CIVIL ENGINEERING JOURNAL

Article no. 4

THE CIVIL ENGINEERING JOURNAL 1-2024

GEOMONITORING OF THE OPEN-PIT MINE SLOPES DURING SUBSOIL DEVELOPMENT

Roman Shults[1], Marzhan Nurpeissova[2], Shugyla Burlibayeva[3], Aliya Umirbayeva[2] and Turar Turumbetov[3]

1. *King Fahd University of Petroleum and Minerals, Interdisciplinary Research Center for Aviation and Space Exploration, Dhahran, Academic Belt, Bld. 76, Saudi Arabia; roman.shults@kfupm.edu.sa*
2. *Satbayev University, Mining, and Metallurgical Institute named after O.A. Baikonurov, Department of Surveying and Geodesy, Almaty, Satbayev, 22a, Kazakhstan; m.nurpeissova@satbayev.university, a.umirbayevau@satbayev.university*
3. *Al-Farabi Kazakh National University, Faculty of Geography and Environmental Sciences, Department of Cartography and Geoinformatics, Almaty, Al-Farabi Ave, 71, Kazakhstan; burlibayeva.shugyla@gmail.com, turar.kz_star@mail.ru*

ABSTRACT

The concept of geomonitoring and its role in developing the mining industry as a case study of the development of copper and zinc deposits in central Kazakhstan ("East Saryoba" mine) has been considered. As a crucial element of the geomonitoring concept, the control of the open-pit mine's slope stability has been examined. Geomonitoring is being treated as a combination of geodetic monitoring data and geomechanical properties of the surrounding rocks to analyze the possible slopes' collapses. The refined approach of geomonitoring has been developed to provide appropriate reliability and accuracy. The technology is based on complex knowledge about the geological structure of the object of monitoring and applying state-of-the-art geodetic methods. Research on the geomechanical properties of the open-pit mine has been carried out. The results of these studies have been used to determine the collapse zones of the slopes of the open-pit mine. The limit values for the slopes' collapse zone and inclination angle for the prospective excavation regions in the open-pit mine have been calculated using the equilibrium state equation. Those values, namely, the size of the collapse zone and the slope's inclination angle, were used for the geodetic target setup. As a case study, the displacements of these targets were measured using robotic total stations placed on the control points over the geodetic network. For the installation of both geodetic equipment during the geomonitoring design and accomplishment, the authors developed the permanent measuring station construction, which provides fast and accurate centering. The first results showed that the problem of the geomonitoring design could be solved based on geomechanical rock properties accounting and their combination with the results of geodetic measurements.

KEYWORDS

Geomonitoring, Open-pit mine, Vertical displacements, Deformation target, Geomechanical properties, Slope stability

INTRODUCTION

The world industry of minerals mining affects both the global economy and the environment. The leading countries worldwide are conducting grave studies concerning reducing the impact of their mining activity on the environment. Among those countries by far is the Republic of Kazakhstan. The country occupies one of the prominent places in the balance of global minerals and raw materials. It is well-known that the country has a high potential for further developing mineral resources on the world market. Currently, in Kazakhstan, open pit mining technology is developing most of the mineral deposits. The deployment of robust geomonitoring systems is the solution to mitigate the unwanted impact of the mining industry on the environment. The state-of-the-art mining activity requires an essential improvement in monitoring the geomechanical processes occurring in the mining zones based on monitoring the open-pit slopes state. The question of slope stability in open-pit mines is a subject of numerous studies [1-5]. The present publications are focused on the application of equilibrium state methods. The work [6] indicates that approaches to estimate the stability of the open-pit mine slopes were developed years ago. However, the most widely used methods are still based on the equilibrium state condition. Those methods require detailed information obtained as a result of geological studies about the ground's inner structure. Furthermore, it is hardly possible to forecast the slope stability even with detailed information about the grounds' structure. Geological data alone are not capable of ensuring the precise slope movement model. This is the case when geodetic monitoring data come in handy and may complement a pure geological model [7-9]. A number of scholars have examined the application of geodetic technologies for slope monitoring using miscellaneous geodetic equipment. Among the terrestrial geodetic methods, the critical role plays total stations [10] and terrestrial laser scanners [11,12]. Among aerial surveying technologies, the primary contribution is UAVs equipped with cameras and LiDARs. Numerous studies have investigated the UAV photogrammetry application for geodetic monitoring [13-15]. Space technologies are another branch of geodetic technologies. Researchers have become increasingly interested in applying satellite and ground-based radar technologies for precision monitoring [16-26. The data collected by any mentioned methods, or their fusion are analyzed in different GIS platforms [27,28]. Besides monitoring the slopes of the open-pit mine, the problem of landslide monitoring is worth noting, which is similar to slope monitoring [29-32]. Even though the landslides are mostly natural objects, their monitoring is performed using the same LiDAR technologies, total stations, UAVs, and InSAR technology. This list is by no means exhaustive. However, it shows us the leading role of geodetic technologies in such a complicated task.

Therefore, combining geological knowledge and geodetic measurements leads to the more general concept of geomonitoring [33-35]. However, it raises the question of how to organize geodetic monitoring as a part of geomonitoring so its results are compatible with geological data. The answer is that it is necessary to find the slope stability parameters using geological data and, in what follows, control these parameters using geodetic methods. Of course, under such parameters, we mean just geometrical, as long as only these values are the subject of geodetic measurements. The stability factor characterizes the slope stability. The value of this factor shows the relative surplus of the rock mass strength compared to the shear stress [36-38]. Scientists account for the adjacent rock mass's geomechanical properties and hydrogeological conditions for the stability factor calculation. To date, no study has explicitly looked at the problem of geomonitoring using the key geometrical characteristics, namely, slope inclination angle and the size of the collapse zone. This study addresses the geomonitoring design issue and its part of geodetic monitoring. Given the centrality of this issue, as the first step, let us consider the general concept of geomonitoring and the features of the study area.

This paper is organized into five subsections. Section Material and Methods provides an overview of geomonitoring, a brief description of the study area, and a basic theoretical framework for open-pit mine geomonitoring design and its practical application. The results section deals with analyzing the first onsite application of the developed geomonitoring concept and its discussion. The last subsection outlines the conclusions.

MATERIAL AND METHODS

General geomonitoring approach and study area

The traditional concept of geomonitoring boils down to the following steps: design, observations, simulation, and prediction [39-41]. The contemporary geomonitoring concept is presented below (Figure 1).

