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ASSESSMENT OF HEIGHT DETERMINATION ACCURACY IN COMPARISON OF MEASUREMENTS FROM THE GLOBAL NAVIGATION SATELLITE SYSTEMS AND HIGH-PRECISION LEVELLING AT GEODYNAMIC TEST SITE

The article compares the height determination results from the satellite measurements and high-precision levelling at the geodynamic test site at the Zhezkazgan deposit in 2021–2023. It is shown that the geometric levelling and satellite navigation systems have different initial height reference surfaces which generally non-coincide and are non-parallel. Nevertheless, the created structure of the satellite and levelling network at the geodynamic test site, as well as the adopted observation procedure enable accurate height determination during geodynamic monitoring.

Keywords: *high-precision levelling, global navigation satellite systems, heights*
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Introduction

Satellite navigation systems are the high-precision tools of positioning of points both in horizontal and vertical planes [1]. It is important that height levelling uses vertical lines and helps calculating normal heights relative to the quasi-geoid, while satellite systems determine geodetic altitudes along the normal to the ellipsoid. The quasi-geoid, as against the ellipsoid, has an undulated shape and is a non-regular mathematical model, which leads to incongruence and parallel disalignment of these surfaces and produces different altitude systems [2]. In geodesy and geodynamics, heights play a key role as they show changes of terrains due to both natural and induced processes; different height systems are used for these purposes [3].

In Kazakhstan and in other countries where mineral mining is an important economic sector [4, 5], precision of height determination using different technologies, such as the Global Navigation Satellite Systems (GNSS) and levelling, is a relevant objective. Accuracy of height measurements is critical in monitoring of terrain variations, especially under strong manmade impact intrinsic to mining regions [6].

Since each of the methods has its specifics, such as labor intensity of levelling or dependence of GNSS on geometry of satellites and atmospheric conditions, it is important to compare accuracy and reliability of these technologies [7]. This is necessary for their efficient application in geomonitoring and infrastructure safety improvement.

Foreign research demonstrates a high interest to enhancing precision and reliability of height determination for the geodetic and geodynamic purposes.

Chinese research is worth attention as it focuses on the development and testing of a new gravimetric level measurement method using GNSS. This method allows high-precision determination of normal height difference and can represent an alternative to the traditional high-precision levelling by offering a more efficient and accurate method of monitoring height variations in different natural conditions [8].

Russian scientists investigated complex terrain height measurement using GNSS and geometric levelling as a case-study of Lebanon. In addition, the precision of the global geoid model EGM2008 was tested under those conditions, and the need of corrections toward higher accuracy of height measurements was checked [9].

In the framework of the present research, the geodynamic test site at the Zhezkazgan deposit is discussed.

For the Zhezkazgan deposit, the challenge connected with the height determination accuracy consists in creation of a local geoid model to improve height measurement precision, especially under conditions of the irregular terrain and strong manmade impact. For another thing, when there is no need to overwatch a huge number of benchmarks, it is possible to use GNSS, especially in monitoring of local sites.

The main goal of the research was to determine heights using GNSS and levelling, and to assess the height determination accuracy of these methods.

For reaching the goal, some objectives were set, namely:

1. Collection of data on height marks using modern geodetic technologies;
2. Accuracy and consistency assessment of GNSS and levelling data;
3. Determination of height differences;
4. Building of time series to analyze variations in height marks over a certain period of time.

Materials and methods

GNSS observations. The field work on satellite determination of coordinates of deformation points at the geodynamic test site at the Zhezkazgan deposit lasted from June 2021 to May 2023.

The static mode observations involved sessions not shorter than 5 h at a point, with a write period of 15 s and elevation mask of 10°, and used GPS receivers Leica Geosystems. The measurements were taken at 24 points, and one point belonged to the State Geodetic Network [10].

Orynbassarova, Akhmetov et al. reported GNSS data processing using two methods [11]. The first method with multi session post-processing in Giodis used remote points of IGS (International GNSS Service), which resulted in the root mean square errors (RMSE) in a range of a few centimeters, insufficient for revealing deformations.

Table 1 gives the final results of post-processing of multiple sessions between 14 and 17 of June, 2021.

