1-8 OP-194	295.88645	4.07	295.87741	0.17	-9.04	1.13	No
N1-8 N1023	296.18189	4.07	296.17225	0.62	-9.64	1.28	No
N1-5 5999	315.43630	4.28	315.43164	1.35	-4.66	1.75	No
N1-5 43/11	323.73377	4.25	323.73126	1.36	-2.51	1.76	Yes
N1-5 1/19	317.28803	4.21	317.28551	1.46	-2.52	1.84	Yes
N1-5 C-35	313.98864	4.16	313.98555	1.13	-3.09	1.59	Yes
N1-5 1/8	312.68790	4.16	312.68558	1.13	-2.32	1.59	Yes
N1-5 2/15	310.28735	4.14	310.28521	1.19	-2.14	1.63	Yes
N1-5 2/12	309.48558	4.13	309.48272	1.19	-2.86	1.63	Yes
N1-5 138	309.19923	4.11	309.19734	1.18	-1.89	1.63	Yes
N1-5 3/21	302.85994	4.07	302.85758	0.74	-2.36	1.34	Yes
N1-5/6 104	295.02365	4.16	295.01259	1.16	-11.06	1.61	No
N1-5/6 MN-105	295.55738	4.18	295.55295	1.15	-4.43	1.61	No
N1-5/6 106	297.06646	4.20	297.06000	1.19	-6.46	1.63	No
N1-5/6 MN-113	298.12023	4.27	298.11091	1.40	-9.32	1.79	No
N1-V CP-412	302.16544	4.07	302.16218	0.71	-3.26	1.33	Yes
N1-5/7 24/25	302.99522	4.08	302.99171	0.81	-3.51	1.38	No
N1-5/7 24/24	303.13530	4.08	303.09317	0.82	-42.13	1.39	No
N1-5/7 5913	303.23945	4.10	303.23664	0.98	-2.81	1.49	Yes
N1-5/7 MN-148	301.81391	4.11	301.81072	1.05	-3.19	1.54	Yes
N1-5/7 MN-147	300.85548	4.12	300.85312	1.11	-2.36	1.58	Yes
N1-5/7 MN-146	297.91962	4.13	297.91835	1.07	-1.27	1.55	Yes
N1-5/7 19/4	298.87444	4.14	298.86879	1.12	-5.65	1.58	No
N1-6/7 18 28	297.66913	4.15	297.66136	1.13	-7.77	1.59	No
N1-6/7 5741	294.11018	4.15	294.09695	1.10	-13.23	1.57	No

Benchmark	1st. order		Levelling network of Ljubljana		ΔH_i	$\sigma_{\Delta H_i}$	Stab.
	$H_i^{1st.}$ [m]	$\sigma_{H_i^{1st.}}$ [mm]	H_i^{Lj} [m]	$\sigma_{H_i^{Lj}}$ [mm]	[mm]	[mm]	
N1-6/7 205	294.73023	4.16	294.71795	1.08	-12.28	1.56	No
N1-6/7 162	297.77466	4.17	297.76887	1.08	-5.79	1.56	No
N1-6/7 5837	296.61650	4.20	296.61292	1.33	-3.58	1.74	Yes
N1-6/7 41/11	295.22079	4.21	295.21557	1.38	-5.22	1.78	No
N1-7/8 HE1	294.28323	4.08	294.28103	0.90	-2.20	1.44	Yes
N1-7/8 MN-5997	276.81805	4.13	276.81496	1.09	-3.09	1.56	Yes
N1-7/8 MN-180	290.70075	4.11	290.69709	1.10	-3.66	1.57	Yes
N1-7/8 MN-5982	287.98517	4.12	287.98535	1.11	0.18	1.58	Yes
N1-7/8 MN-190	278.25499	4.13	278.25031	1.14	-4.68	1.60	No
N1-7/8 MN-6000	274.47191	4.14	274.46592	1.28	-5.99	1.70	No
N1-7/8 MN-33/2	273.94045	4.15	273.93072	1.31	-9.73	1.72	No
N1-7/8 HE1b	268.61868	4.15	268.60802	1.30	-10.66	1.72	No
N1-5 HM-220	320.54263	4.22	320.53966	1.45	-2.97	1.83	Yes
N1-GOLOV N1322	364.22090	/	364.21101	1.24	-9.89	1.67	No

Table 10 shows that the accuracy estimates in determining the heights of benchmarks in the first-order levelling network is about 4 mm, which is an excellent result for levelling networks in Slovenia. The estimated accuracy in determining the height difference in this case is more than 4 mm, which means that all benchmarks are stable. except for benchmark N1-5/7 24/24, where the height difference is -42.13 mm. In Table 10 we also see that the height differences of the benchmarks range from -13.23 mm for benchmark N1-6/7 5741, with the exception of benchmark N1-5/7 24/24, to 0.18 mm for benchmark N1-7/8 MN-5982. It is therefore clear that estimating the accuracy in determining the heights of the benchmarks in the national network in a smaller area is not suitable for assessing the stability of the benchmarks. If in the equation for the accuracy estimation of height differences we replace the accuracy in the first-order network with the average accuracy of determining the heights of benchmarks with a connection to the benchmark N1-8 FR1014 (Table 9), we obtain a more suitable accuracy estimation of differences for assessing the stability of benchmarks, since all benchmarks are assessed as stable if their height displacement is less than -3.66 mm (benchmark N1-7/8 MN-180).

6.3 Adjustment of the levelling network of Ljubljana with connection to stable benchmarks of the 1st order levelling network of Slovenia and accuracy assessment

When adjusting the levelling network with a connection to stable benchmarks of the first-order levelling network in Slovenia, we determined the heights of benchmarks in the SVS2010 height system (datum Koper), the official height system of Slovenia (UL RS, 2018). The heights of benchmarks are determined in the system of normal heights (Koler et al., 2019, Medved et al., 2020).

6.3.1 Accuracy analysis

The quality of the levelling measurement can be assessed using various criteria. For the levelled height differences in the Ljubljana levelling network, we performed following accuracy assessments:

a) Based on the deviations of the height differences measured on both sides of the levelling lines

In precise levelling, we always measure the height differences of the levelling lines in both directions. In the levelling network of Ljubljana, 877 levelling lines were measured. Based on the deviations that we obtain when measuring the height differences in both directions, we estimate the accuracy of the levelling according to the equation:

$$\sigma_{line} = \sqrt{\frac{1}{4 \cdot n_{line}} \cdot \left[\frac{\Delta^2_{line}}{d}\right]} \tag{7}$$

where are:

σ_{line} ... standard deviation based on the deviations of the levelling lines measured on both directions,
n_{line} ... number of levelling lines,
Δ_{line} ... deviation of the measured height difference of the individual levelling line in mm,
d ... length of the individual levelling line in km.

b) Based on the deviations when closing the levelling loops

Based on the deviations when closing levelling loops, we estimate the accuracy of the levelling using the equation:

$$\sigma_{loop} = \sqrt{\frac{1}{2 \cdot n_{loop}} \cdot \left[\frac{\Delta^2_{loop}}{d}\right]} \tag{8}$$

where are:

σ_{loop} ... standard deviations for deviations when closing levelling loops in *mm*,
n_{loop} ... number of levelling loop (121),
Δ_{loop} ... deviations when closing levelling loops in *mm*,
d ... length of the levelling loop in *km*.

c) Assessment of accuracy based on the corrections of the measured height differences after adjustment

The reference standard deviation of the measured height differences after adjustment is calculated using the following equation:

$$\hat{\sigma}_0 = \sqrt{\frac{[pvv]}{r}} \tag{9}$$

where are:

$\hat{\sigma}_0$ ... reference standard deviation after adjustment,
r ... number of redundant observations,
p ... weight,
v ... correction of the measured height difference after adjustment.