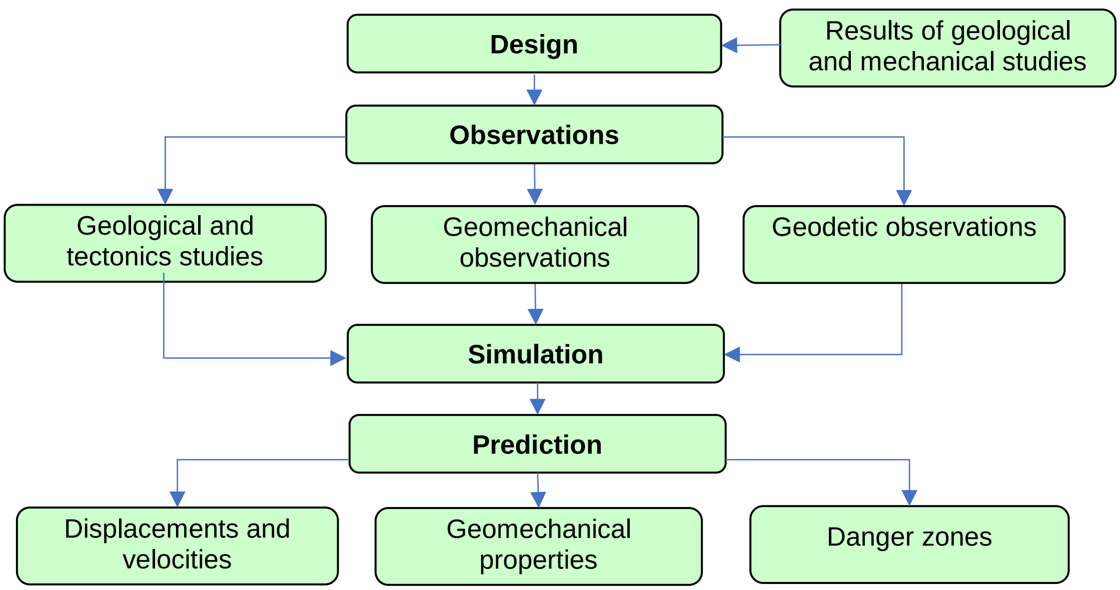

Fig. 1 – Scheme of the geomonitoring concept

Modern geomonitoring is an integrated process that uses different sensors for the observations. The results of these observations feed to the core of the monitoring system, the simulation block. The state-of-the-art concept of geomonitoring on the open-pit mine territories comprises three primary data sources. Geological, mechanical, and geodetic studies yield these data. For the case of open-pit mine geomonitoring, the primary goal is to determine the slopes' stability, which is described by spatial displacements of deformation targets. However, at the design step, those data are not being used. The crucial parameter for reliable geomonitoring is the width of the possible collapse zone B_0 (see Figure 2).

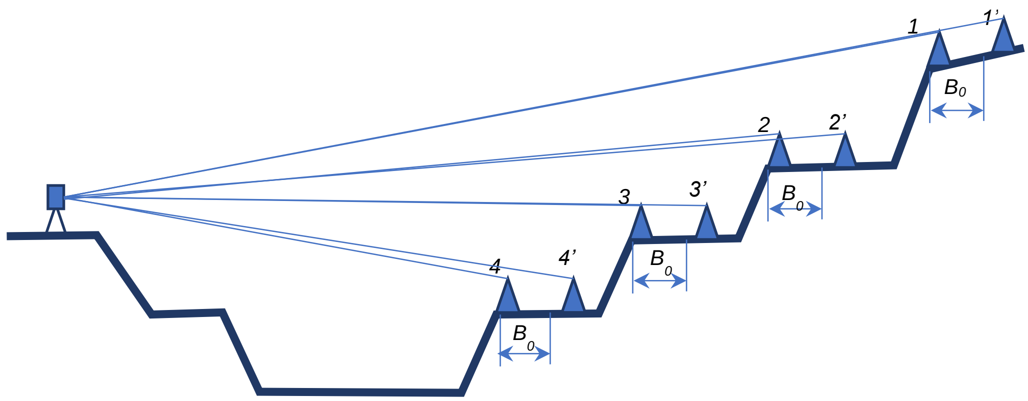

Fig. 2 – Station profile line and surveillance equipment

At each step of an open-pit mine, two targets must be placed—the first at the step rim and the second out of the possible collapse zone. Owing to the value B_0, the surveyor can correctly set up the monitoring targets. To calculate the value B_0 for the geomonitoring at the design stage, one needs to know the following ground properties: adhesion by crack, angle of friction, hardness of the rock, and density. These characteristics will be examined as a case study of the "East Saryoba" mine, located in Central Kazakhstan (Figure 3).

Fig. 3 – Study area, "East Saryoba" mine

The "East Saryoba" orefield is considered a large development mine. Since its discovery, 119 ore bodies have been explored. The largest deposits are in the northeast and have a length of up to 3200 m and a thickness of up to 17 m (Figure 4).

The output of the geomechanical properties research will be presented in the following subsection. These results have been used to determine the slopes' collapse zones and limit values for the slopes' inclination angle for the prospective excavation zones in the open-pit mine. Those values will be used for the emplacement of the deformation targets.

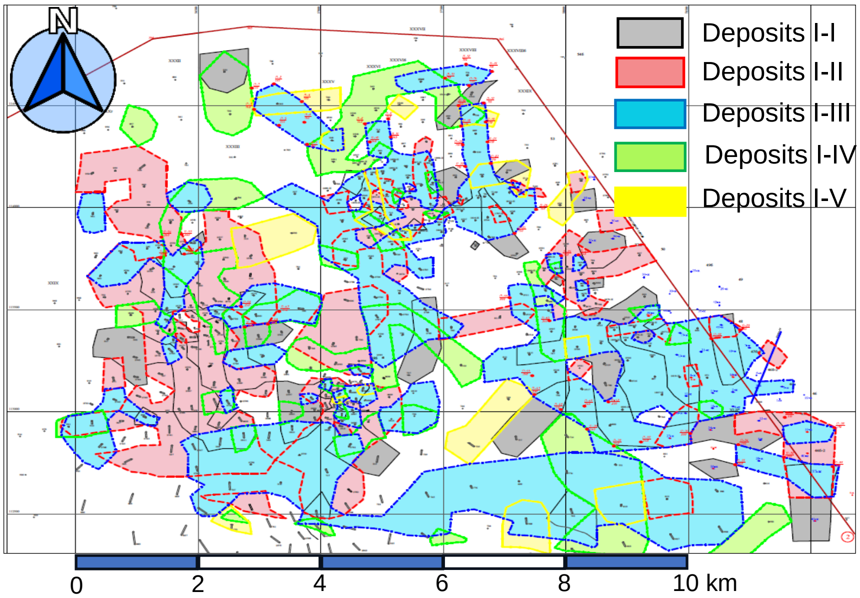

Fig. 4 – The combined contour of ore deposits in the depth range +340 m to 0 m "East Saryoba"

Geomechanical studies

Several geological studies have been conducted for the "East Saryoba" deposit. The present study has employed the results of geological surveys analyzed in the laboratory and field testing. Satbayev University conducted different research and obtained indicators of rock strength properties. Table 1 shows the physical and mechanical properties of the deposit rocks based on the laboratory test results.