The second method with the background station ZHEZ situated in Zhezkazgan provided stable static observations. The obtained RMSE ranged within millimeters, which met requirements of high-precision geodetic surveying.

Table 2 offers the processing results of the second method in the multi-site module of Giodis.

From graphic comparison, the first method yields RMSE of 0.06–0.08 m and the second method—the uniform values of 0.0038–0.0049 m for all points, which proves its efficiency for revealing deformation processes (**Fig. 1**).

Then, GNSS data were processing using program GAMIT/GLOBK (version 10.71), allowing network solution relative to the points of IGS to

Table 1. Heights H of benchmarks on geodynamic test site in multi session post-processing in Giodis

Point	H, m	RMSE, m
RP14_178	347.9801	0.0651
RP07_177	352.7594	0.0670
RP14_175	350.4167	0.0651
RP27_84	348.7131	0.0651
RP40_65bis	362.3393	0.0777
RP05_67	363.8516	0.0808
RP09_66	367.5358	0.0781
RP02_100	357.0425	0.0235
RP36_30bis	359.1758	0.0244
RP19_100	363.1907	0.0245
RP05_212	385.3141	0.0594
RP04_110	360.3716	0.0873
RP09_112	374.8623	0.0591
RP13_18	374.2460	0.0592
RP04_76	360.3716	0.0873
RP59_23	369.2009	0.0883
RP54_21	371.3633	0.0872
RP15_23	369.1710	0.0871
RP99_127	355.7892	0.0654
RP77_127	358.3046	0.0653
RP68_128	358.2526	0.0653
SAYI	372.5577	0.0675

Table 2. Heights H of benchmarks on geodynamic test site from multi-site module of Giodis

Point	N, m	RMSE, m
RP14_178	348.0063	0.0036
RP07_177	352.7861	0.0036
RP14_175	350.5539	0.0036
RP27_84	348.8506	0.0036
RP40_65bis	362.3564	0.0043
RP05_67	363.8681	0.0043
RP09_66	367.6655	0.0043
RP02_100	357.0670	0.0042
RP36_30bis	359.3220	0.0042
RP19_100	363.3380	0.0042
RP05_212	385.6223	2.5210
RP04_110	387.8600	0.4826
RP09_112	375.0982	0.4816
RP13_18	374.4935	3.4154
RP04_76	360.3777	0.0035
RP59_23	369.2083	0.0035
RP54_21	371.4814	0.0035
RP15_23	369.2887	0.0035
RP99_127	355.8451	0.0038
RP77_127	358.4715	0.0038
RP68_128	358.4197	0.0038
SAYI	372.6172	0.0049

avoid dependence on stability of mineral deposit sites [12]. The processing used the European Terrestrial Reference System and 16 stations of IGS.

Numerous static data generated by GAMIT make it possible to assess quality of positioning. RMSE is an indicator of uncertainties of the preliminary solution. Usually, high-quality data have a root mean deviation of 4 mm [13]. In most events, RMSE slightly exceed 5 mm, which is reflective of multipathing higher than average. The values from 10 mm to 15 mm point at the high but yet admissible noise. In our case, RMSE was 7 mm.

In the accuracy assessment using the weighted least squares, χ^2 is a measure of the weighted root mean square error (WRMS) and for the noncorrelated data is determined as a sum of squares of residual values in each observation divided by a preset error. The value χ^2 in the context of GNSS measurements means the normalized root mean deviation and is used as an indicator of quality of the model fitting to data. By the degrees of freedom df ($NRMS = \chi^2/df$, NRMS—Normalized Root Mean Square), an ideal value is 1.0. The standard deviation σ is equal to the uncertainty multiplied by the square root of χ^2/df.

Then, the quantitative estimation embraced the daily scatter of WRMS and NRMS of the baseline relative to their linear trend per sessions (**Table 3**). The values of NRMS for the permanent local stations vary between 0.9 and 4.4. NRMS less than 1.0 suggests a small redundancy or the reduced weight of data, which allows more realistic estimates of rates. The values higher than 1.0 are reflective of very small standard deviations or non-compensated errors in coordinates [13]. The values of WRMS are expectedly higher for the vertical coordinate as compared with the horizontal coordinate, and range from 4.2 mm to 9.4 mm.

