Failure Estimation of the Majdanpek Open Pit East Face Based on Inverse Velocity Model

Miloš Marjanović, Stefan Milanović, Nikola Simić, Lazar Kričak

Failure Estimation of the Majdanpek Open Pit East Face Based on Inverse Velocity Model | Miloš Marjanović, Stefan Milanović, Nikola Simić, Lazar Kričak | Regional Symposium on Landslides in the Adriatic-Balkan Region, Belgrade, 15-18th May 2024 | 2024 | |

10.18485/resylab.2024.6.ch46

http://dr.rgf.bg.ac.rs/s/repo/item/0008855

Failure estimation of the Majdanpek open pit east face based on inverse velocity model

Miloš Marjanović[(1)], Stefan Milanović[(1)], Nikola Simić[(1)], Lazar Kričak[(1)]

1) University of Belgrade, Faculty of Mining and Geology, Belgrade, Djusina 7, milos.marjanovic@rgf.bg.ac.rs

Abstract The Majdanpek open pit mine south district is currently active mining prospect of copper ore exploitation in eastern Serbia. Its depth is approaching the termination depth and occurrences of large-scale instabilities and global instability of the final pit slope is possible. These can generate catastrophic mass movement inside an area that encloses a regional road route and the Pek River bed which is channelled along the outer contour of the pit. The displacements that were noted in early 2023, in the eastern face of the pit draw further concern and required a detailed monitoring campaign to be undertaken quickly. It included several approaches, but in this work focus was on surveying on 5 static benchmarks through the period January-July 2023. Due to the unknown status of the displacement acceleration or deceleration on its progressive failure path, the inverse velocity calculation of the entire series was undertaken. The series involved surveying of benchmarks using the absolute coordinates measured manually by a total station every 4-5 days. Displacements trends indicated constant cumulative increment with different rates at different benchmarks with periods of acceleration and deceleration. Long-term trend suggests that steep part of the progressive failure curve is not reached. However, inverse velocity trend in most benchmarks suggests slight decrease, indicating possible global progressive failure. Other monitoring approaches confirmed only local failures, while limit equilibrium stability models suggest both, presence of local failures and marginally stable slopes with safety approaching one. Inverse velocities estimated failure by the end of 2023. Extensive precaution measures were undertaken to avoid such scenario, including constant early warning evacuation system, as well as immediate remediation measures on reshaping the slope.

Keywords displacement, survey, inverse velocity, open pit

Introduction

The Majdanpek south district open pit mine (Fig. 1), one of the many in the realm of eastern Serbia copper mines is located within the outskirts of the Majdanpek town. The Pek River crosses through the upper horizons of the pit, as well as the regional road No. 33. After more than 60 years of exploitation, the current pit elevation is at about 100 m ASL and its crest at 620 m ASL suggests that it is soon to be approaching its terminal depth of 550 m, as further deepening is considered a bad practice, both economically and for safety reasons (Read and Stacey, 2009). Further deepening below elevation 120 m, as well as tailing atop the crest is working twice-fold to reach that limit, while at the same time it creates stability problems due to mass removal in the base and increase of the mass on top of the slope. In addition, the mine contour has nowhere to spread further, which significantly reduces options regarding the slope engineering (reducing the slope angle and increasing the number of benches cause extension of the pit contour which cannot be suited due to infrastructural constraints). Another potential concern is possible transition to the underground excavation, which raises new stability issues, especially regarding yielding at such higher stresses (creep) or sudden and quick failures along larger structural interfaces (Brummer et al., 2006). The north face of the pit was notorious for its constant displacements and constant need for mitigation and remediation. However, the displacements have been visualized in the east face as well, firstly as subtle tension cracks in the tailing material, but subsequently as gaping cracks several meters deep (Fig. 2). Although displacement tolerance is considerably larger than in urban and infrastructural Geotechnical practice, quick development of these disturbing features opted for a comprehensive monitoring project in January-July 2023. There are alerting examples of large-scale slope failures in open pits, especially in the cases of transiting to underground excavation and further disturbing of rock masses by blasting and stress concentration along discontinuities, e.g., Palabora mine (Stewart et al., 2001). They result in millions of cubic meters of materials and immense material damage, which is especially concerning given the site's disposition (vicinity to urban, natural and infrastructure domains).