Tab. 1 - Geomechanical properties of rocks in the sample data of Satbayev University for 2002-2008

Sampling depth, m	Name of the rock	Uniaxial compression strength σ_{com}, MPa	Uniaxial Strength σ_p, MПa	Density γ, 10^3 kg/m^3	Adhesion in block *k*, MPa	Angle of friction, degrees	Hardness of rock, *f*
50.1-51.8	Cement rock	110	13.0	2.66	25	32	8.0
83.5-84.0		125	14.0	2.67	28	32	8.3
112.0-113.0		126	14.3	2.68	32	31	8.6
152.6-153.0		139	14.5	2.71	34	31	9.2
170.0-170.8		140	14.8	2.72	34	29	9.5
218.1-218.6		140	14.8	2.73	35	31	9.6
53.6-54.0	Greenstone	138	16.0	2.62	36	30	7.6
115.0-115.6		160	16.8	2.65	42	30	8.2
155.0-156.0		170	16.0	2.67	46	30	8.8
200.0-201.5		171	16.2	2.69	48	30	9.0

The study of rock geomechanical properties was repeated in 2018. The results are presented in Table 2.

Tab. 2.- Geomechanical properties of rocks in the sample data of Satbayev University for 2018

Sampling depth, m	Name of the rock	Uniaxial compression strength σ_{com}, MPa	Uniaxial Strength σ_p, MПa	Density γ, 10^3 kg/m^3	Adhesion in block *k*, MPa	Angle of friction, degrees	Hardness of rock, *f*
260	Cement rock	170.1	16.5	2.71	37	28	8.2
265		173.1	17.2	2.72	49	30	8.8
545		170.0	16.0	2.73	45	30	9.0
545		172.0	16.9	2.71	48	35	8.2
505		170.0	16.2	2.72	48	30	8.8
505		170.0	16.8	2.73	50	38	9.5

Using data from Tables 1 and 2, we obtained the analytical dependencies that describe the relationship between the slopes' parameters and the rock properties (Figure 5 and Table 4).

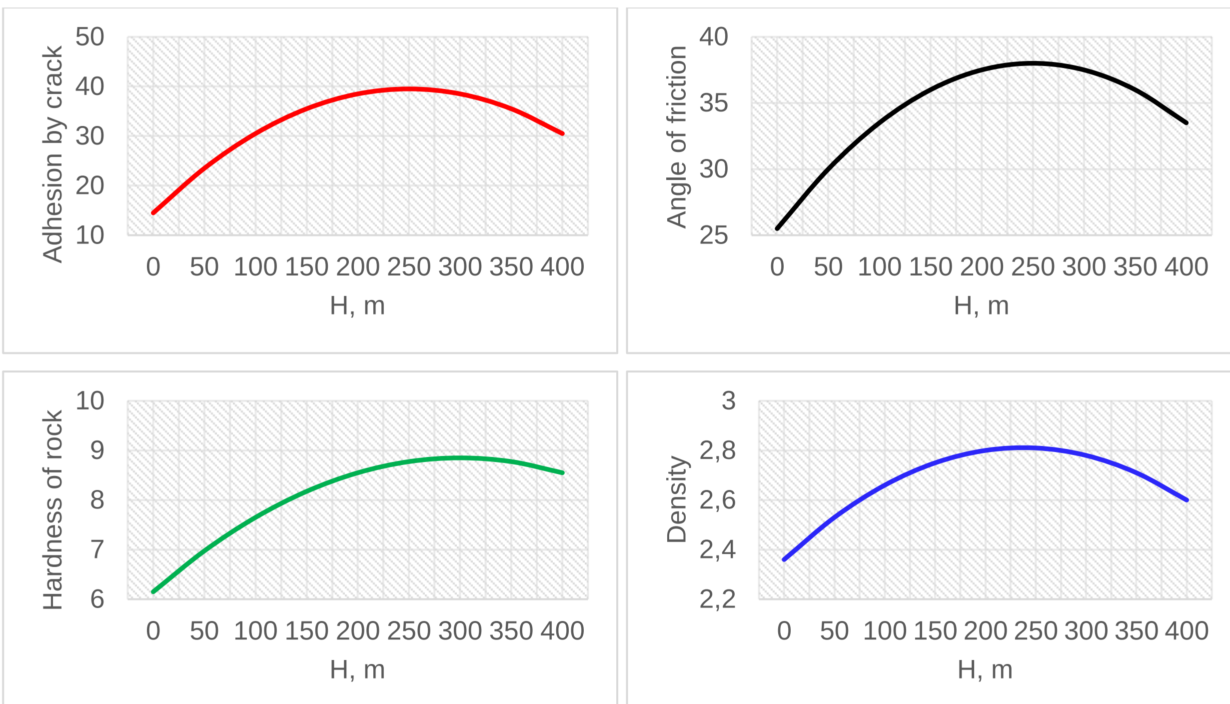

Fig. 5 – Analytical dependencies for rock geomechanical properties at the "East Saryoba" mine.

The analysis shows that rocks' strength properties change significantly with the depth of their occurrence.

The next step is the calculation of the slopes' stability. Having this parameter, one may calculate the possible collapse zone B_0 and critical slope inclination δ, the parameters that are crucial for geomonitoring. The equilibrium condition has been used to accomplish this task:

$$M_y = Rtg\varphi_S \sum_{i=1}^{i=k} P_i cos\theta_i + RC_S \sum_{i=1}^{i=k} L_i, \qquad (1)$$

where R – radius of the cylindrical sliding surface; $P_i = h_i b_i \gamma_S$ (h_i – block's height; b_i – block's width, γ_S – simulated density); θ_i – inclination angle of the sliding surface; φ_S – a simulated value of the inner friction angle; C_S – a simulated value of the adhesion; L_i – length of the sliding surface. The meaning of these values can be clarified in Figure 6.