The accuracy of the GNSS data from the background station ZHEZ located in Zhezkazgan was also estimated (**Table 4**). The calculations show that RMSE in each monitoring cycle exceeds the allowable value ±3 mm for the horizontal component and ±5 mm for the vertical component, which is sufficient for obtaining high-precision results to meet the standards of the geodynamic test sites and for the high-precision operations.

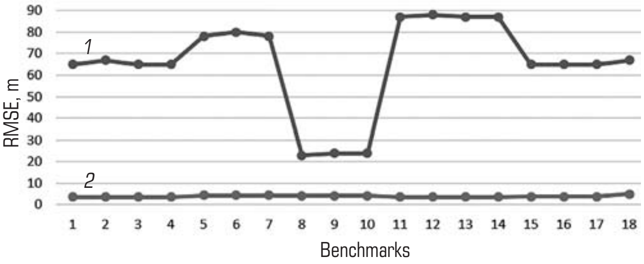

Fig. 1. Comparison of RMSE of heights H per benchmarks:
1 – multi session processing with remote points of IGS (International GNSS Service);
2 – multi-site method using background station ZHEZ

These results prove that the 5 h-long sessions and the applied methods of data processing provide the required geodynamic monitoring accuracy and ensure a reliable ground for the deformation observation (**Table 5**).

Levelling. Levelling class I and II at geodynamic and manmade test sites is the part of a package of geophysical surveys meant for production of quality characteristics of the earth's surface deformations [14].

High-precision levelling at the moment is carried out in 126 profile line. Altogether, there were 146 profile lines 42 km in total length. High-precision levelling used DNA03 digital levels. Levelling was performed from the terrestrial triangulation point Sai [10].

This research used only profile lines with the available values of the GNSS measurements.

Table 3. Accuracy assessment of GNSS measurements per sessions

Session	WRMS, mm			NRMS, mm		
	Longitude E	Latitude N	Height H	Longitude E	Latitude N	Height H
Series 0 (cycle 1), 14–17 June 2021						
1	2.9	2.3	6.1	1.6	1.2	1.0
2	4.5	3.2	8.5	2.3	1.6	1.3
3	3.4	2.7	7.6	1.7	1.2	1.1
4	3.7	2.9	6.1	2.1	1.6	1.1
5	2.4	3.3	7.1	1.2	1.6	1.1
6	5.0	3.3	9.4	2.6	1.6	1.4
Series 1 (cycle 2), 4–7 October 2021						
1	5.1	4.5	6.0	3.6	2.8	1.3
2	4.0	3.9	8.0	2.6	2.3	1.7
3	4.8	4.1	4.5	3.2	2.5	0.9
4	6.7	5.5	7.1	4.4	3.3	1.5
5	4.6	3.5	4.3	3.2	2.2	0.9
6	4.0	4.5	5.7	2.6	2.5	1.1
Series 2 (cycle 3), 3–6 May 2022						
1	4.1	3.2	4.2	2.6	2.0	0.9
2	6.0	4.3	7.6	3.6	2.5	1.4
3	4.1	2.8	4.8	2.8	1.8	1.1
4	3.6	3.9	8.3	2.3	2.3	1.7
5	4.5	3.6	8.2	2.7	2.3	1.6
6	5.9	4.8	8.4	3.5	3.0	1.7
7	4.7	3.6	8.0	2.8	2.3	1.6
8	5.7	2.7	7.7	3.0	1.7	1.4

Table 4. Accuracy assessment of GNSS measurements using background station ZHEZ per measurement series

Session	H, m	RMSE, m
Zero series, June 2021		
1	352.710	±0.003
2	352.710	
3	352.714	
4	352.707	
5	352.715	
6	352.708	
First series, October 2021		
1	352.702	±0.005
2	352.709	
3	352.698	
4	352.704	
5	352.700	
6	352.696	

According to the Levelling Guide of the Republic of Kazakhstan dated March 16, 2023, No. 94/HK, for each levelling class, the limit random and repeated root mean square errors, and the allowable errors of closure were determined on the test sites [15]. These data are compiled in **Table 6**.

