

Analytical Review of the Methods of Studying Open Pit Slope Stability Under the Conditions of Mining Operations Digitalization

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<p>Received: <i>January 26, 2026</i> Peer-reviewed: <i>April 22, 2026</i> Accepted: <i>May 8, 2026</i></p>	<p>ABSTRACT Open-pit slope stability is one of the key factors determining the safety and efficiency of open-pit mining operations. With increasing pit depth, growing complexity of rock mass structure, and intensification of mining activities, the need for advanced methods for studying slope stability based on digital technologies is steadily increasing. The aim of this study is to systematize and comparatively analyze modern methods for investigating open-pit slope stability, taking into account their capabilities and limitations under mining conditions. The paper presents an analytical review of computational geomechanical approaches, geodetic instrumental methods, terrestrial laser scanning, UAV-based photogrammetry, and satellite radar interferometry (InSAR). A comparative analysis of these methods is performed based on key parameters, including data type, spatial coverage, and capabilities for deformation analysis. The results show that each method has specific advantages and limitations related to data characteristics, observation conditions, and analytical potential. It is established that none of the methods, when used individually, provides a complete and reliable description of slope stability. The highest level of informativeness is achieved through the integration of different methods within comprehensive analytical approaches. The results of this study provide a systematic understanding of the role of modern digital methods in slope stability research and confirm the перспективность of developing integrated digital systems for monitoring and assessing open-pit slope stability.</p>
	<p>Keywords: Slope stability, Computational Method, Instrumental Method, Terrestrial Laser Scanning, Earth Remote Sensing, Integrated Digital System.</p>
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Introduction

Open pit slope stability is one the key factors defining safety and productivity of open pit mining operations. Increase of open mine depths, growing complexity of rock massif structure and intensification of mining operations lead to slope failures, disturbance of production processes and significant

economic losses. In this regard, the study of the stability state of open pit slopes remains an actual scientific and practical task in the mining industry.

Currently, a wide range of methods are used to research the open pit slope stability, including computational geomechanical approaches, instrumental geodetic observations, and remote sensing methods. Digital technologies gained their momentum,

these are terrestrial laser scanning, photogrammetry based on unmanned aerial photography, SAR interferometry and numerical modeling have been significantly developed to obtain spatial data on the geometry of slopes and the development of deformation processes.

Modern studies of the open pit slope stability are increasingly based on the use of digital methods that expand possibilities of assessing the condition of open pit slopes and analyzing the development of deformation processes. At the same time, the applied methods are focused on solving various problems of stability research, including assessment of the current condition of slopes, identification of potentially dangerous zones, analysis of deformation mechanisms and justification of deformation development forecast, which conditions need for their comparative and integrated consideration.

The aim of this study is to systematize and comparatively analyze modern methods for investigating the stability of open-pit slopes, taking into account the capabilities of digital technologies and assessing their applicability in open-pit mining conditions. The study examines the capabilities and limitations of computational, geodetic, and remote sensing methods, compares them according to key parameters, and determines the role of their integration in the analysis and prediction of deformation processes.

In this context, the following research questions are addressed: which methods provide the most informative description of open-pit slope stability, what are the limitations of their application under real mining conditions, and to what extent the integration of different approaches improves the reliability of stability assessment and deformation prediction.

Analytical Review of Modern Methods of Studying the Open Pit Slope Stability

Computational Methods

Computational methods of assessing open pit slope stability traditionally occupy a central place in the practice of open pit mining operations design and operation. Their basis is analysis of the limit equilibrium of the rock massif with determination of the stability coefficient for the assumed failure surface. Classical methods, such as the methods of Fellenius, Bishop, Yanbu, Spencer and their modifications, have become widespread due to their relative ease of implementation and normative confidence [[1], [2], [3]].

Application of computational methods allows for taking into account geometrical parameters of slopes, physical and mechanical properties of rocks, and influence of underground waters and external loads. At the same time, these approaches, as a rule, assume a priori setting of the failure surface shape and use of averaged massif characteristics, which significantly limits their applicability under the conditions of complex geological structure and pronounced structural heterogeneity of rocks [[2], [4]].

Introduction of numerical modeling methods, including finite element, finite difference and discrete element methods, has ensured further development of classical design schemes. Numerical models allow for analyzing the stress-strain state of the massif in two- and three-dimensional presentation, for taking into account the layer-by-layer structure, tectonic disturbances and stages of mining operations [[5], [6]]. The application of such approaches expands possibilities of studying the mechanisms of slope failure and assessing influence of various factors on their stability.