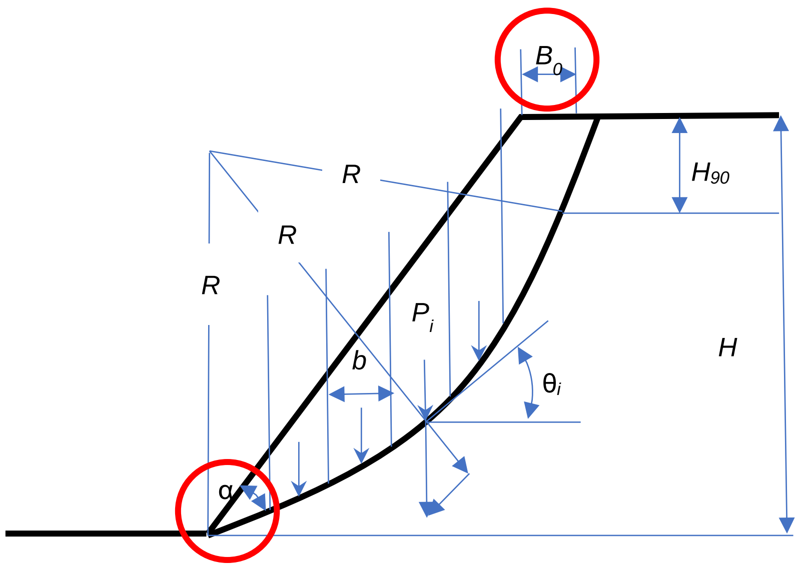

Fig. 6 – Diagram of slope stability calculation

The two indispensable parameters for geomonitoring have been calculated. The width of the possible collapse zone equals:

$$B_0 = {2H[1 - ctg\alpha tg((\alpha + \varphi_S)/2)] - 2H_{90}} / {ctg(45° - \varphi_S/2) + tg((\alpha + \varphi_S)/2)}, \quad (2)$$

the value H_{90} can be calculated as:

$$H_{90} = 2C_S ctg(\alpha - \varphi_S/2)/\gamma_S. \quad (3)$$

The values B_0 for each slope were used for target emplacement along the east side of the W-E profile (Figure 7). The vertical displacements for the targets along this profile were determined and will be analyzed in the results section.

The second parameter—the allowable slope's inclination angle—has been found through simulation. The most suitable method for fractured rocks is the one that simulates stable slope parameters, considering rocks' sliding surface and strength properties. The simulation was carried out for each block of pit mine cross-section W-E (Figure 7). The results are given in Table 5.

Along with calculating the allowable slope's inclination angle, pit slopes were partitioned into zones accounting for stability factors. The complex analysis of data in Table 5 and the stability factor showed that the eastern and western sides of the mine have the slope's stability at angles of 65-70^0. In fact, the actual slope's angles do not exceed 50°. Therefore, from the geomechanical point of view, the slopes are treated as stable.

Fig. 7 – Orientation of the profile W-E on the "East Saryoba" mine

Tab. 5 - Allowable slope's inclination angles for cross-section W-E.

Relative height H/H_{90}	Angle of friction, deg			
	25	30	35	40
1	90.0	90.0	90.0	90.0
1.5	84.0	84.5	85.0	85.5
2	77.3	78.1	79.6	80.6
2.5	71.0	72.5	74.4	76.0
3	65.2	68.0	70.2	72.8
3.5	60.2	64.0	66.5	69.9
4	56.0	60.1	63.6	67.5
4.5	52.5	56.9	60.9	65.2

The cross-section of the pit mine and the targets is given in Figure 8.

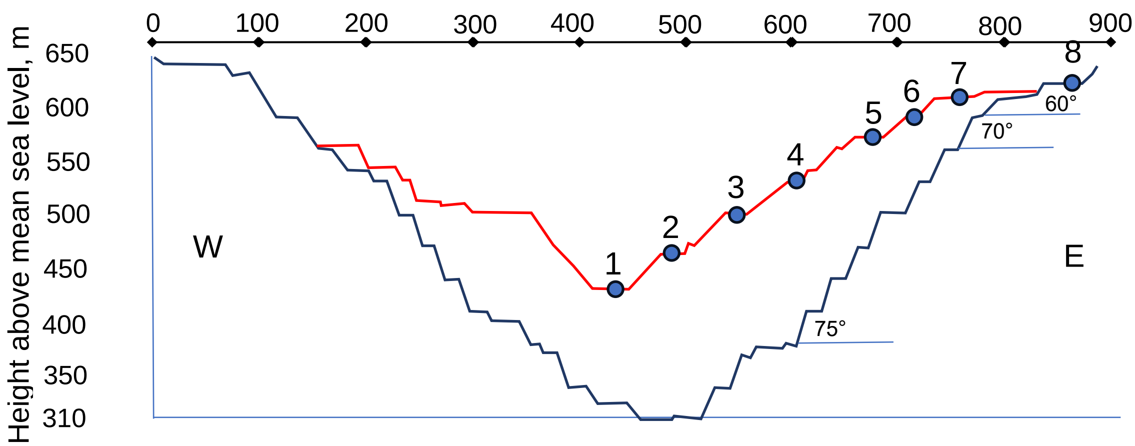

Fig. 8 – Current and prospective profiles of deposit development for "East Saryoba" mine.

Totally 16 deformation targets were placed along the east profile W-E, two for each slope. The distances between them were equal to B_0. Under such a premise, the first target is treated as deformed, and the second is treated as stable for control. The targets were attached to the slope surface and marked by retroreflective targets. The total station was used (Figure 9, c) to measure the displacements of these targets. For reliable observations, we have developed a permanent measuring station installed at the reference points for monitoring (Figure 9, a). This station aims to facilitate observation procedures, increase measurement accuracy, and speed up monitoring procedures.

(a) (b) (c)

Fig. 9 – Measuring station: (a) Design of the permanent measuring station: 1- concrete or steel pillar; 2- metal plate 3- mark center; 4-steel set; 5- frame hole; 6,7- attachment screws; 8 - butt; 9- cover; (b) Cover setup; (c) Total station setup and measurements.

RESULTS

Monitoring results

After setting the targets along the profile W-E, the measurements were accomplished. Total station Leica carried out observations of the vertical displacements of rock mass from the permanent measuring station placed outside the pit mine. For 2015-2019, seven epochs of geodetic observations were performed. The first epoch was considered a "zero" epoch with no displacements. According to the observations' results, the vertical displacements were fixed for deformed targets (Figure 10) and stable targets (Figure 11). The analysis of the results shows that the displacements of the deformed targets (Figure 10) tend to increase with height. The targets placed at the top rims of the pit mine have significant displacements. During the first observation years, the displacements did not exceed 25 mm. However, further observations have shown an evident trend. This trend is clear from the mean vertical displacement for each target that is calculated by

$$S_{mean} = \frac{\sum S_i}{q}, \tag{4}$$

where q is the number of observation epochs; $\sum S_i$ - total vertical displacement for all epochs. The graph of mean displacement is attached to Figure 10.