Table 11 contains the results of the accuracy assessments for the measurement of the levelling network.

Table 11: Accuracy assessments for the measurement of the levelling network of Ljubljana.

Standard deviation	**[*mm*]**
σ_{line}	0.45
σ_{loop}	0.51
$\hat{\sigma}_0$	0.75

By adjusting the levelling network, we also obtained data on the accuracy of the determination of the normal heights of the benchmarks, which are summarised in Table 12.

Table 12: The accuracy of determining the normal heights of benchmarks.

Accuracy of normal height	σ_H	**Benchmark**
Minimum	1.49 mm	NMN-P1 38/20
Maximum	0.07 mm	NMN-P1 1/25
Average	0.76 mm	

From the accuracy analysis, we can conclude that the measurements were carried out with high quality, as the calculated accuracies of the measurements and the accuracy assessments of the determination of the normal heights are within the expected limits, considering the equipment used and the accuracy of the levelling device specified by the manufacturer (Table 12). Furthermore, the field teams did an excellent job as they followed all instructions for performing high-precision levelling measurements.

7 CONCLUSIONS

As part of the renovation of the levelling network of Ljubljana, an analysis and review of the initial state was first carried out, based on which the project for the “new” (modernised) levelling network was developed. The levelling network consists of 121 levelling loops, 756 benchmarks and the total length of all levelling lines is 353.53 km. All levelling lines were measured on both directions, so that a total of 707.06 km of levelling lines were measured. The measurements of the levelling polygons were conducted in accordance with the conditions for the 1st order urban levelling network as defined in the Technical Instructions for the Use of the New National Height System (version 1.0, dated 20 February 2020).

With this project, the levelling network of Ljubljana was measured and adjusted as a whole for the first time since 1984. The heights (normal height system) of the benchmarks in the levelling network were determined by connecting to 21 benchmarks whose heights were determined in the new 1st order levelling network in Slovenia. The heights of the benchmarks are determined in the official height system SVS2010 datum Koper.

The measurements were conducted with precise digital levels compared to invar bar-code rods, and within a period of less than a year, which reduces the effects of errors that could arise due to possible height shifts of the benchmarks during the measurement. Prior to adjustment, the measured height differences between the benchmarks were corrected for the temperature correction of the bar-code rod, the metre pair of invar bar-code rods and the difference in the base of the rods. This reduced the effects of systematic errors that influence all measurements. All differences in the bilaterally measured height differences and deviations in the closing of levelling loops are within the permissible deviations for the 1st order urban levelling network.

The adjustment was carried out using the indirect method, in which the sum of the squares of the corrections of the measured values (height differences) is minimised. The accuracy assessment based on the deviations of the height differences measured on both directions was 0.45 mm and based on the deviations when closing levelling loops 0.51 mm. The reference standard deviation based on the corrections of the measured height differences after adjustment was 0.75 mm/km, and the accuracy of the height determination ranged from 0.07 mm to 1.49 mm. The average accuracy of height determination was 0.76 mm. Based on the working method, the equipment used and the order of the levelling network, we can conclude that the levelling network of Ljubljana is of adequate quality.

With the renovation and modernisation of the levelling network, the Municipality of Ljubljana has obtained a high-quality, homogeneous height network in a unified national coordinate system, which will be of crucial importance for the design, construction and maintenance of structures that are connected to other structures and require heigh accuracy in determining their height. It will provide a common basis for the planning of interventions in space and the recording of changes in space. The geodetic reference points of the levelling network – benchmarks installed on stable structures with an average distance between benchmarks of 403 m or 7 benchmarks/km^2, taking into account the areas of urban expansion.

The restored and improved levelling network is also a significant asset for public utility service providers, who are obliged to record public utility infrastructure data in the Joint Cadastre of Public Utility Infrastructure. For the utility infrastructure managed by JP VOKA SNAGA d.o.o. and ENERGETIKA LJUBLJANA, d.o.o., in addition to the accuracy of the horizontal coordinates, the height accuracy of the data is also essential. It should be noted that high-quality data on the heights of GJI structures can only be obtained by connecting to benchmarks with precise height data. The benchmarks of upgraded levelling network of Ljubljana make this possible, and it is up to us to use them conscientiously and professionally in our work.

Acknowledgment

This article was prepared as part of a public tender: "Renovation and Upgrade of the Levelling Network of Ljubljana", financed by the Municipality of Ljubljana. The authors would like to thank the Municipality of Ljubljana for addressing the need to renovate the city's levelling network. The result is a high quality, homogeneous height network in a unified national coordinate system, which will be crucial for the planning, construction and maintenance of structures for the further development of Ljubljana. We would also like to thank all those involved in the successful implementation of the extensive levelling network of Ljubljana renovation project.

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SANACIJA NIVELMANSKE MREŽE MESTNE OBČINE LJUBLJANA

OSNOVNE INFORMACIJE O ČLANKU:

GLEJ STRAN 327

1 UVOD

Mestna občina Ljubljana (MOL) potrebuje za prostorsko načrtovanje, umeščanje objektov v prostor, projektiranje, gradnjo, evidentiranje in vzdrževanje objektov enotno kakovostno geodetsko osnovo. Pri projektiranju, gradnji in vzdrževanju objektov, ki se navezujejo na druge objekte, se velikokrat zahteva milimetrska točnost določitev njihove višine. V Republiki Sloveniji se po določilih Zakona o državnem geodetskem referenčnem sistemu (UL RS, 2014) in Uredbe o določitvi parametrov višinskega dela vertikalne sestavine državnega prostorskega koordinatnega sistema (UL RS, 2018) uporablja novi Slovenski višinski sistem 2010 (SVS2010, datum Koper), ki je nadomestil stari Slovenski višinski sistem 2000 (SVS2000, datum Trst, Koler at al., 2019, Medved at al., 2020).

Zaradi intenzivnejše urbanizacije in staranja komunalne infrastrukture so se v zadnjih letih povečale investicije v gradnjo in obnovo mestne komunalne in druge infrastrukture. Za gradnjo komunalne infrastrukture je izredno pomembno, da imamo vzpostavljeno dobro višinsko mrežo. Mestna nivelmanska mreža Ljubljane je zaradi uničenja, posedanja in preračuna višin reperjev postala pomanjkljiva, nezanesljiva in zaradi izmer v različnih časovnih obdobij tudi nehomogena. Vse to povzroča težave pri pripravi projektov, gradnji in evidentiranju nepremičnin.

Posledice problematike mestne nivelmanske mreže so se začele kazati na projektih MOL, saj so se večkrat pojavila neskladja pri gradbenih delih in evidentiranju infrastrukture. Težava se je skozi leta le še krepila, saj je bilo vedno več problematičnih reperjev. Za njeno rešitev je MOL konec leta 2021 v okviru javnega naročila razpisal projekt sanacije in nadgradnje nivelmanske mreže mestne občine Ljubljana. Projekt je izvajal konzorcij treh podjetij: LGB d. o. o. kot vodilnega partnerja ter Geodetske družbe d. o. o. in Geodetskega zavoda Celje d. o. o. kot partnerjev. Kot pogodbeni podizvajalci so sodelovali Univerza v Ljubljani, Fakulteta za gradbeništvo in geodezijo, Katedra za geodezijo, GEOFOTO d. o. o., Geograd d. o. o., LUZ d. d. in Aleš Breznikar s. p. Skupno je v projektu sodelovalo več kot dvajset geodetskih strokovnjakov, od tega devet pooblaščenih inženirjev geodezije. S podpornim kadrom je bilo v projektu udeleženih več kot trideset oseb (LGB, 2023).