In one of the studies [7], computational methods are complemented by multiple-factor analysis oriented at identifying key geological and geomechanical factors that determine slope stability. At the same time, classification and empirical approaches based on the use of integral indices of the massif state are used, which allow for performing rapid assessment of stability, but they are of general nature and expedient mainly for preliminary analysis [[8], [9]].

A number of studies address risks and typical methodological errors that occur in calculations of open pit slope stability. It is noted that the reliability of the obtained results is largely determined by the quality of the input data, correctness of the choice of the calculation scheme and validity of the accepted assumptions [4]. These aspects become particularly important when assessing stability in specific environments including layered massifs, man-made formations and non-metallic mineral open pit mines [[10], [11], [12]].

Computational methods provide a basic engineering assessment of open pit slope stability and remain an important tool for geomechanical analysis. At the same time, their application is not oriented at operative detection of deformations and direct analysis of hazardous processes development. In this regard, it is advisable to consider computational methods as a part of complex approaches that provide for the integration of computational models

with the results of instrumental geodetic observations and remote sensing data, which is discussed in the following sections of this review.

Geodetic Instrumental Methods

Geodetic instrumental methods are widely used in the study of the open pit slope stability as an instrumental basis for obtaining data on the deformations of rock massifs. In contrast to computational approaches, geodetic observations make it possible to record actual slope displacements in time, which provides a transition from computational stability assessment to the analysis of its current state [[13], [14]].

The tacheometric method is traditionally used to study deformation processes in the zones of potential instability of open pit slopes. Repeated high-precision measurements of survey marker coordinates allow for identifying directions and velocities of displacements, and for assessing nature of deformations, which is an important part of the rock massif stability analysis. At the same time, the point nature of tacheometric observations and the need to ensure direct visibility between the instrument and the object of observation limit the possibilities of spatial analysis of the slope condition, especially in case of their considerable length and complex configuration [[15], [16]].

Satellite geodetic methods based on the use of GNSS technologies are applied in the studies of open pit slope stability to form time series of displacements and arrange quasi-continuous observations. The use of stationary GNSS points allows for analyzing dynamics of deformation processes and identifying trends in their development, which is taken into account when assessing massif stability under the conditions of active mining operations [[17], [18]]. However, it should be emphasized that the accuracy and reliability of GNSS measurements in deep quarries can be reduced due to the screening of satellite signals, reflection from the surfaces of mining equipment and structures, and influence of dynamic loads, which requires a reasonable choice of observation schemes [18].

The joint use of tacheometric and satellite geodetic measurements is applied in the studies of open pit slope stability. This approach improves the reliability of open pit slope stability assessment due to mutual validation of data and compensating for the limitations of individual methods. Geodetic data in this case are used not only to record deformations, but also to analyze compliance of the actual behavior of the slope with the design geomechanical models [[13], [14]].

The scientific literature discusses the issues of methodological support of the geodetic observations in the open pit slope stability studies, including selection of the system of survey markers and working survey markings, justification of the frequency of measurements and methods for the results processing. Correct interpretation of geodetic data is a key condition for their use in stability assessment and in the process of making engineering decisions [[16], [19]].

Geodetic methods play an important role in studying the open pit slope stability, while providing highly accurate reliable information on the actual deformations of the rock massifs. At the same time, the limited spatial coverage and point nature of the observations necessitate their integration with other numerical methods of stability studies to ensure a holistic understanding of the slope stability condition.

Terrestrial Laser Scanning

Terrestrial Laser Scanning (TLS) has become widespread in recent years in the study of open pit slope stability due to the possibility of obtaining a detailed three-dimensional representation of their geometry. Unlike point geodetic measurements, TLS provides a continuous description of the slope surface with high spatial detailing, which significantly expands the possibilities of analyzing their condition [[20], [21], [22]].

One of the key areas of TLS application is the study of geometric parameters of slopes and their changes with time. Comparison of three-dimensional models formed based on multiple measurements by terrestrial laser scanning allows for detecting spatial displacements of the slope surface, analyzing the distribution of deformations and localizing zones of potential instability. Such data are used to assess the nature of deformation behavior of slopes and to clarify understanding of their failure mechanisms [[22], [23]].

The main advantage of TLS is the possibility of detailed analysis of structural features of rock massifs. Based on point clouds, the fracture systems, layering and other structural elements that determine the kinematic conditioning of slope stability are identified. The use of laser scanning data increase's reliability of stability assessment due to a more accurate specification of the geometry and orientation of structural disturbances in geomechanical models [[24], [25]].