From the accomplished measurements and calculations, the values of the random and repeated RMSE were obtained for the test site and for individual profile line (PL) (**Table 7**). The comparison of the calculated

Table 5. Subsidence of benchmarks by GNSS measurements in 2021–2023, m

SITE	Jun 2021	Oct 2021	May 2022	Sep 2022	May 2023	Oct–Jun 2021	May 22–Jun 21	Sep 22–Oct 21	May 23–Jun 21	May 23–May 22
RP02_GPS	357.022	356.876	357.009	356.815	356.538	–0.146	–0.013	–0.061	–0.484	–0.471
RP04_GPS	360.379	360.361	360.381	360.351	360.378	–0.018	0.002	–0.010	–0.001	–0.002
RP05_GPS	385.366	385.362	385.191	385.371	385.381	–0.004	–0.175	0.009	0.015	0.190
RP07_GPS	351.672	351.475	351.600	351.415	351.481	–0.197	–0.072	–0.060	–0.191	–0.119
RP09_GPS	375.032	374.986	375.015	375.001	–	–0.046	–0.017	0.014	–	–
RP13_GPS	374.404	374.393	374.420	374.403	–	–0.012	0.015	0.010	–	–
RP14_GPS	350.553	350.541	350.517	350.517	–	–0.012	–0.036	–0.024	–	–
RP15_GPS	369.289	369.263	369.263	367.279	–	–0.026	–0.025	–1.984	–	–
RP19_GPS	363.334	363.353	363.335	363.313	363.298	0.018	0.001	–0.040	–0.036	–0.037
RP26_GPS	361.995	361.983	361.902	361.968	361.961	–0.012	–0.093	–0.014	–0.035	0.058
RP27_GPS	348.834	348.827	348.838	348.831	348.837	–0.008	0.003	0.004	0.003	0.000
RP36_GPS	359.329	359.286	359.290	–	–	–0.043	–0.039	–	–	–
RP40_GPS	362.359	362.359	362.341	362.337	362.308	0.000	–0.018	–0.022	–0.051	–0.033
RP54_GPS	371.482	371.332	371.354	371.329	371.336	–0.150	–0.128	–0.004	–0.147	–0.018
RP59_GPS	369.207	369.013	369.142	368.927	369.010	–0.194	–0.065	–0.086	–0.198	–0.132
RP68_GPS	358.406	358.439	358.427	358.422	–	0.033	0.021	–0.017	–	–
RP77_GPS	358.465	358.432	358.449	358.438	358.434	–0.032	–0.015	0.005	–0.030	–0.015
RP99_GPS	355.841	355.224	355.766	355.596	355.671	–0.617	–0.074	0.372	–0.170	–0.096
RR04_GPS	387.797	387.590	387.733	387.543	387.608	–0.207	–0.064	–0.046	–0.188	–0.124
RR05_GPS	363.880	363.675	363.608	363.518	363.515	–0.206	–0.273	–0.157	–0.365	–0.093
RR09_GPS	367.651	367.656	367.659	367.656	–	0.005	0.008	0.000	–	–
RR14_GPS	348.003	347.990	347.992	347.994	348.001	–0.013	–0.011	0.004	–0.001	0.010
RR19_GPS	366.787	367.017	367.029	367.028	367.019	0.229	0.242	0.011	0.232	–0.010
SAIY_GPS	372.614	372.611	372.639	372.616	372.625	–0.003	0.024	0.004	0.011	–0.014

Table 6. Random and repeated root mean square errors of levelling

Levelling class	Limit RMSE		Allowable closure errors on test sites and in lines f, mm
	Random η, mm/km	Repeated σ, mm/km	
I	0.8	0.08	3 mm $\sqrt{L}$ *
II	2.0	0.20	5 mm $\sqrt{L}$
III	5.0	–	10 mm $\sqrt{L}$
IV	10.0	–	20 mm $\sqrt{L}$

**L* — perimeter of test site or length of line, km

Table 7. Actual random and repeated root mean square errors of levelling

No.	RMSE		
	Random η, mm/km	Repeated σ, mm/km	Allowable closure errors on test sites and in lines f, mm
Test sites	15.49	1.55	13.2
PL 18	0.5	0.05	2.39
PL 112	1.23	0.12	3.72
PL 212	1.16	0.016	1.32
PL 100	0.30	0.030	1.86
PL 30bis	0.65	0.065	2.7
PL 128	3.04	0.30	5.85
PL 127	1.68	0.17	4.35
PL 76	3.01	0.30	5.82
PL 84	1.69	0.17	4.35

data with the standard values in Table 6 estimates the conformity of the measurements and the regulatory documents.