2 IZMERE NIVELMANSKE MREŽE NA OBMOČJU LJUBLJANE V OBDOBJU OD 1895 DO 2002

Mestna nivelmanska mreža Ljubljane je bila prvič nivelirana v letih 1895 in 1896, vanjo je bilo vključenih 263 reperjev. Izmera celotnega območja Ljubljane je bila izvedena med letoma 1940 in 1941. V nivelmansko mrežo 1. reda je bilo vključenih 70 reperjev. Sestavljena je bila iz sedmih zank in štirih slepih poligonov. Natančnost celotne mreže je bila slaba, saj zaradi vojnih blokad ni bilo mogoče izvesti kakovostnih meritev. V letu 1941 je bila nivelmanska mreža prvič razvita po Ljubljanskem barju, a je bila kmalu uničena. Leta 1949 je bila stabilizirana in izmerjena nivelmanska mreža po obrobju in preko Ljubljanskega barja. Večina reperjev je bila kasneje uničena (Koler, 1989; Hlebec, 2000).

Sledila je izmera med letoma 1962 in 1963, ki je zajemala celotno območje Ljubljane in njenega predmestja. Zaradi nestabilnih tal vanjo ni bil vključen barjanski del. V nivelmansko mrežo 1. reda je bilo vključenih 493 reperjev, sestavljena je bila iz 38 zank in 101 nivelmanskega poligona. Med letoma 1964 in 1965 se je območje Ljubljane začelo širiti. Zato so mestni nivelmanski mreži dodali šest zank in en slepi poligon na obeh straneh Save in severnem delu Barja. Vzpostavljeni so bili tri fundamentalni reperji, ki so pomenili višinsko izhodišče in osnovo za kontrolo posedanja. Leta 1970 so dodali 24 reperjev na območju Medvod. Tako se je mreža povečala za eno nivelmansko zanko, sestavljeno iz petih nivelmanskih poligonov (Hlebec, 2000).

Sledile so sistematične izmere za potrebe določitve vertikalnih pomikov reperjev na območju Ljubljane in Ljubljanskega barja. Prvi izmeri sta bili izvedeni v obdobju med letoma 1971 in 1976. Stabilizirani so bili novi reperji v novih nivelmanskih zankah, ki so segale tudi na območje barja. Vzpostavili so 47 zaključenih zank in dva slepa poligona. Nivelmanska mreža je bila navezana na štiri obstoječe fundamentalne reperje (FR-1- FR-4). Kasneje so bili stabilizirani še štiri fundamentalni reperji na območju barja (FR-5, FR-6, FR-7 in FR-8). Izmera novih fundamentalnih reperjev je potekala leta 1974 (Vodopivec, 1976).

Leta 1984 so bili nivelirani vsi nivelmanski poligoni mestne nivelmanske mreže 1. reda na območju Ljubljanskega barja. V tem letu je bil izdelan tudi predlog za širitev mreže na zahodnem delu in dopolnitev vzhodnega dela Ljubljanskega barja (Vodopivec, Kogoj, Goršič, 1985). V obdobju med letoma 1987 in 1989 so bili v izmero vključeni tudi nivelmanski poligoni na zahodnem delu barja. Govorimo o sistematični izmeri celotnega Ljubljanskega barja, ki se je navezovala na fundamentalne reperje FR-5, FR-6 in FR-7 (Vodopivec et al., 1988; Vodopivec et al., 1990).

Leta 1991 sta bila na zahodnem delu barja stabilizirana dodatna dva fundamentalna reperja FR-9 in FR – 10. Izkazalo se je, da sta bila postavljena na nestabilnih tleh in sta se posedla. Sledili sta izmeri leta 1992 in 1994, ki sta zajeli enako nivelmansko mrežo kot izmera leta 1987. Nivelmanska mreža je bila navezana in izravnana na FR 3, FR-4, FR-6 in FR-7 (Vodopivec et al., 1992, 1994).

V letu 1994 je bila izvedena tudi sanacija nivelmanske mreže v dveh delih. Prvo območje je obsegalo šest zank na območju Dolnic, Šiške, Savelj in Šentvida, mreža pa je bila navezana na FR-2 in FR-4 (Breznikar, Koler, 1994). Drugo območje je obsegalo tri obstoječe zanke in eno novo na območju Kozarij in Brda, mreža pa je bila navezana na FR-2 (Hlebec, 2000).

Leta 1996 je sledila izmera mreže šestih zank na območju Ljubljanskega barja, ki je bila navezana na fundamentalne reperje FR-3, FR-5, FR-6 in FR-7. Mestni nivelmanski mreži Ljubljana se je priključil mestni nivelman občine Vrhnika (Vodopivec, Breznikar, Koler, 1997).

Sanacija, ki je bila izvedena leta 2000 na območju Bežigrada, je vključevala 82 obstoječih in 40 novo stabiliziranih reperjev (Hlebec, 2000). Leta 2002 je bila zadnjič izmerjena nivelmanska mreža na območju vzhodnega dela Ljubljanskega barja (Vodopivec et al., 2002; Ježovnik in Jakljič, 2003).

3 PROJEKT SANACIJE IN OBLIKA NIVELMANSKE MREŽE MOL

3.1 Pregled reperjev na terenu

Za potrebe priprave projekta sanacije nivelmanske mreže MOL je bil v letu 2021 izveden pregled reperjev v okviru projekta Priprava podatkov za projekt sanacije in nadgradnje nivelmanske mreže mestne občine Ljubljana na območju 45 katastrskih občin. Podlaga za pregled reperjev je bila zbirka podatkov državnih geodetskih točk, ki jo vodi GURS in iz katere je bilo prevzetih 1061 reperjev z oznako uporabni.

S terenskim pregledom je bilo ugotovljeno, da zbirka podatkov državnih geodetskih točk ni povsem skladna z dejanskim stanjem na terenu. Na podlagi tega so bili določeni novi statusi reperjev (preglednica 1). Rezultati pregleda so pokazali, da je 51 % reperjev uporabnih, 25 % reperjev je uničenih, 14 % omejeno uporabnih, 10 % jih na terenu ni bilo odkritih.

Preglednica 1: Statusi reperjev

Status	Opis
Uporaben	Na terenu je jasno razpoznaven in uporaben kot geodetsko izhodišče pri izvajanju geodetskih storitev.
Omejena uporaba	Na terenu je odkrit, vendar je njegova uporaba na terenu omejena, saj je nad njim ali ob njem premalo prostora za izvedbo kakovostnih geodetskih meritev.
Uničen	Reper, ki ni več uporaben za izvedbo geodetskih meritev.
Neodkrit	Na terenu ni bil najden.

Določen je bil tudi status glede na dostopnost reperjev (preglednica 2).

Preglednica 2: Status reperjev glede na njihovo dostopnost

Status	Opis
Dostopen	Objekt, na katerem je reper stabiliziran, je prosto dostopen.
Nedostopen	Objekt, na katerem je reper stabiliziran, je ograjen ali varovan, zato do njega ni mogoče prosto dostopati.

Poleg obstoja, dostopnosti in uporabnosti obstoječih reperjev so bile določene okvirne lokacije za vgradnjo novih reperjev.