Figure 1 Plan view of the Majdanpek south district open pit (red).

Figure 2 Gaping cracks and local benching between conjugated failure planes on the abandoned tailing horizon 550 m.

Methodology

Management of landslides, especially at the open pit slopes require constant displacement monitoring, to avoid any incidents that might affect staff and equipment. Cumulative displacements, with appropriate frequency of measurements, are one good indicator, but assuming the stage of the curve is difficult in an on-going survey. The same applies for velocity derived as displacement per temporal frequency of measurements (mm/day), although acceleration and deceleration phases can be recognized. An alternative is to use inverse velocity, i.e., temporal frequency vs. displacement (day/mm) as its threshold cut-off is zero, when theoretically the velocity of failure approaches infinity. Once day/mm trend is established (usually following the linear fashion) it is possible to linearly extrapolate the trend and determine the time when it will reach zero, i.e., the moment of failure.

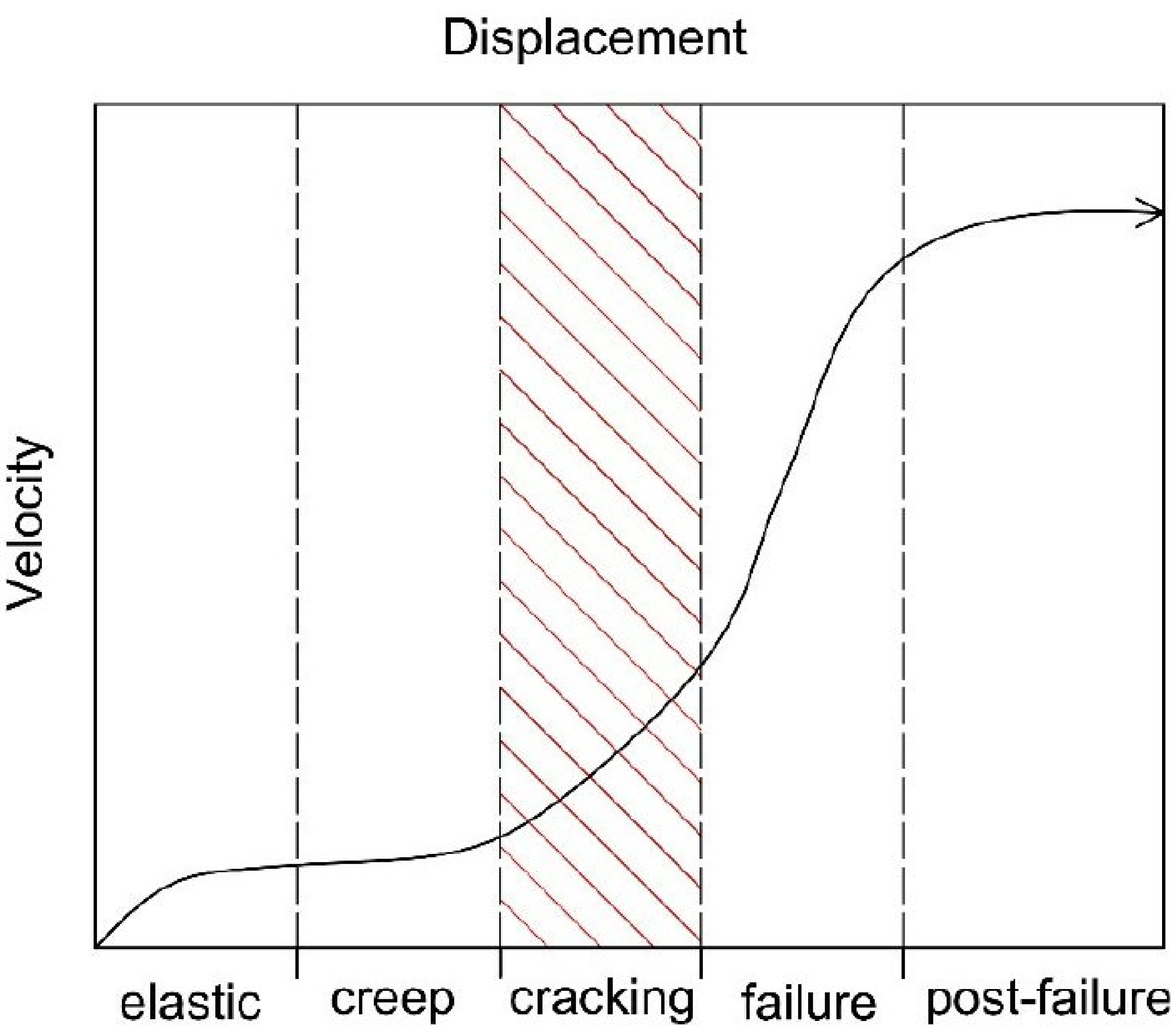

Figure 3 Schematic progressive failure curve and phases of deformation, with current slope state (shaded area).

The concept of inverse velocity to predict slope failure time are dating back to the 80's (Fukuzono, 1985) and have been perfected and updated more recently (Rose and Hungr, 2007; Carlà et al., 2017: Zhou et al., 2020). There are some important assumptions and limitations involved. Firstly, it assumes the creep motion along a progressive failure curve, which has several states with increasing acceleration, but the last stage is mainly linear (Fig. 3). Secondly, it presumes several invariants, and constat conditions slope conditions. Consequently, it is not suitable for structurally controlled and brittle failure modes, nor it is utterly realistic for open pits where significant slope profile change is common, hydrogeological conditions change, loading and unloading is taking place, as well as blasting and other mining activities. However, there are reports on successful estimation and avoiding of catastrophic scenarios using the inverse velocity approach (Rose and Hungr, 2007).