Unlike the deformed targets in Figure 10, stable targets have considerably smaller displacements. The maximum displacement reached 11 mm for the upper rim of the pit mine. The displacements of the stable targets mainly change randomly. There is only an insignificant trend for upper targets for the last observation year (points 7‘ and 8‘).

DOI 10.14311/CEJ.2024.01.0004

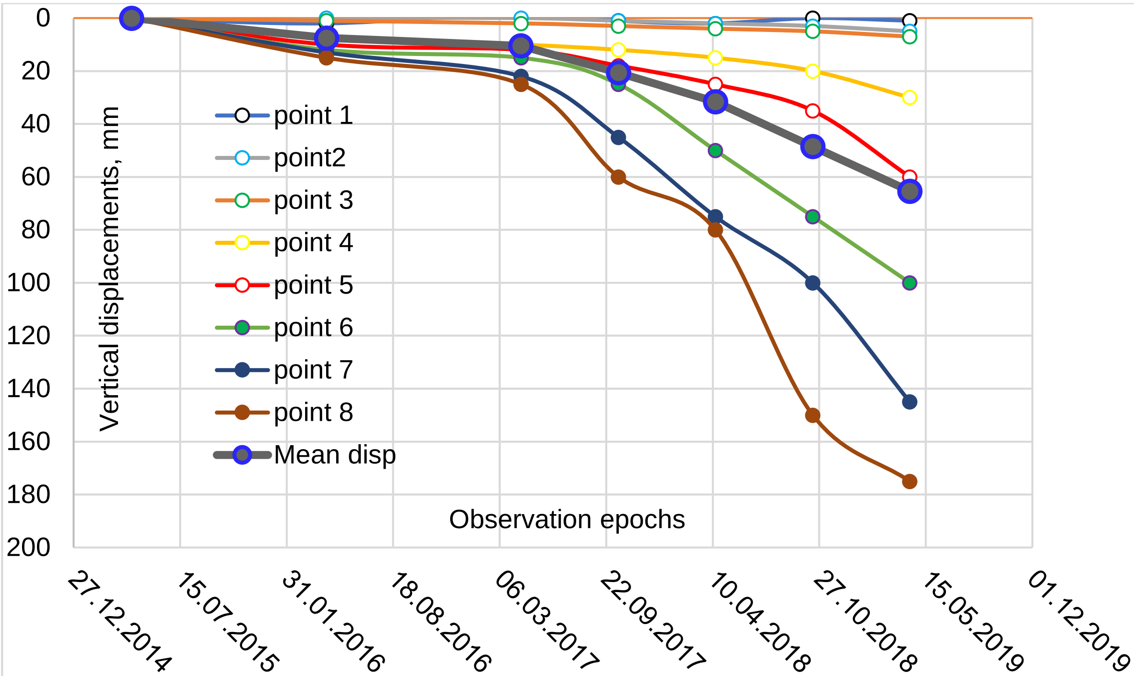

Fig. 10 – Displacements of deformed targets

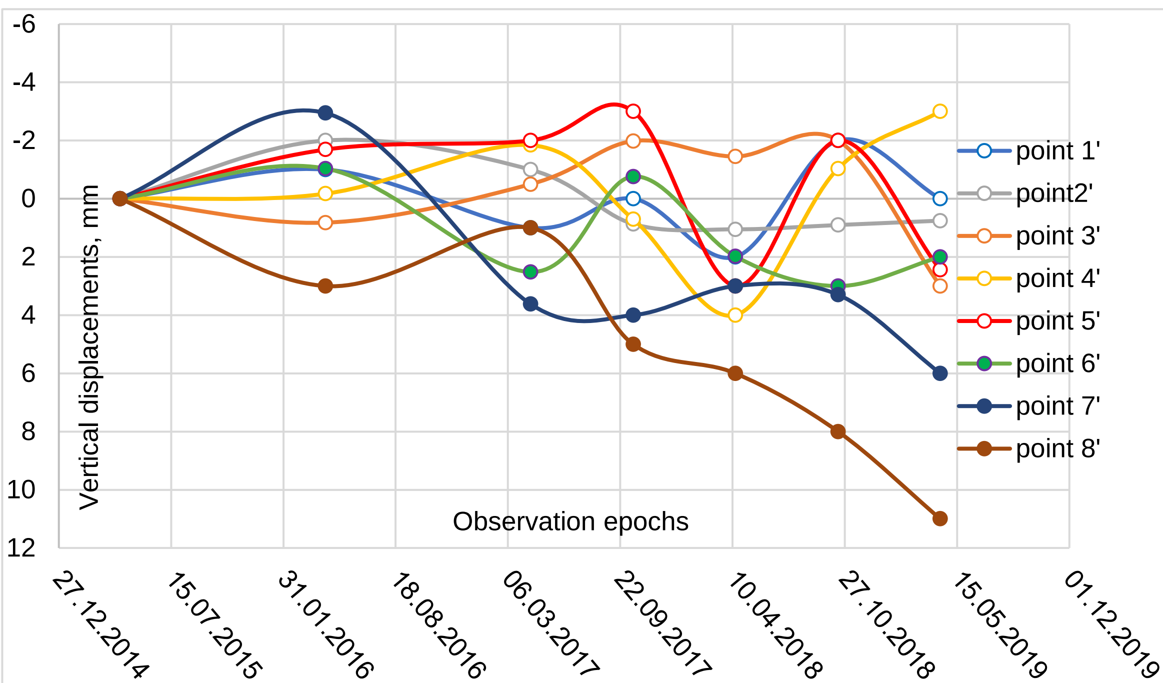

Fig. 11 – Displacements of stable targets

For the deformed targets, we may calculate the mean displacement velocity

$$v_{meanS_Q} = \frac{\sum_i^q v_Q}{q}, \tag{5}$$

where $\sum_i^q v_Q$ - the total velocity of the vertical displacement.

The velocity graphs are presented in Figure 12. This figure includes the graph of the mean displacement velocity.