3.2 Oblika nivelmanske mreže MOL

Na območju MOL je bilo v preteklosti izvedenih več izmer nivelmanskih poligonov različnih redov (preglednica 3).

Preglednica 3: Statistični kazalci o reperjih, vključenih v izmero nivelmanske mreže MOL

Red in številka nivelmanskega poligona	Število reperjev
N1-5, N1-5/7, N1-6/7, N1-7/8, N1-8	41
N1-P26-8	3

Red in številka nivelmanskega poligona	Število reperjev
N2-P22-1	1
N4-P266	1
NMN-P1 – stari reperji	441
NMN-P1 – novi reperji	269
Skupaj	**756**

Obojestransko je bilo izmerjenih 877 nivelmanskih linij v skupni dolžini 707,07 kilometra. Zbrali smo tudi statistične kazalce o izmerjenih nivelmanskih linijah (preglednica 4).

Preglednica 4: Statistični kazalci za nivelmanske linije v nivelmanski mreži MOL

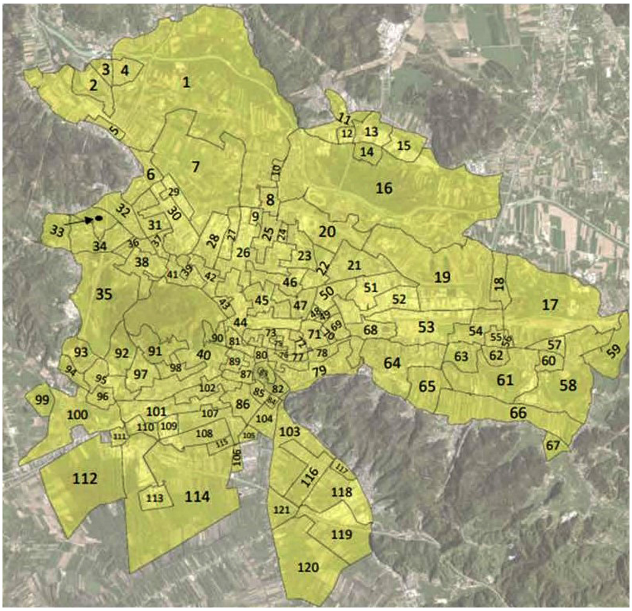
Dolžina nivelmanske linije	d [*m*]	Od–do
Minimalna	7,44	NMN-P1 18/32–NMN-P1 164
Maksimalna	2136,59	NMN-P1 39/76–NMN-P1 39/99
Povprečna	402,66	

Iz preglednice 4 vidimo, da je velika razlika med minimalno in maksimalno dolžino nivelmanske linije. Minimalne dolžine nivelmanskih linij so običajno med reperji, ki so stabilizirani na istem objektu. V tem primeru imamo običajno stabiliziran visoki reper oziroma reper z luknjico in v njegovi bližini še tako imenovani nizki reper. Maksimalna dolžina je med reperjema, ki sta stabilizirana na območju Rakove jelše, saj na tem območju ni ustreznih objektov, ki bi omogočali stabilizacijo dodatnih reperjev. V projektni dokumentaciji je bil določen kriterij za določitev gostote stabilizacije novih reperjev. Tako je predvideno, da je razdalja med reperji okoli 400 m in okoli 7 reperjev/km2. Iz preglednice 4 vidimo, da povprečna dolžina nivelmanskih linij ustreza kriteriju, ki je bil določen v projektni dokumentaciji.

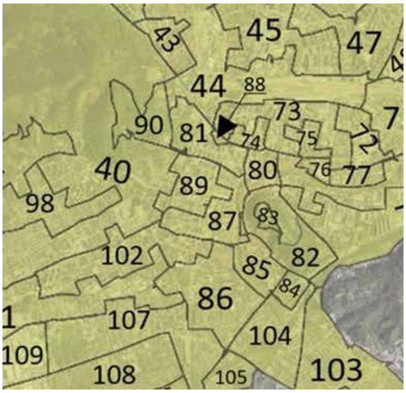
Nivelmanska mreža MOL je sestavljena iz 121 nivelmanskih zank (slika 1). Pri oblikovanju nivelmanskih zank je bilo upoštevano, da število novo stabiliziranih reperjev ni presegalo števila, ki je bilo določeno s projektno dokumentacijo, in da dolžine nivelmanskih linij niso presegale predvidene dolžine izmer nivelmanskih linij. Deloma so bile upoštevane tudi oblike starih zank, vendar smo zaradi zgoraj naštetih pogojev in predvsem stabilizacije novih reperjev na območjih, kjer so podatki o višinah pomembni za razvoj mesta, nivelmanske zanke na novo označili (slika 1). Zbrani statistični kazalci nivelmanske mreže MOL (preglednica 8) kažejo, da so razlike med dolžinami nivelmanskih zank velike, kar je pričakovano za mestne nivelmanske mreže, saj so v mestnem središču krajše (slika 2) in na obrobju mesta daljše (slika 1).

Preglednica 5: Statistični kazalci o dolžinah nivelmanskih zank nivelmanske mreže MOL

Dolžina nivelmanske zanke	d [*km*]	Številka zanke
Minimalna	0,526	88
Maksimalna	29,883	1
Povprečna	4,926	



Slika 1: Oznake nivelmanskih zank v nivelmanski mreži MOL (vir podlage: DOF2020).

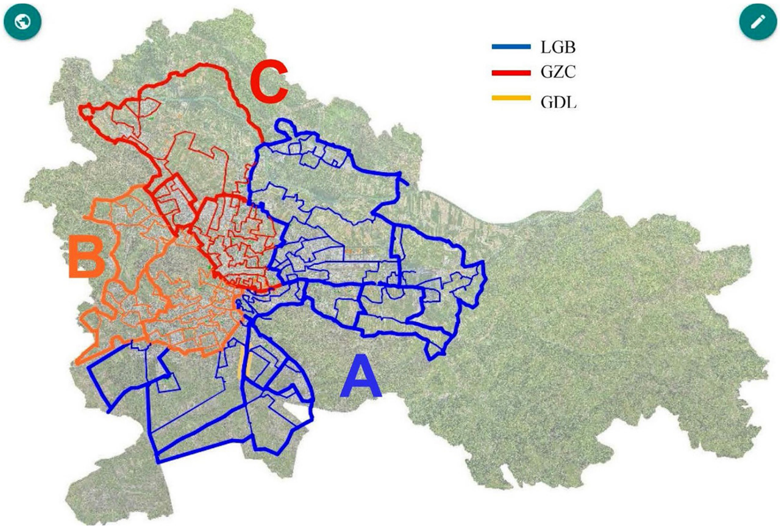


Slika 2: Nivelmanske zanke v mestnem središču (vir podlage: DOF2020).

4 IZMERA NIVELMANSKE MREŽE MOL

4.1 Razdelitev območja izmere med partnerji na projektu

Nivelmansko mrežo MOL smo razdelili na tri območja, za vsakega posameznega partnerja pri izvedbi projekta. Pri oblikovanju območij smo poleg skupne predvidene dolžine linij upoštevali ključne značilnosti terena in morebitne okoliščine, ki bi lahko oteževale izvedbo meritev. Mestna občina Ljubljana namreč na svojih 275 km2 površine združuje strogi staromestni center, območje Barja, Grajski grič, Rožnik, številne premostitvene objekte, železniško infrastrukturo ipd., ki vplivajo na potek meritev. Delitev med območji je potekala od strogega centra do robov občine. Pri tem smo skušali čim bolj slediti glavnim mestnim vpadnicam, kot so Celovška cesta, Dunajska cesta, Tržaška cesta in Dolenjska cesta. Območja smo poimenovali s črkami A, B in C (slika 3). Predvidene oznake smo dosledno upoštevali pri dodeljevanju imen linij in s tem zagotovili revizijsko sled pri izvedbi projekta.