The open pit was monitored by various techniques:

- conventional fixed benchmarks survey;
- photogrammetric imaging using drone;
- terrestrial radar interferometry;
- piezometer water table surveillance
- visual inspection.

In this work, the focus is on the results of surveying measurements which have been undertaken from January to July 2023, with average frequency of 4-5 days. Absolute coordinates in Gaus-Kruger Zone 7 reference system were determined in each visit manually, using a total station. Nine benchmarks were initially installed, but four of them succumbed to local instabilities and were not monitored throughout the entire period. Their spatial positioning was arrayed in a 3x3 grid covering the central part of the eastern face of the pit (Fig. 4). The benchmarks are allocated in rows following the bench geometry, so all three in a row are more-or-less of same elevation. They are labelled R1-9 starting from the lower towards the upper positions. Although not in focus, other techniques were used to cross-compare with results of surveying.

Results and discussion

The main issue in interpreting the surveying results is weather the slope is globally or locally unstable, and weather failures are structurally controlled. The initial stability analysis suggests fair factors of safety in range 1.3-1.4, but these were not conducted in saturated nor in seismic conditions, and major structures were not taken into account. When all these additional factors are introduced, the factor of safety drops to one, which is marginally stable case, open to interpretation in favour of global slope failure. Alongside, the stability model identifies many local failures in the upper horizons, hosted in the tailing material. Due to intensive activities in the lower horizons, three lower (labelled R1-3) and one middle (labelled R7) benchmarks were compromised, leaving five in the upper part functional through the entire observation period.