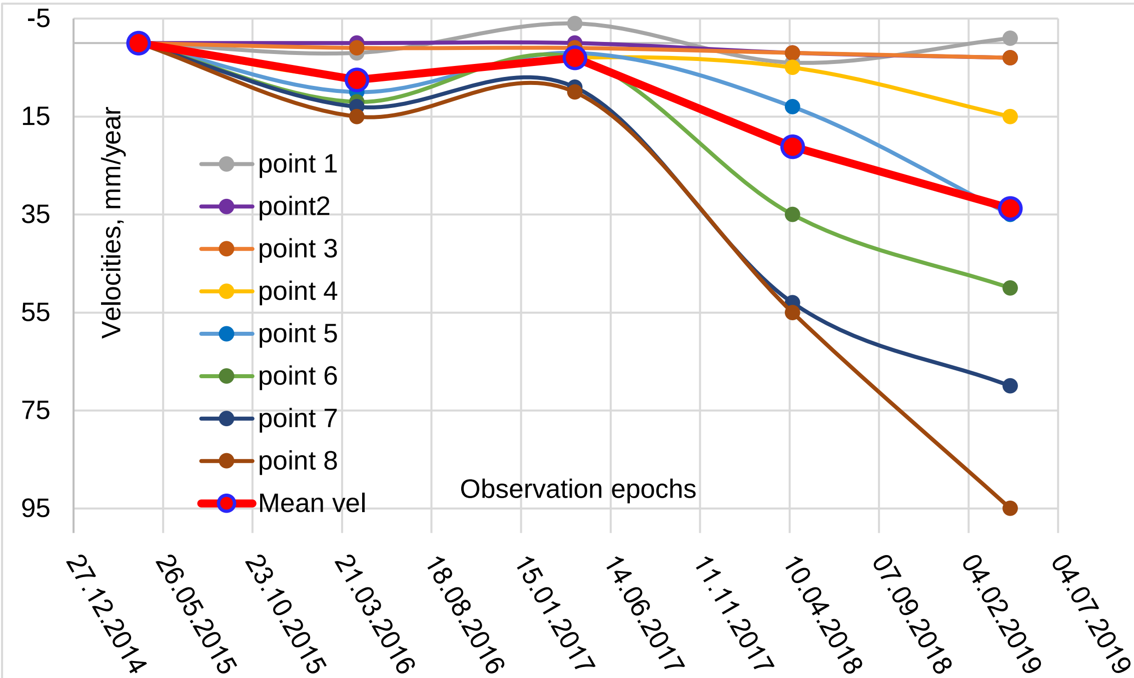

Fig. 12 – Graphs of target velocities

Since the number of epochs is limited, developing a prediction model based on statistical premises will provide unreliable results. The correct solution is the application of the interpolation model. However, the determined values of displacements are contaminated by random measurement errors. Therefore, applying the interpolation model that will simulate the deformation process and smooth the effect of random errors is recommended. One such model is the spline function (parabolic or cubic). The approximation is carried out using the least squares approach to reduce the impact of the random errors. Parabolic and cubic spline models describe the deformation process for all deformed targets with accuracy, as shown in Table 6. The model based on cubic spline provides more smoothed results with smaller values of root mean square errors (RMS) and absolute residuals.

The results of the least squares cubic spline approximation are presented in Figure 13.

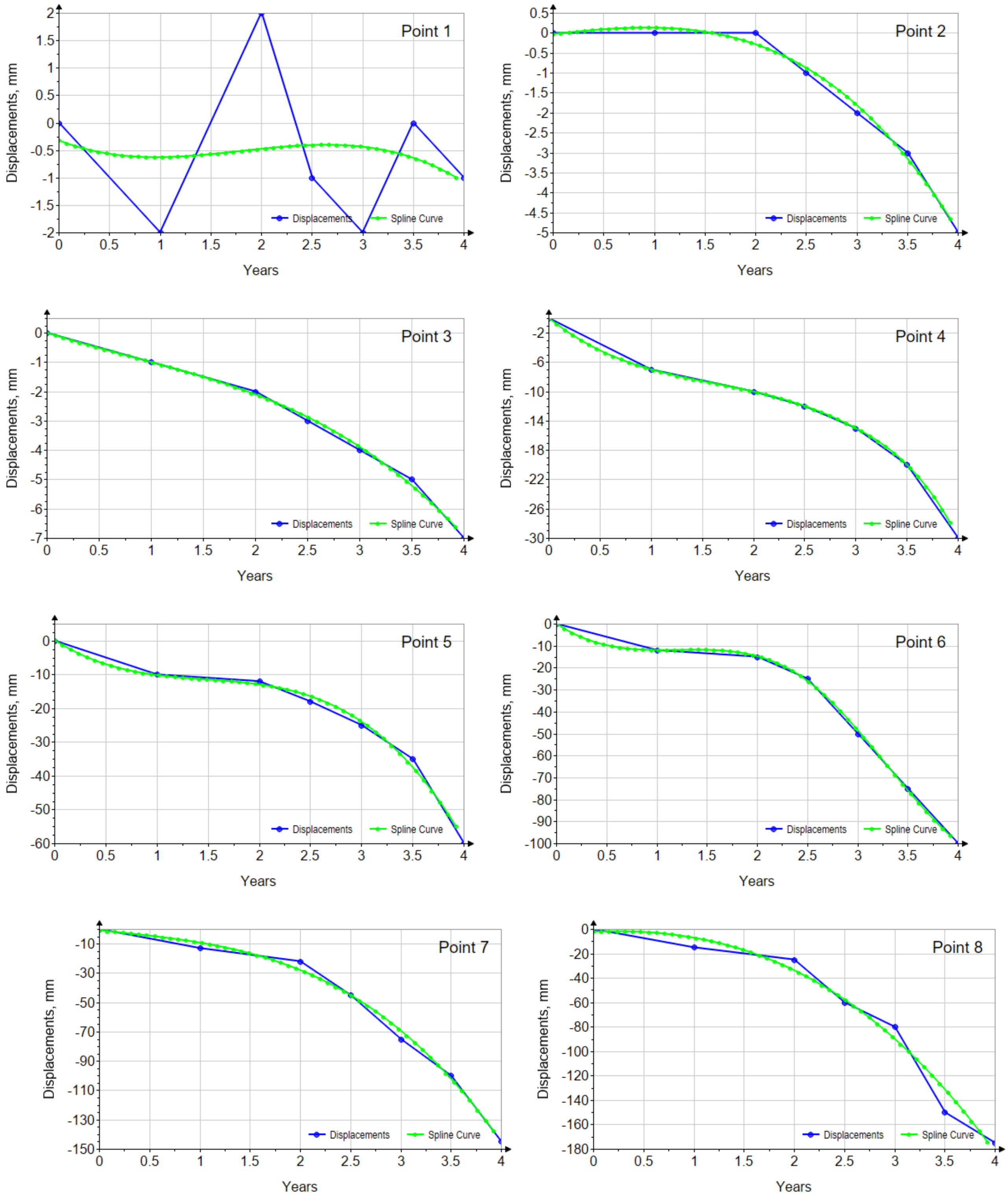

Fig. 13 – Graphs of cubic spline approximation for deformed targets

DOI 10.14311/CEJ.2024.01.0004

Tab. 6 - Approximation accuracy.