Slika 3: Razdelitev nivelmanske mreže MOL na tri območja (vir podlage: DOF2020 D96).

4.2 Spletna aplikacija za organizacijo dela izvajalcev

Usklajevanje med projektno pisarno in terenskimi ekipami je izrednega pomena za uspešno izvedbo projekta. V ta namen smo razvili spletno aplikacijo, ki omogoča hiter in preprost pretok informacij (slika 4). Vsem deležnikom smo omogočili dostop do aplikacije, kjer se na spletni karti prikazujejo vsi podatki v zvezi z izvedbo meritev in stanjem projekta.

Slika 4: Pregled statusov linij nivelmanske mreže MOL v spletni aplikaciji (vir podlage: DOF2020).

S spletno aplikacijo si je lahko vsak izvajalec organiziral delo po svoje in pri tem ni dodatno obremenjeval projektne pisarne. Prav tako je vsak izvajalec preko spletne aplikacije dobil povratno informacijo glede statusa nivelmanskih linij (linija pripravljena na merjenje, linija izmerjena, obdelana ali izravnana).

4.3 Instrumentarij, dodatni pribor in izvedba terenskega dela

Izmero nivelmanskih linij smo izvedli s preciznimi digitalnimi nivelirji (Leica Geosystems LS15, Leica Geosystems DNA03), ki po podatkih proizvajalca zagotavljajo natančnost niveliranja do 0,4 mm/km obojestransko merjenih višinskih razlik (standard ISO 17123-2), komparirano precizno nivelmansko lato z vpetim invar trakom s kodno razdelbo in podporno nogo za vertikalno postavljanje nivelmanskih lat. Med pomožni pribor lahko štejemo stative, kovinske podložke, imenovane tudi »žabe«, in digitalne oziroma kontaktne termometre za merjenje temperature invar traku. Vodili smo evidenco uporabljenega instrumentarija in pribora, ki temelji na certifikatih za posamezno opremo.

Pred začetkom izmere smo instrumente prilagodili temperaturi delovnega okolja. Glede na zahteve po standardu ISO 17123-2 smo za vsako stopinjo razlike v temperaturi med prostorom, v katerem je bil instrument shranjen, in temperaturo delovnega okolja, počakali dve minuti. Sledila je nastavitev delovišča in konfiguracija instrumenta (preglednica 6).

Preglednica 6: Nastavitve instrumenta

Podatek	Nastavitev
Dolžina nivelmanske late	Običajno 3 m, v nekaj primerih 2 m.
Način čitanja	Obojestranske meritve (dvojni nivelman) – časovno simetrični odčitki »zadaj-spredaj-spredaj-zadaj« na instrumentu »BFFB«).
Konfiguracija meritev	Nastavitev: »Mean-S« (n min: 3; n max: 6); »sDevM/20m: 0,00010«. Od 3 do 6 meritev na posamezni lati, da je dosežena standardna deviacija odčitka na razdalji 20 m vsaj 0,0001 m.
Odstopanja dvojnih odčitkov	Dovoljeno odstopanje dvojnih odčitkov: 0,00015 m.
Dolžina vizure	Do 30 m. Razlika dolžin »spredaj–zadaj« manjša od 1 m. Razlika vsot dolžin »spredaj–zadaj« manjša od 1 m.
Višina vizure	Višina vizure vsaj 0,6 m nad tlemi, najmanjši/največji odčitek na nivelmanski lati (0,2 m/2,8 m).

Vodja izmere je v instrument vpisal še ime nivelmanske linije, datum in čas izmere, številke nivelmanskih lat, ime reperja in številko uporabljene nivelmanske late ter temperaturo invar traku nivelmanske late na reperju in vmesno temperaturo ob večjih spremembah. Vodja izmere je vodil nivelmanski zapisnik tudi v analogni obliki.

Vsakodnevno smo (pred začetkom niveliranja) opravili preizkus horizontalnosti vizurne osi nivelirja po Förstnerjevi metodi, s katero določamo nehorizontalnost vizurne osi, ki jo instrument nato upošteva pri nadaljnjih meritvah. Rezultate dnevnega preizkusa smo vnašali v pripravljen obrazec.

4.4 Dovoljena odstopanja obojestransko merjenih nivelmanskih linij

Vse nivelmanske linije smo nivelirali obojestransko – »tja« in »nazaj« po pravilih za izmero nivelmanskih mrež visoke natančnosti. Dovoljeno odstopanje za obojestransko merjene nivelmanske linije je izračunano za nivelmanske linije mestne nivelmanske mreže 1. reda (GURS, 2020) po enačbi:

$$\Delta_{dov}^{lin} = 4 \cdot \sqrt{d + 0,04 \cdot d^2} \quad (1)$$

kjer je:

Δ_{dov}^{lin} ... dovoljeno odstopanje obojestransko merjene višinske razlike v mm,

d ... povprečna dolžina nivelmanske linije v km.

Če je bilo odstopanje obojestransko merjene višinske razlike večje od dovoljenega, je bila nivelmanska linija ponovno izmerjena.

5 PREDHODNA OBDELAVA MERITEV

5.1 Kontrola surovih meritev

Terenske ekipe so vsakodnevno izvozile meritve in jih naložile na dogovorjeno spletno mesto. Program za kontrolo meritev, ki ga je izdelal vodilni partner, je vsakodnevno preveril vse surove meritve in projektni pisarni poslal poročilo o ustreznosti meritev in morebitnih napakah (preglednica 7).

Preglednica 7: Vrsta napake, ugotovljena pri kontroli surovih podatkov s programom

Napaka v surovih podatkih nivelmanske izmere	
Napaka v branju datoteke	Neustrezno število reperjev (pričakovana le 2)
Napačno vpisani atributi (datum, čas, temperatura …)	Neustrezen vpis začetne oziroma končne nivelmanske late glede na število stojišč nivelirja
Prekoračitev maksimalne dolžine na posameznem stojišču	Prekoračitev razlike dvojnih odčitkov na nivelmanski lati (zadaj oziroma spredaj)
Prekoračitev seštevka razlik dolžin late zadaj in late spredaj na nivelmanski liniji	

Projektna pisarna je poročilo vsakodnevno pregledala in, če je bilo mogoče, odpravila logične napake. Če napak ni bilo mogoče popraviti, je meritve zavrnila in nivelmansko linijo vrnila v ponovno merjenje. Če je bila meritev potrjena, je projektna pisarna nivelmansko linijo označila kot sprejeto, kar je bilo grafično prikazano tudi v spletni aplikaciji. Tako so izvajalci dobili povratno informacijo, da so bile meritve uspešno pregledane.

5.2 Obdelava surovih meritev

Pri izmeri smo uporabljali komparirane invar nivelmanske late in merili temperaturo invar traku med izmero. Na podlagi podatkov o kalibraciji nivelmanskih lat in merjeni temperaturi izračunamo popravek metra nivelmanske late, temperaturni popravek in popravek pete late po enačbi:

$$L = l_0 + L' \cdot \{1 + [m_0 + \alpha \cdot (T - T_0)]\} \cdot 10^{-6} \quad (2)$$

kjer so:

L ... popravljen odčitek na nivelmanski lati,

L' ... odčitek na nivelmanski lati,

m_0 ... popravek razdelbe nivelmanske late,

T ... temperatura nivelmanske late v času izmere,

T_0 ... temperatura nivelmanske late v času kalibracije,

α ... temperaturni razteznostni koeficient razdelbe.