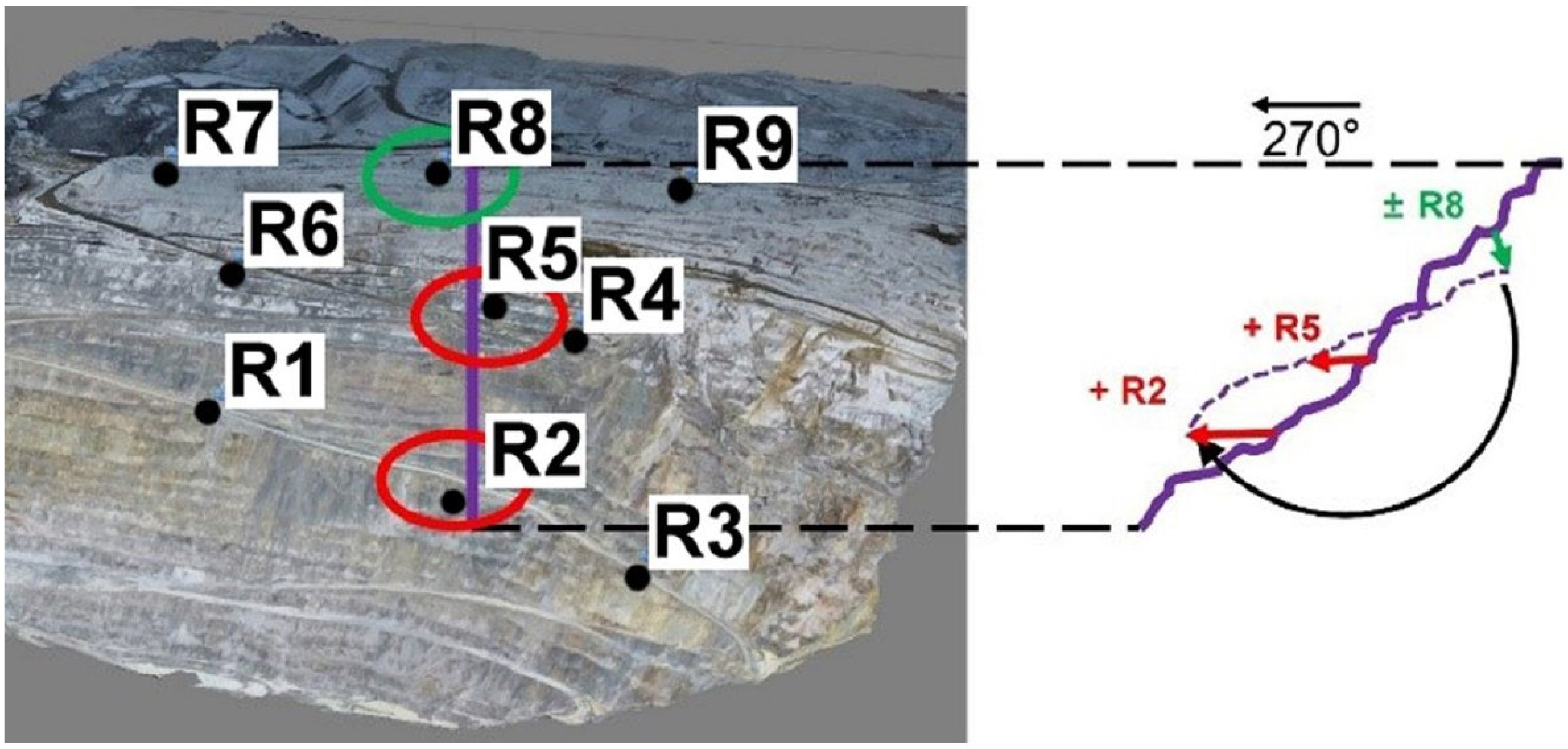

Figure 4 Schematic display of global rotational failure based on initial benchmark measurements.

Initially, during the first month of the survey, the lower benchmarks R1-3 showed indications of more dominant horizontal component vs. vertical displacement (~30 mm/day vs. ~10 mm/day, respectively), whereas the topmost benchmarks showed twice larger vertical displacements than horizontal (~20 mm/day vs. ~10 mm/day, respectively). This is an indication for global rotational slip, which has been further measured (Fig. 5). After this period, in March 2023 the lower benchmarks were destroyed and became inaccessible, partly due to regular mine operations, but partly due to deformations.

Cumulative displacement suggests that there are periods of acceleration and deceleration, which are synchronized across all benchmarks (Fig. 5), indicating that global failure is possible, and that inelastic creep is in progress. Displacement rate is the highest in benchmark R 8, reaching 60 mm/day. Smaller accelerations were obvious in Jan-Feb (ranging between 10-20 mm/day), and Apr-May (ranging between 20-30 mm/day), while the most prominent one is in Jun-July (ranging between 30-40 mm/day). In between, the displacement rate is constant at about 5-10 mm/day. Such rate corresponds to Slow to Moderate landslides according to conventional classification (Hungr et al., 2014), while in domestic mining legislation they can be considered level 4 of 5, which is an alerted stage, just before immediate actions.

Despite the heavy rainfall which was often in first part of the 2023, causing flooding in the Pek River area. there was no direct correlation of these accelerations with the rainfall. as R^2 value was as low as 0.3. Mining activities were also uncorrelated, due to simultaneous unloading of the lower horizons and loading of the upper ones. In addition, the unloading was undertaken on the in the upper horizons comprising of the tailing material, to prevent local failures.