Target	Parabolic spline		Cubic spline	
	RMS, mm	Abs max, mm	RMS, mm	Abs max, mm
1	1.3	2.4	1.2	2.5
2	0.2	0.4	0.2	0.3
3	0.3	0.2	0.1	0.2
4	0.6	0.4	0.0	0.0
5	6.9	4.4	1.3	2.5
6	9.8	4.9	0.8	1.5
7	9.2	4.8	3.6	6.0
8	17.4	9.9	9.7	18.7

The obtained results presented in Figure 13 and Table 6 provide a clear explanation of the deformation process. The suggested observation scheme with two deformation targets on each slope ensured the correct interpretation of the whole pit mine displacement. It was determined that the targets emplaced in the possible collapse zone had undergone vertical displacements. The largest displacements were detected for the deformation targets placed on the upper levels of the pit mine (points 5-8). The calculated velocities show the increasing speed of the deformation process. Therefore, it is recommended that the time between observation epochs be decreased by up to three months.

CONCLUSION

The paper presents the results of geomonitoring and considers its role in the mining industry. The monitoring of the open-pit mine's slope stability has been examined. The critical point of the geomonitoring is a combination of geodetic monitoring data and rock geomechanical properties. Geomechanical studies of rock mass strength properties and structural features have been conducted. The results of geomechanical studies were leveraged to calculate the width of the possible collapse zone and the allowable slope's inclination angle for the "East Saryoba" mine. With these two parameters, geodetic monitoring technology has been improved.

The geodetic monitoring has been accomplished for the slopes of the "East Saryoba" mine. Total station observations have been leveraged for vertical displacement measurements. The preliminary results have shown the high efficiency of geomonitoring in the suggested approach. The results have demonstrated the growth of the vertical displacements from the pit mine bottom (7 mm) to the rim (175 mm). The vertical displacements are free of total displacements of the whole pit mine and present each slope's pure vertical displacement. Prospective research will have to address the geomonitoring problem in more detail. Future studies will have to concentrate on integrating additional measuring equipment, e.g., inclinometers, extensometers, etc., into geomonitoring schemes and address the issue of the complex processing and analysis of different data and measurements.

REFERENCES

[1] Yang Z., Gao Q., Li M.-H., Zhang G. 2014. Stability Analysis and Design of Open-Pit Mine Slope in China: A review. Electronic Journal of Geotechnical Engineering, Vol. 19: 10247-10266.

[2] Ortega J. H., Rapiman M, Lecaros R., Medel F., Padilla F., Garcia A. Predictive index for slope instabilities in open pit mining. Available online: https://arxiv.org/abs/1607.05085 (accessed on 04 August 2023) https://doi.org/10.48550/arXiv.1607.05085

[3] Harries N., Noon D., Rowley K. 2006. Case studies of slope stability radar used in open-cut mines. In: Proceedings of the International Symposium on Stability of Rock Slopes 335-342.
[4] Sjoberg, J. Large scale slope stability in open pit mining – a review. Technical report 1996:10T, Lulea university of technology, 1996, 229 p.
[5] Karam K.S., He M.C., Sousa L.R. 2015. Slope stability risk management in open pit mines. In: Proceedings of the 7th GiT4NDM and 5th EOGL International Conference, UAE, Al-Ain, 19p
[6] Stacey T.R., Xianbin Y., Armstrong R., Keyter G.J. 2003. New slope stability considerations for deep open-pit mines. Journal of the South African Institute of Mining and Metallurgy, 103(6): 373–389.
[7] Little, M.J. 2006. Slope monitoring strategy at prust open pit operation. In: Proceedings of the International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, 211-230.
[8] Vinoth S., Kumar L.A., Kumar E. 2015. Slope Stability Monitoring by Quantification and Behavior of Microseismic Events in an Opencast Coal Mine. Jour. Geol. Soc. India, Vol.85: 450-456.
[9] Narendranathan S., Nikraz H. 2011. Optimal System Design for Instrumented Slope Monitoring in Open Pit Mines. In: Proceedings of the International Conference on Advances in Geotechnical Engineering, Perth, Australia, 311-317.
[10] Rákay Š., Zuzik J., Weiss G., Labant S. 2013. Surveying of inaccessible rock faces and volume calculation of the irregular solids using robotic total station. Acta Montanistica Slovaca, 18(3): 164-171.
[11] Bazarnik M. 2018. Slope stability monitoring in open pit mines using 3D terrestrial laser scanning. In: Proceedings AG 2018 – 4th International Conference on Applied Geophysics, E3S Web of Conferences, 66. https://doi.org/10.1051/e3sconf/20186601020
[12] Long N.Q., Buczek M.M., Hien L.P., Szlapin'ska S.A., Nam B.X., Nghia N.V., Cuong C.X. 2018. Accuracy assessment of mine walls' surface models derived from terrestrial laser scanning. Int J Coal Sci Technol, 5(3): 328–338. https://doi.org/10.1007/s40789-018-0218-1
[13] Pagano M., Palma B., Ruocco A., Parise M. 2020. Discontinuity Characterization of Rock Masses through Terrestrial Laser Scanner and Unmanned Aerial Vehicle Techniques Aimed at Slope Stability Assessment. Appl. Sci, 10(8): 2960. https://doi.org/10.3390/app10082960
[14] Török Á., Bögöly G., Somogyi Á., Lovas T. 2020. Application of UAV in Topographic Modelling and Structural Geological Mapping of Quarries and Their Surroundings—Delineation of Fault-Bordered Raw Material Reserves. Sensors, 20(2): 489. https://doi.org/10.3390/s20020489
[15] Tong X., Liu X., Chen P., Liu S., Luan K., Li L., Liu S., Liu X., Xie H., Jin Y., Hong Z. 2015. Integration of UAV-Based Photogrammetry and Terrestrial Laser Scanning for the Three-Dimensional Mapping and Monitoring of Open-Pit Mine Areas. Remote Sens, 7(6): 6635-6662. https://doi.org/10.3390/rs70606635
[16] Gee D., Bateson L., Sowter, A., Grebby S., Novellino A., Cigna F., Marsh S., Banton C., Wyatt L. 2017. Ground Motion in Areas of Abandoned Mining: Application of the Intermittent SBAS (ISBAS) to the Northumberland and Durham Coalfield, U.K. Geosciences, 7(3): 85. https://doi.org/10.3390/geosciences7030085
[17] Czikhardt R., Papco J., Bakon M., Liscak P., Ondrejka P., Zlocha M. 2017. Ground Stability Monitoring of Undermined and Landslide Prone Areas by Means of Sentinel-1 Multi-Temporal InSAR, Case Study from Slovakia. Geosciences, 7(3): 87. https://doi.org/10.3390/geosciences7030087
[18] Pavelka,K., Šedina,J., Matoušková, E., Hlaváčová, I., Korth, W. 2019. Examples of different techniques for glaciers motion monitoring using InSAR and RPAS, European Journal of Remote Sensing, 52:sup1, 219-232, DOI: 10.1080/22797254.2018.1559001
[19] Hlaváčová, I.; Halounová, L.; Stanislav, P. 2016. SENTINEL-1 InSAR Processing of Corner Reflector Information in the Northern-Bohemian Coal Basin. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2016 XXIII ISPRS Congress, Prague. Göttingen: Copernicus GmbH (Copernicus Publications, 2016. p. 763-767. ISSN 2194-9034. DOI: 10.5194/isprs-archives-XLI-B7-763-2016
[20] Kumar A., Villuri V.G.K. 2015. Role of mining radar in mine slope stability monitoring in open cast mines. Procedia Earth and Planetary Science, 11: 76 – 83.
[21] Solari L., Montalti R., Barra A., Monserrat O., Bianchini S., Crosetto M. 2020. Multi-Temporal Satellite Interferometry for Fast-Motion Detection: An Application to Salt Solution Mining. Remote Sens, 12(23): 3919. https://doi.org/10.3390/rs12233919