Vse sprejete meritve so bile vsakodnevno obdelane s posebej prilagojenim programom za obdelavo in izravnavo nivelmanske mreže. Rezultat vsakodnevnega pregleda so bile obdelane meritve in izravnava nivelmanske mreže. Tako smo lahko sproti kontrolirali mrežo in odkrivali morebitne grobe pogreške.

5.3 Izračun odstopanj pri zapiranju nivelmanskih zank

Na podlagi popravljenih merjenih višinskih razlik izračunamo povprečno vrednost popravljenih višinskih razlik in jih povežemo v zaključene nivelmanske zanke, ki tvorijo nivelmansko mrežo MOL (slika 1). Vsota popravljenih povprečnih vrednosti merjenih višinskih razlik v zanki mestne nivelmanske mreže (Δ_{zan}) mora biti enaka nič oziroma manjša od dovoljenega odstopanja (GURS, 2020), ki ga izračunamo po enačbi:

$$\Delta_{dov}^{zan} = 2 \cdot \sqrt{d + 0{,}04 \cdot d^2} \quad (3)$$

kjer je:

Δ_{dov}^{zan} ... dovoljeno odstopanje pri zapiranju nivelmanske zanke v mm,

d ... povprečna dolžina nivelmanske zanke v km.

V preglednici 8 so zbrane statistične cenilke o zapiranju nivelmanskih zank.

Preglednica 8: Statistične cenilke zapiranja nivelmanskih zank

	Številka zanke	d [km]	Δ_{zan} [mm]	Δ_{dov}^{zan} [mm]
Minimalna	112	8,11	–6,55	± 6,56
Maksimalna	121	3,88	0,00	± 4,23

6 IZRAVNAVA NIVELMANSKE MREŽE MOL IN ANALIZA NATANČNOSTI

V nivelmansko izmero je bilo vključenih 41 reperjev, katerih višine so bile določene v okviru izmere nove nivelmanske mreže 1. reda Slovenije (Koler et al., 2019; Medved et al., 2020). Da bi določili stabilne reperje nivelmanske mreže 1. reda, ki bi jih uporabili za navezavo mestne nivelmanske mreže 1. reda, smo izravnavo nivelmanske mreže MOL izvedli v več korakih.

6.1 Izravnava nivelmanske mreže z navezavo na reper N1-8 FR1014

Nivelmansko mrežo smo najprej izravnali z navezavo na fundamentalni reper državne nivelmanske mreže N1 8 FR1014, ki je stabiliziran v Črnučah (slika 5). Merjene višinske razlike smo izravnali z računalniškim programom VimWin ver. 5.1, ki so ga izdelali na UL FGG (Ambrožič, 2016).

Slika 5: Fundamentalni reper N1-8 FR1014.

Z izravnavo nivelmanske mreže MOL z navezavo na reper N1-8 FR1014 smo dobili podatke o referenčnem standardnem odklonu ($\hat{\sigma}_0$) in o natančnosti določitve normalnih višin reperjev (σ_H), ki so bili zajeti v izmero nivelmanske mreže MOL (preglednica 9).

Preglednica 9: Ocene natančnosti izravnave nivelmanske mreže MOL z navezavo na fundamentalni reper N1 8 FR1014

	Ocene natančnosti	
	σ_H [mm]	Reper
Minimalna	1,68	NMN-P1 R1
Maksimalna	0,17	N1-8 OP-194
Povprečna	1,12	
	$\hat{\sigma}_0$ [mm]	
Po izravnavi	0,65	

Iz preglednice 9 vidimo, da je bila izmera nivelmanske mreže MOL izvedena kakovostno in glede na uporabljeno metodo izmere v okviru pričakovane natančnosti.

6.2 Višinski pomiki in analiza stabilnosti reperjev 1. reda

Višinske pomike izračunamo iz razlik višin reperjev med novo in staro izmero nivelmanske mreže po enačbi:

$$\Delta H_i = H_i^{MOL} - H_i^{1.\ \mathrm{red}} \tag{4}$$

kjer so:

ΔH_i ... razlika nadmorskih višin reperja »i« v mm,

H_i^{MOL} ... nadmorska višina reperja »i«, določena v nivelmanski mreži MOL,

$H_i^{1.\ red}$ ... nadmorska višina reperja »i«, določena v novi nivelmanski mreži 1. reda Slovenije.

Oceno natančnosti višinskega pomika reperja izračunamo po enačbi (preglednica 10):

$$\sigma_{\Delta H_i} = \sqrt{\sigma^2_{H_i^{MOL}} + \sigma^2_{H_i^{1.red}}} \quad (5)$$

kjer so:

$\sigma_{\Delta H_i}$ ... ocena natančnosti razlike nadmorskih višin reperjev »i«,

$\sigma^2_{H_i^{MOL}}$ ... ocena natančnosti nadmorske višine reperja »i« v izmeri nivelmanske mreže MOL,

$\sigma^2_{H_i^{1.red}}$ ... ocena natančnosti nadmorske višine reperja »i« v izmeri nivelmanske mreže 1. reda Slovenije.

Reperje ocenimo za stabilne, če je (Savšek-Safić et al., 2008):

$$\Delta H_i \leq 3 \cdot \sigma_{\Delta H_i} \quad (6)$$

Kriterij v enačbi 6 dejansko predstavlja mejo, ki višinsko spremembo reperja označi kot statistično značilen višinski pomik. Gre za statistično testiranje, kjer preizkušamo ničelno domnevo o tem, da ni prišlo do višinskega pomika. Pri tem kot testno statistiko obravnavamo razmerje višinske spremembe in pripadajoče natančnosti ($T = \Delta H / \sigma_{\Delta H}$), ki se glede na linearno zvezo s primerjanima višinama v enačbi 4 porazdeljuje po normalni porazdelitvi in jo ob izbrani stopnji tveganja α primerjamo s kritično vrednostjo. Če vrednost testne statistike T preseže izračunano kritično vrednost, potem ničelno hipotezo zavrnemo in lahko ob izbrani stopnji tveganja trdimo, da je prišlo do višinskega pomika oziroma je ta pomik statistično značilen. Ob običajno izbrani stopnji tveganja $\alpha = 1$ %, je kritična vrednost 2,57. V našem primeru smo to mejo postavili na 3, kar pomeni, da v primeru zavrnitve ničelne hipoteze in s tem trditve, da je prišlo do višinskega pomika, tvegamo bistveno manj kot 1 % (Marjetič et al., 2012).