All these findings cannot unambiguously eliminate possibility that benchmarks are related to several independent local failures, but it is likely that the failure is not structurally controlled, as accelerations are subtle and synchronized across large area.

Displacement rates are calculated for Northing, Easting and Z directions and total vector. Given the slope orientation, the total horizontal vector more-or-less coincides with westward movement. Therefore, the most interesting are findings for -Y and -Z (vertical) directions. The inverse velocity linear trends (Fig. 6) are suggesting that the creep is still not in the final acceleration phase, as the trend gently declines towards the horizontal axis for all benchmarks. Benchmark R9 is showing biased values as it has both uplift and subsiding, so its general trend is parallel to horizontal axis. In other words, there are no accelerations and decelerations at R9 position, and its overall displacement rate is minor in comparison to other benchmarks, which is also apparent from the cumulative plot (Fig. 5). For this reason, R9 is not visualized in Fig. 6.

All linear trends are calculated using least square method. Their linear extrapolations (Fig. 6) are not ideally aligned, but all indicate failure by the end of 2023 or beginning of 2024.

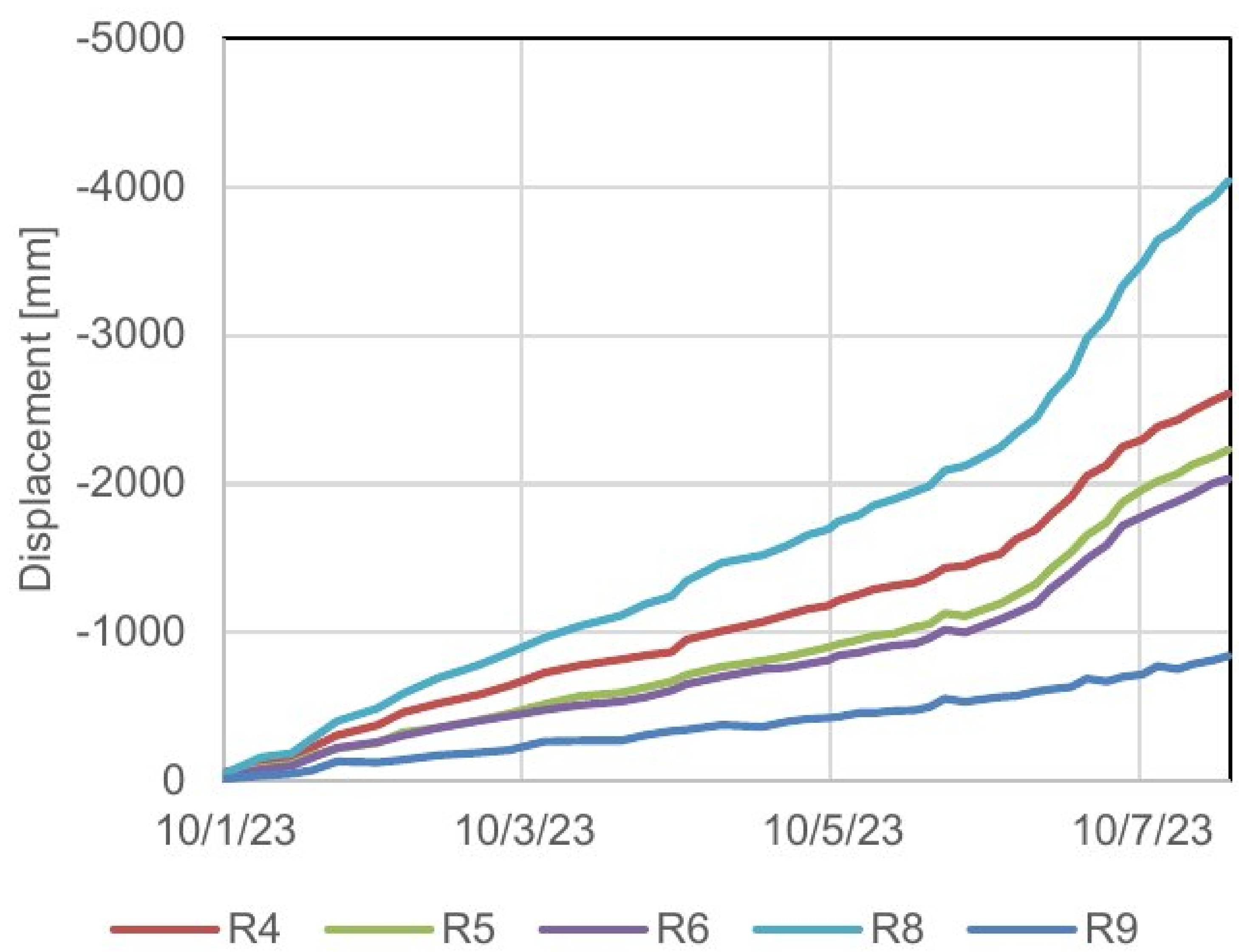

Figure 5. Cumulative vertical displacement for Jan-Jul 2023 on benchmarks R4-9.