[22] Brown C., Daniels A., Boyd D.S., Sowter A., Foody G., Kara S. 2020. Investigating the Potential of Radar Interferometry for Monitoring Rural Artisanal Cobalt Mines in the Democratic Republic of the Congo. Sustainability, 12(23): 9834. https://doi.org/10.3390/su12239834

[23] Wei L., Feng Q., Liu F., Mao Y., Liu S., Yang T., Tolomei C., Bignami C., Wu L. 2020. Precise Topographic Model Assisted Slope Displacement Retrieval from Small Baseline Subsets Results: Case Study over a High and Steep Mining Slope. Sensors, 20(22): 6674. https://doi.org/10.3390/s20226674

[24] Chen D., Chen H., Zhang W., Cao C., Zhu K., Yuan X., Du Y. 2020. Characteristics of the Residual Surface Deformation of Multiple Abandoned Mined-Out Areas Based on a Field Investigation and SBAS-InSAR: A Case Study in Jilin, China. Remote Sens, 12(22): 3752. https://doi.org/10.3390/rs12223752

[25] Liang H., Li X., Zhang L., Chen R.-F., Ding X., Chen K.-L., Wang C.-S., Chang C.-S., Chi C.-Y. 2020. Investigation of Slow-Moving Artificial Slope Failure with Multi-Temporal InSAR by Combining Persistent and Distributed Scatterers: A Case Study in Northern Taiwan. Remote Sens, 12(15): 2403. https://doi.org/10.3390/rs12152403

[26] Zheng L., Zhu L., Wang W., Guo L., Chen B. 2020. Land Subsidence Related to Coal Mining in China Revealed by L-Band InSAR Analysis. Int. J. Environ. Res. Public Health, 17(4): 1170. https://doi.org/10.3390/ijerph17041170

[27] Theilen-Willige B., Ait Malek H., Charif A., El Bchari F., Chaïbi M. 2014. Remote Sensing and GIS Contribution to the Investigation of Karst Landscapes in NW-Morocco. Geosciences, 4(2): 50-72. https://doi.org/10.3390/geosciences4020050

[28] Chalkias C., Ferentinou M., Polykretis C. 2014. GIS-Based Landslide Susceptibility Mapping on the Peloponnese Peninsula, Greece. Geosciences, 4(3): 176-190. https://doi.org/10.3390/geosciences4030176

[29] Bláha P. 2009. Landslide and its complex investigation. Acta Montanistica Slovaca, 14(3): 221-231.

[30] Dalyot S. 2015. Landform Monitoring and Warning Framework Based on Time Series Modeling of Topographic Databases. Geosciences, 5(2): 177-202. https://doi.org/10.3390/geosciences5020177

[31] Desrues M., Lacroix P., Brenguier O. 2019. Satellite Pre-Failure Detection and In Situ Monitoring of the Landslide of the Tunnel du Chambon, French Alps. Geosciences, 9(7): 313. https://doi.org/10.3390/geosciences9070313

[32] Bossi G., Mantovani M., Frigerio S., Schenato L., Marcato G., Pasuto A. 2016. A Monitoring Network to Map and Assess Landslide Activity in a Highly Anthropized Area. Geosciences, 6(3): 40. https://doi.org/10.3390/geosciences6030040

[33] Bonetto S., Umili G., Ferrero A.M., Carosi R., Simonetti M., Biasi A., Migliazza M.R., Bianchini S. 2020. Geostructural and Geomechanical Study of the Piastrone Quarry (Seravezza, Italy) Supported by Photogrammetry to Assess Failure Mode. Geosciences, 10(2): 64. https://doi.org/10.3390/geosciences10020064

[34] Tao Z., Zhu C., Zheng X., He M. 2018. Slope stability evaluation and monitoring of Tonglushan ancient copper mine relics. Advances in Mechanical Engineering, Vol. 10(8): 1–16. https://doi.org/10.1177/1687814018791707

[35] Wessels S.D.N. Monitoring and management of a large open pit failure. Master of Science in Engineering, University of Witwatersrand, Johannesburg, November 2009.

[36] Gilani S.-O., Sattarvand J. 2015. A new heuristic non-linear approach for modeling the variable slope angles in open pit mine planning algorithms. Acta Montanistica Slovaca, 20(4): 251-259.

[37] Pandit B., Tiwari G., Latha G.M., Babu G.L.S. 2018. Stability Analysis of a Large Gold Mine Open-Pit Slope Using Advanced Probabilistic Method. Rock Mechanics and Rock Engineering, 51: 2153–2174. https://doi.org/10.1007/s00603-018-1465-6

[38] Fleurisson J.-A. 2012. Slope Design and Implementation in Open Pit Mines: Geological and Geomechanical Approach. Procedia Engineering, 46: 27 – 38.

[39] Mphathiwa N., Cawood F.T. 2014. Design principles for optimizing an established survey slope monitoring system. The Journal of The Southern African Institute of Mining and Metallurgy, 114: 463-470.

[40] Osasan K.S., Afeni T.B. 2010. Review of surface mine slope monitoring techniques. Journal of Mining Science, 46(2): 177-186.

[41] Ammirati L., Mondillo N., Rodas R.A., Sellers C., Di Martire D. 2020. Monitoring Land Surface Deformation Associated with Gold Artisanal Mining in the Zaruma City (Ecuador). Remote Sens, 12(13): 2135. https://doi.org/10.3390/rs12132135