Preglednica 10: Analiza stabilnosti reperjev nivelmanske mreže 1. reda Slovenije

Reper	1. red		MOL		ΔH_i [mm]	$\sigma_{\Delta H_i}$ [mm]	Stab.
	$H_i^{1.\ red}$ [m]	$\sigma_{H_i^{1.\ red}}$ [mm]	H_i^{MOL} [m]	$\sigma_{H_i^{MOL}}$ [mm]			
N1-8 PNI-210	294.69940	4.07	294.69817	0.45	–1.23	1.21	Da
N1-8 OP-194	295.88645	4.07	295.87741	0.17	–9.04	1.13	Ne
N1-8 N1023	296.18189	4.07	296.17225	0.62	–9.64	1.28	Ne
N1-5 5999	315.43630	4.28	315.43164	1.35	–4.66	1.75	Ne
N1-5 43/11	323.73377	4.25	323.73126	1.36	–2.51	1.76	Da
N1-5 1/19	317.28803	4.21	317.28551	1.46	–2.52	1.84	Da
N1-5 C-35	313.98864	4.16	313.98555	1.13	–3.09	1.59	Da
N1-5 1/8	312.68790	4.16	312.68558	1.13	–2.32	1.59	Da
N1-5 2/15	310.28735	4.14	310.28521	1.19	–2.14	1.63	Da
N1-5 2/12	309.48558	4.13	309.48272	1.19	–2.86	1.63	Da
N1-5 138	309.19923	4.11	309.19734	1.18	–1.89	1.63	Da

Reper	1. red $H_i^{1.\ red}$ [m]	$\sigma_{H_i^{1.\ red}}$ [mm]	MOL H_i^{MOL} [m]	$\sigma_{H_i^{MOL}}$ [mm]	ΔH_i [mm]	$\sigma_{\Delta H_i}$ [mm]	Stab.
N1-5 3/21	302.85994	4.07	302.85758	0.74	–2.36	1.34	Da
N1-5/6 104	295.02365	4.16	295.01259	1.16	–11.06	1.61	Ne
N1-5/6 MN-105	295.55738	4.18	295.55295	1.15	–4.43	1.61	Ne
N1-5/6 106	297.06646	4.20	297.06000	1.19	–6.46	1.63	Ne
N1-5/6 MN-113	298.12023	4.27	298.11091	1.40	–9.32	1.79	Ne
N1-V CP-412	302.16544	4.07	302.16218	0.71	–3.26	1.33	Da
N1-5/7 24/25	302.99522	4.08	302.99171	0.81	–3.51	1.38	Ne
N1-5/7 24/24	303.13530	4.08	303.09317	0.82	–42.13	1.39	Ne
N1-5/7 5913	303.23945	4.10	303.23664	0.98	–2.81	1.49	Da
N1-5/7 MN-148	301.81391	4.11	301.81072	1.05	–3.19	1.54	Da
N1-5/7 MN-147	300.85548	4.12	300.85312	1.11	–2.36	1.58	Da
N1-5/7 MN-146	297.91962	4.13	297.91835	1.07	–1.27	1.55	Da
N1-5/7 19/4	298.87444	4.14	298.86879	1.12	–5.65	1.58	Ne
N1-6/7 18 28	297.66913	4.15	297.66136	1.13	–7.77	1.59	Ne
N1-6/7 5741	294.11018	4.15	294.09695	1.10	–13.23	1.57	Ne
N1-6/7 205	294.73023	4.16	294.71795	1.08	–12.28	1.56	Ne
N1-6/7 162	297.77466	4.17	297.76887	1.08	–5.79	1.56	Ne
N1-6/7 5837	296.61650	4.20	296.61292	1.33	–3.58	1.74	Da
N1-6/7 41/11	295.22079	4.21	295.21557	1.38	–5.22	1.78	Ne
N1-7/8 HE1	294.28323	4.08	294.28103	0.90	–2.20	1.44	Da
N1-7/8 MN-5997	276.81805	4.13	276.81496	1.09	–3.09	1.56	Da
N1-7/8 MN-180	290.70075	4.11	290.69709	1.10	–3.66	1.57	Da
N1-7/8 MN-5982	287.98517	4.12	287.98535	1.11	0.18	1.58	Da
N1-7/8 MN-190	278.25499	4.13	278.25031	1.14	–4.68	1.60	Ne
N1-7/8 MN-6000	274.47191	4.14	274.46592	1.28	–5.99	1.70	Ne
N1-7/8 MN-33/2	273.94045	4.15	273.93072	1.31	–9.73	1.72	Ne
N1-7/8 HE1b	268.61868	4.15	268.60802	1.30	–10.66	1.72	Ne
N1-5 HM-220	320.54263	4.22	320.53966	1.45	–2.97	1.83	Da
N1-GOLOV N1322	364.22090	/	364.21101	1.24	–9.89	1.67	Ne

Iz preglednice 10 vidimo, da so ocene natančnosti določitve nadmorskih višin reperjev v nivelmanski mreži 1. reda okoli 4 mm, kar je za državne nivelmanske mreže sicer odličen rezultat. Ocena natančnosti določitve razlike višin v tem primeru znaša več kot 4 mm, kar pomeni, da so vsi reperji stabilni razen reperja N1-5/7 24/24, kjer je razlika višin –42,13 mm. Iz preglednice 10 tudi vidimo, da so razlike višin reperjev od –13,23 mm na reperju N1-6/7 5741, če ne upoštevamo reperja N1-5/7 24/24, do 0,18 mm na reperju N1-7/8 MN-5982, zato je seveda jasno, da na manjšem območju ocena natančnosti določitve višin reperjev v državni mreži ni primerna za oceno stabilnosti reperjev. Če v enačbi za oceno natančnosti razlik nadmorskih višin, natančnost v mreži 1. reda nadomestimo s povprečno natančnostjo določitve višin reperjev z navezavo na reper N1-8 FR1014 (preglednica 9), dobimo primernejšo oceno natančnosti razlik za oceno stabilnosti reperjev, saj so ocenjeni kot stabilni vsi reperji, katerih višinski pomik je manjši od –3,66 mm (reper N1-7/8 MN-180).

6.3 Izravnava nivelmanske mreže MOL z navezavo na stabilne reperje nivelmanske mreže 1. reda Slovenije in analiza natančnosti

Z izravnavo nivelmanske mreže MOL z navezavo na stabilne reperje 1. reda Slovenije smo višine reperjev določili v višinskem sistemu SVS2010 (datum Koper), ki je uradni višinski sistem Slovenije (UL RS, 2018). Višine reperjev so določene v višinskem sistemu normalnih višin (Koler et al., 2019; Medved et al., 2020).

6.3.1 Analiza natančnosti

Kakovost nivelmanske izmere lahko ocenimo na podlagi različnih kriterijev. Za nivelirane višinske razlike v nivelmanski mreži MOL smo izvedli naslednje ocene natančnosti:

a) Na podlagi odstopanj obojestransko merjenih višinskih razlik nivelmanskih linij

Pri preciznem nivelmanu vedno merimo višinske razlike nivelmanskih linij v eno in drugo smer. V nivelmanski mreži MOL je bilo izmerjeno 877 nivelmanskih linij. Na podlagi odstopanj, ki jih dobimo pri merjenju višinskih razlik v obe smeri, ocenimo natančnost niveliranja po enačbi:

$$\sigma_l = \sqrt{\frac{1}{4 \cdot n_l} \cdot \left[\frac{\Delta_l^2}{d}\right]} \tag{7}$$

kjer so:

σ_l ... standardni odklon na podlagi odstopanj obojestransko merjenih nivelmanskih linij,

n_l ... število nivelmanskih linij,

Δ_l ... odstopanje merjene višinske razlike posamezne nivelmanske linije v milimetrih,

d ... dolžina posamezne nivelmanske linije v kilometrih.

b) Na podlagi odstopanj pri zapiranju nivelmanskih zank

Na podlagi odstopanj, ki jih dobimo pri zapiranju nivelmanskih zank, ocenimo natančnost niveliranja po enačbi:

$$\sigma_z = \sqrt{\frac{1}{2 \cdot n_z} \cdot \left[\frac{\Delta_z^2}{d}\right]} \tag{8}$$

kjer so:

σ_z ... standardni odklon na podlagi odstopanj pri zapiranju nivelmanskih zank,

n_z ... število nivelmanskih zank (121),

Δ_z ... odstopanje pri zapiranju nivelmanskih zank,

d ... dolžina posamezne nivelmanske zanke v kilometrih.

c) Ocena natančnosti na podlagi popravkov merjenih višinskih razlik po izravnavi

Referenčni standardni odklon merjenih višinskih razlik po izravnavi izračunamo po naslednji enačbi:

$$\hat{\sigma}_0 = \sqrt{\frac{[pvv]}{r}} \tag{9}$$

kjer so:

$\hat{\sigma}_0$ ... referenčni standardni odklon utežne enote po izravnavi,

r ... število nadštevilnih opazovanj,

p ... utež,

v ... popravek merjene višinske razlike po izravnavi.