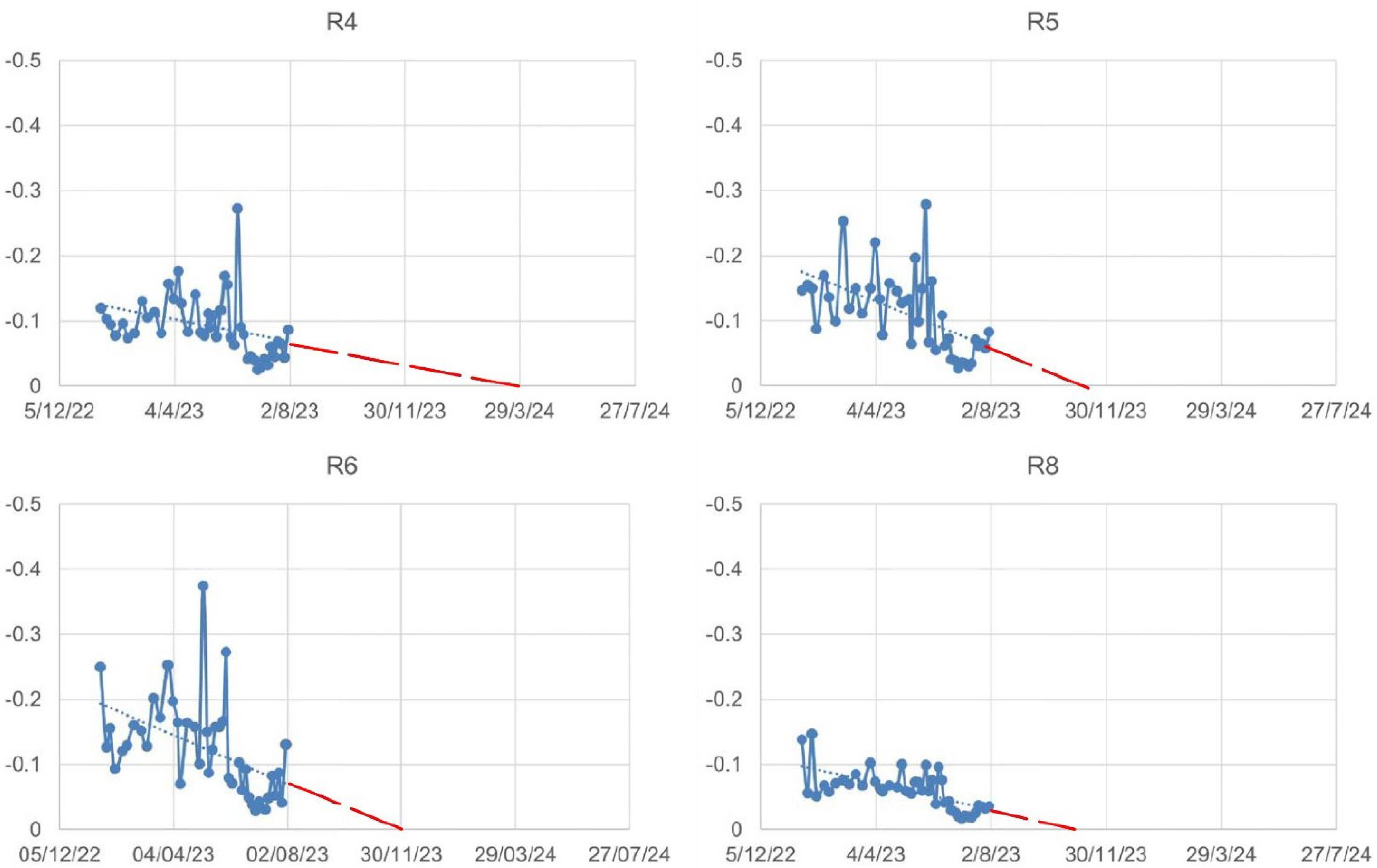

Figure 6 Inverse velocity plots of vertical displacements and extrapolated time of failure (red dashes).

As the immediate measures were undertaken to prevent further displacement acceleration (including reshaping of the slope geometry and draining), this pessimistic estimation was luckily never confirmed, although it remains a big question weather the failure would follow the estimated linear trend or curve back upward and decelerate to a new steady state, as previously seen in some examples (Carlà et al., 2018). It is likely that a simple creep mechanism cannot entirely approximate the behaviour of a large rock slope, and that other complexities and additional factors were more influential than anticipated.

Conclusion

This work describes a case study of an open pit mine and its unstable slope, which was potentially facing a global failure. With factors of safety approaching one and visually observed cracks and dislocations in the beginning of 2023, a monitoring system was engaged using several techniques, acquiring data from hourly to weekly basis. The purpose of these measurements was to determine the current state of the slope and predict further displacement behaviour. In this work, the focus was on benchmark survey, including 9 positions in total, 5 of which survived the monitoring period. All analysis showed periods of considerable accelerations, within six-month period and implied undertaking of immediate actions to increase the slope stability. Accordingly, the slope was reshaped and drained, while further long-term stability plans were underway. The inverse velocity model was showing rather pessimistic estimation, which included a pessimistic outcome of global slope failure on 4 of 5 surveying benchmarks, by the end of 2023, while one benchmark indicated failure in March 2024. It is also important to mention that theoretically the moment of failure takes place even sooner than the trend reaches zero. Such scenarios were luckily avoided, but the analysis was used to persuade immediate actions and plan future long-term slope stability, especially in case the exploitation transits to underground excavation. Even more elaborate monitoring system is therein required, with operative early warning system installed to set alarms when thresholds are reached.