The test site perimeter $L = 19.369$ km.

The actual random and repeated RMSE are never higher than the allowable values, which confirms the conformity of the measurements to the regulatory standards.

For the further accuracy assessment of height determination, the subsidence values of benchmarks are given in **Table 8**.

Results

This section reports the main levelling results and GNSS measurements. The verification and joint interpretation of the data are performed.

Let us analyze Rp 40 in profile line 65bis. In **Fig. 2*a*** there are the GNSS measurements at Rp 40 in the mode of 5 hour statics (June 2021–May 2023), in Fig. 2b there are the high-precision levelling results (June 2020–June 2022). At this benchmark, a pending subsidence trend is observed, with insignificant fluctuations, and there is a good agreement of the data of the two observation techniques. According to the levelling in 2022, there is a subsidence of 20 cm, and the GNSS measurements show the same yearly mean rate.

A similar situation is observed at benchmark Rp 05 in Line 67, where the both methods show progressive subsidence, and this fact is confirmed by a good agreement of the levelling results and GNSS data (**Fig. 3**).

It is important that Rp 40 and Rp 05 are set far from each other, and their subsidence may have a common cause connected with the presence of underground voids which induce gradual ground failure and development of deformations of ground surface [16].

The observation data agreement was checked up using another benchmark. At benchmark Rp 77 of profile line 127 over the period of 2021–2022, subsidence of 2 mm was given by the both methods of observation (**Fig. 4**).

The curves of the levelling results and GNSS measurements at benchmark Rp 27 Line 84 reveal a slight elevation trend of ground in 2021–2022, which is most likely connected with such seasonal factors as freezing–thawing (**Fig. 5**).

Table 8. Height marks of benchmarks per years, m

SITE	05. 2021	06.2021	09.2021	06.2022	05.2022	06.2022–06.2021	05.2022–05.2021	06.2022–05.2021	06.2022–09.2021
RP02_	–	416.4165	–	–	416.4179	–	1.4	–	–
RP04_	–	447.0323	–	447.0325	–	0.2	–	–	–
RP05_	–	423.1876	–	423.1603	–	–27.3	–	–	–
RP07_	410.9623	–	–	–	410.9607	–	–1.6	–	–
RP09_	–	426.9768	–	426.9716	–	–5.2	–	–	–
RP14_	409.8115	–	–	–	409.8121	–	0.6	–	–
RP15_	428.5762	–	–	428.5651	–	–11.1	–	–	–
RP19_	422.6708	–	–	422.6696	–	–	–	–1.2	–
RP36_	418.6338	–	–	418.6313	–	–	–	–2.5	–
RP40_	–	421.6872	–	421.6671	–	–20.1	–	–	–
RP59_	428.4862	–	428.485	428.4845	–	–	–	–	–0.5
RP77_	417.7678	–	–	417.7671	–	–	–	–0.7	–
RP99_	411.8052	–	–	411.8027	–	–	–	–2.5	–
RR04_	–	419.6797	–	419.6786	–	–1.1	–	–	–
RR05_	–	444.6003	–	444.5999	–	–	–0.4	–	
RR09_	–	434.2437	–	434.2433	–	–	–0.4	–	