V preglednici 11 so zbrani rezultati ocen natančnosti za izmero nivelmanske mreže MOL.

Preglednica 11: Ocene natančnosti izmere nivelmanske mreže MOL

Standardni odklon	[*mm*]
σ_l	0,45
σ_z	0,51
$\hat{\sigma}_0$	0,75

Z izravnavo nivelmanske mreže MOL smo dobili tudi podatke o natančnosti določitve normalnih višin reperjev, ki so zbrane v preglednici 12.

Preglednica 12: Natančnost določitve normalnih višin reperjev nivelmanske mreže MOL

Natančnost normalne višine	σ_H [*mm*]	Reper
Minimalna	1,49	NMN-P1 38/20
Maksimalna	0,07	NMN-P1 1/25
Povprečna	0,76	

Na podlagi analize natančnosti lahko ugotovimo, da so bile meritve opravljene kakovostno, saj so izračunane natančnosti opravljenih izmer in ocene natančnosti določitve normalnih višin v pričakovanih mejah glede na uporabljeni instrumentarij in natančnost nivelirja, ki jo navaja proizvajalec (preglednica 12). Poleg tega so terenske ekipe delo opravile odlično, saj so upoštevale vsa navodila o izvedbi nivelmanske izmere visoke natančnosti.

7 ZAKLJUČEK

V okviru sanacije nivelmanske mreže MOL sta bila najprej opravljena analiza in pregled izhodiščnega stanja, na podlagi česar je bil izdelan projekt »nove« (nadgrajene) nivelmanske mreže MOL. Nivelmansko mrežo MOL sestavlja 121 nivelmanskih zank, 756 reperjev, skupna dolžina vseh nivelmaskih linij znaša 353,53 kilometra. Vse nivelmanske linije so bile merjene obojestransko, tako jih je bilo skupno izmerjenih kar 707,06 kilometra. Meritve nivelmanskih poligonov so bile izvedene v skladu s pogoji, ki veljajo za 1. red mestne nivelmanske mreže, kot je opredeljeno v Tehničnem navodilu za uporabo novega državnega višinskega sistema (različica 1.0, datum 20. 2. 2020).

S tem projektom je bila nivelmanska mreža MOL prvič po letu 1984 izmerjena in izravnana kot celota. Nadmorske višine (sistem normalnih višin) reperjev v nivelmanski mreži MOL so bile določene z navezavo na 21 reperjev, katerih višina je bila določena v okviru izmere nove nivelmanske mreže 1. reda Slovenije. Višine reperjev so določene v uradnem višinskem sistemu SVS2010 datum Koper.

Meritve so bile opravljene s preciznimi digitalnimi nivelirji, kompariranimi invar nivelmanskimi latami in v časovnem obdobju, krajšem od enega leta, s čimer se zmanjša vpliv pogreškov, ki bi utegnili nastati zaradi morebitnih višinskih pomikov reperjev med izmero. Pred izravnavo so bile merjene višinske razlike med reperji popravljene za temperaturni popravek nivelmanske late, metre para nivelmanskih lat in razliko pete lat. S tem je bil zmanjšan vpliv sistematičnih pogreškov, s katerimi so obremenjene vse meritve. Vse razlike obojestransko merjenih višinskih razlik in odstopanja pri zapiranju nivelmanskih zank so znotraj dopustnih odstopanj za mestno nivelmansko mrežo 1. reda.

Izravnava je bila izvedena po posredni metodi, kjer je vsota kvadratov popravkov merjenih količin (višinskih razlik) najmanjša. Ocena natančnosti na podlagi odstopanj obojestransko merjenih višinskih razlik je znašala 0,45 mm in na podlagi odstopanj pri zapiranju nivelmanskih zank 0,51 mm. Referenčni standardni odklon na podlagi popravkov merjenih višinskih razlik po izravnavi je znašal 0,75 mm/km, natančnost določitve nadmorskih višin pa od 0,07 mm do 1,49 mm. Povprečna natančnost določitve nadmorskih višin je znašala 0,76 mm. Glede na metodo dela, uporabljen instrumentarij in red nivelmanske mreže lahko ugotovimo, da je nivelmanska mreža MOL ustrezne kakovosti.

S sanacijo in nadgradnjo nivelmanske mreže je mestna občina Ljubljana dobila kakovostno, homogeno višinsko mrežo v enotnem državnem koordinatnem sistemu, ki bo ključna pri projektiranju, gradnji in vzdrževanju objektov, ki se navezujejo na druge objekte, pri čemer se zahteva milimetrska točnost določitev njihove višine. To bo skupna podlaga za načrtovanje posegov v prostor in evidentiranje sprememb v njem. Izhodiščne geodetske točke nivelmanske mreže – reperji so vgrajeni na stabilnih objektih s povprečno medsebojno razdaljo 403 metra, kar pomeni 7 reperjev/km2, pri čemer so bila s pokritostjo upoštevana tudi območja širitve urbanizacije.

Sanirana in nadgrajena nivelmanska mreža MOL je pomembna pridobitev tudi za izvajalce gospodarskih javnih služb, ki so zavezani, da podatke gospodarske javne infrastrukture evidentirajo v zbirni kataster GJI. Pri komunalni infrastrukturi, s katero upravljata JP VOKA SNAGA d.o.o. in ENERGETIKA LJUBLJANA, d.o.o., je pri evidentiranju GJI poleg natančnosti horizontalnih koordinat bistvena višinska natančnost podatkov. Zavedati se je treba, da lahko kakovostne podatke o višinah objektov GJI dobimo le z navezavo na reperje z natančnimi nadmorskimi višinami. Reperji sanirane in nadgrajene nivelmanske mreže MOL nam to omogočajo, na nas je, da jih pri svojem delu vestno in strokovno uporabljamo.

Zahvala

Članek je nastal kot rezultat javnega naročila Sanacija in nadgradnja nivelmanske mreže MOL, ki ga je financirala mestna občina Ljubljana. Avtorji se zahvaljujemo mestni občini Ljubljana, da je prisluhnila potrebam po sanaciji mestne nivelmanske mreže Ljubljana, s čimer je dobila kakovostno, homogeno višinsko mrežo v enotnem državnem koordinatnem sistemu, ki bo ključna pri projektiranju, gradnji in vzdrževanju objektov za nadaljnji razvoj MOL. Zahvaljujemo se tudi vsem, ki so sodelovali pri kakovostni izvedbi obsežnega projekta, kot je bila sanacija nivelmanske mreže MOL.

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DOI: https://doi.org/10.15292/geodetski-vestnik.2024.02.327-359

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