References

Brummer R K, Li H, Moss A (2006) The transition from open pit to underground mining: an unusual slope failure mechanism at Palabora. In Proceedings International Symposium on Stability of Rock Slopes in Open Pit Mining and Civil Engineering, Cape Town. The South African Institute of Mining and Metallurgy. pp. 411-420.

Carlà T, Intrieri E, Di Traglia F, Nolesini T, Gigli G, Casagli N (2017) Guidelines on the use of inverse velocity method as a tool for setting alarm thresholds and forecasting landslides and structure collapses. Landslides. 14: 517-534.

Carlà T, Macciotta R, Hendry M, Martin D, Edwards T, Evans T., Farina P., Intrieri E., Casagli N (2018) Displacement of a landslide retaining wall and application of an enhanced failure forecasting approach. Landslides. 15: 489-505.

Fukuzono T (1985) A method to predict the time of slope failure caused by rainfall using the inverse number of velocity of surface displacement. Landslides 22(2): 8-13.

Hungr O, Leroueil S, Picarelli L (2014) The Varnes classification of landslide types, an update. Landslides. 11: 167-194.

Read J, Stacey P (2009) Guidelines for open pit slope design. CSIRO publishing Collingwood, Australia. 495p.

Rose N D, Hungr O (2007) Forecasting potential rock slope failure in open pit mines using the inverse-velocity method. International Journal of Rock Mechanics and Mining Sciences. 44(2): 308-320.

Stewart A, Wessels F, Bird B (2001) Design, Implementation, and Assessment of Open Pit Slopes at Palabora over the Last 20 Years. In: Hustrulid, McCarter, Van Zyl (eds.) Slope Stability in Surface Mining. Society for Mining, Metallurgy and Exploration. Littleton, USA. pp. 177-181.

Zhou X P, Liu L J, Xu C (2020) A modified inverse-velocity method for predicting the failure time of landslides. Engineering geology 268: 105521.