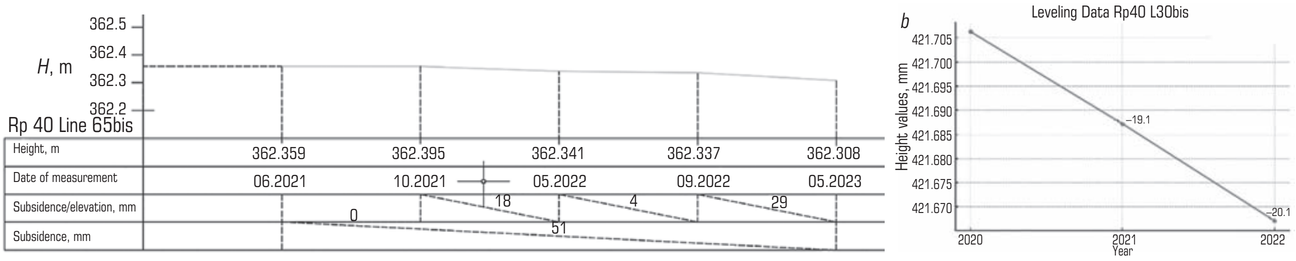

Fig. 2. Data from Rp 40 of profile line 65bis:
a – GNSS observations; *b* – high-precision levelling

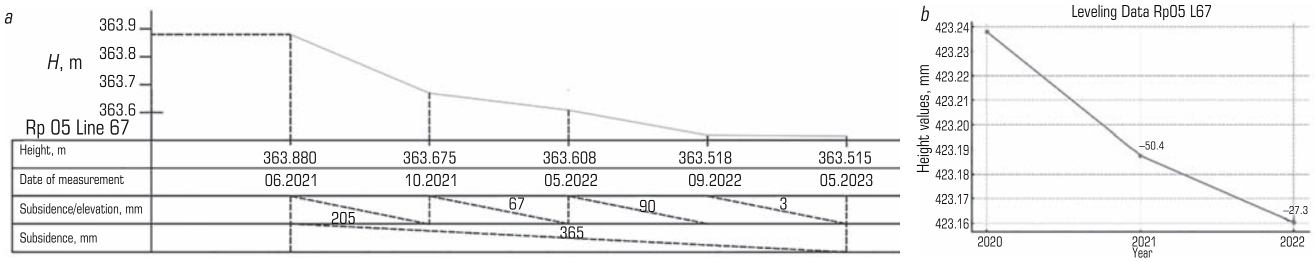

Fig. 3. Data from Rp 05 of profile line 67:
a – GNSS observations; *b* – high-precision levelling

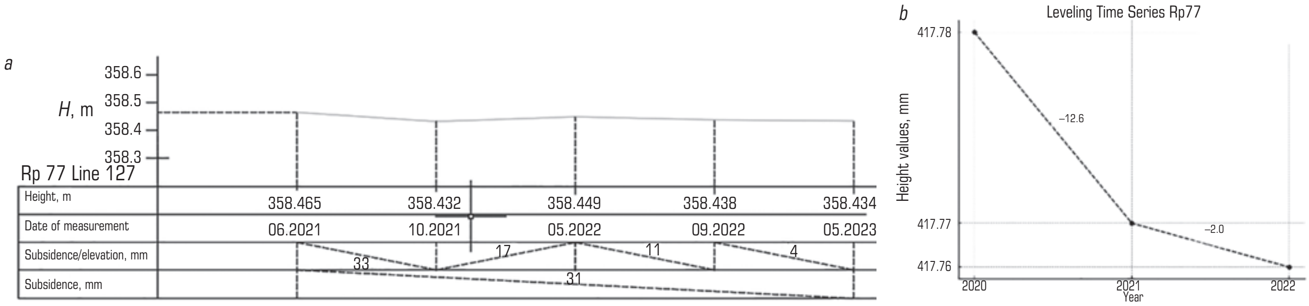

Fig. 4. Data from Rp 77 of profile line 127:
a – GNSS observations; *b* – high-precision levelling

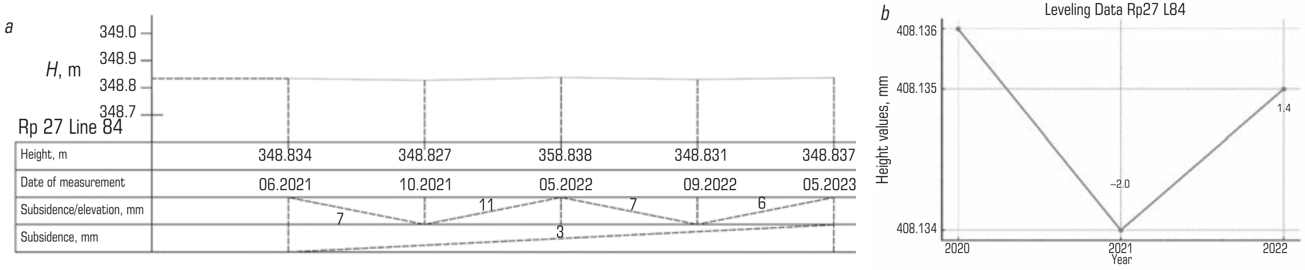

Fig. 5. Data from Rp 27 of profile line 84:
a–GNSS observations; *b*–high-precision levelling

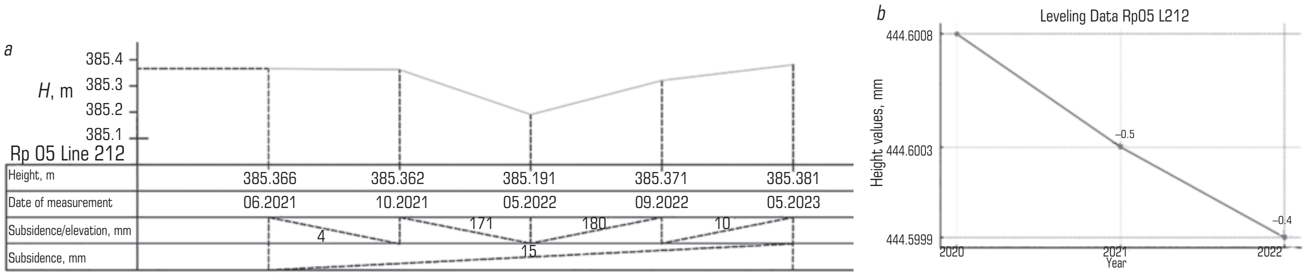

Fig. 6. Data from Rp 05 of profile line 212:
a – GNSS observations; *b* – high-precision levelling

However, alongside with the benchmarks where the measurements of levelling and GNSDS agree, there are benchmarks where the methods produce different results. For instance, the levelling shows a subsidence, while the GNSS data reveal a slight elevation (**Fig. 6**).

A possible cause of the levelling and GNSS information disagreement can be the impact of the external factors (errors, atmospheric oscillations, etc. [17, 18]).

For the assessment of height determination accuracy and agreement of the methods, the height differences were compared. The height differences between the successive measurements by each methods allows detecting the trends of subsidence and elevation.

Discussion

This research preformed verification and joint interpretation of levelling results and GNSS measurements, and evaluated accuracy of height determination by the two methods. The comparative analysis revealed the degree of agreement between the results obtained by the levelling and GNSS measurements. Moreover, the sources of errors were identified, which made it possible to offer recommendations on improvement of the measurement accuracy.

Conclusions

The research aimed to assess the height measurement accuracy of different methods, such as GNSS observations and high-precision levelling, in the course of geodynamic monitoring. The objective of the research was to determine and compare the accuracy of each method in the conditions of induced impact at the Zhezkazgan deposit.

The research findings showed the high accuracy and agreement of the both methods. Verification of the obtained data reveals that the high-precision levelling is an optimal choice for the height variation measurement in the vast areas, whereas the GNSS observations are effective in operational monitoring, when there is no need to embrace many benchmarks at a time.

The GNSS measurements of heights of a few benchmarks is advisable when:

1. The benchmarks are dispersed over an irregular area, where levelling routing is labor intensive;
2. The observations are carried out on a regular basis, which enables the expensive equipment to pay off;
3. It is required to minimize labor intensity.

It is important that the high-precision levelling and GNSS observations are not mutually exclusive but complement one the other. Joint application of these technologies ensures a more complete and exact insight into deformation processes, while minimizing limitations and strengthening benefits of each approach. It is also important that the methods use different reference systems but show a high agreement between the results. This emphasizes reliability of each method.

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