TLS data have been successfully used in the verification of computational models of open pit slope stability. Comparison of the results of numerical modeling and actual deformations detected by laser

scanning data allows for refining the calculation schemes and improve the validity of engineering decisions [[20], [26]].

Application of terrestrial laser scanning has a number of limitations. These include dependence of the data quality on the observation environment, presence of shadow zones, and the need for complex processing and interpretation of point clouds. It is noted that the TLS results themselves do not allow for judging the stability reserve of slopes unambiguously without the use of computational and analytical methods, which emphasizes the auxiliary, although important, nature of this approach in the system of stability studies [[23], [26]].

Terrestrial laser scanning is used for detailed spatial analysis of the geometry and structural features of open pit slopes, while providing a detailed description of their geometry and structural features. The greatest information content of TLS is achieved when it is used as a part of complex approaches that provide for integration of laser scanning data with the results of geodetic observations, photogrammetry and computational geomechanical analysis [[20], [22]].

Photogrammetry Based on Unmanned Aerial Photography

In recent years photogrammetric methods based on unmanned aerial photography have become widespread in the studies of open pit slope stability due to that they combine efficiency, high information content and ability to cover large areas. Use of unmanned aerial vehicles (UAVs) allows for obtaining detailed images of open pit slopes and adjacent areas, based on which digital surface models are formed; the latter are used to analyze the geometric condition of slopes and identify signs of deformation processes [[27], [28]].

Photogrammetric processing of aerial photography data is usually implemented using Structure from Motion (SfM) methods, which ensures construction of three-dimensional slope models and their subsequent comparison in time. Multitemporal analysis of digital surface models makes it possible to detect changes in slope geometry, analyze changes in the shape and volume of surface elements and record development of deformation processes, which is important in the studies of open pit slope stability [[29], [30]].

Numerical models allow for analyzing dynamics of deformation processes and identifying preliminary potential instability zones. At the same time, it is of fundamental importance to ensure sufficient accuracy of the three-dimensional models and correctness of geodetic referencing, since these factors

determine the validity of the use of photogrammetric data in slope stability studies [31].

A significant advantage of photogrammetry based on unmanned aerial photography is the possibility to perform surveys under the conditions that are complicated or unsafe for ground-based observations. This makes it possible to obtain information on the condition of slopes along their entire length and in hard-to-reach areas, which expands the possibilities of spatial analysis of the open pit slope stability compared to point instrumental methods [[27], [32]].

Studies show that photogrammetric methods have a number of limitations for the performance of open pit slope stability studies. These include dependence of the results quality on meteorological conditions, illumination, and survey equipment characteristics, and the possible decrease in accuracy in areas with poor surface texture. Moreover, three-dimensional models derived from UAV data usually require verification by ground-based geodetic observations or laser scanning when they are used for engineering stability assessments [[28], [31]].

Photogrammetry based on unmanned aerial photography is widely used for spatial analysis of the condition of open pit slopes, especially at the stage of identification and localization of deformation processes. The greatest information content of this approach is achieved when it is integrated with terrestrial laser scanning, geodetic observations and computational geomechanical models, which ensures a comprehensive study of the open pit slope stability [[30], [32]].

Earth Remote Sensing Methods (InSAR)

Earth remote sensing methods based on satellite radar interferometry (InSAR) have become widespread in the studies of open pit slope stability due to the possibility of detecting deformations of the earth surface at large areas. Unlike ground-based instrumental methods, InSAR ensures spatial analysis of deformation processes without the need to place measuring instruments directly on the slopes, which is especially relevant for large and hard-to-reach mining objects [[33], [34]].

Modern interferometric approaches, including permanent scatterer methods (PS-InSAR) and small-basis methods (SBAS), allow for generating temporal series of displacements and for analyzing the dynamics of deformation processes in open pit mines over long periods of operation. The obtained data are used to identify zones of stable and unstable behavior of massifs, and to assess trends in defor-

mation development, which is of fundamental importance when studying the stability of open pit slopes [[35], [36]].

Use of InSAR methods is most appropriate for early detection of deformation processes preceding the development of dangerous stability failures. Analysis of spatial and temporal patterns of displacements allows for identifying areas with progressive deformations and for using the obtained information to justify engineering decisions aimed at ensuring stability of open pit slopes [[33], [37]].

At the same time, there are difficulties with the interpretation of InSAR data in the studies of open pit slope stability due to a number of methodological limitations. These include the single-component nature of the measured displacements along the satellite line of sight, influence of atmospheric effects, and decrease in accuracy under the conditions of intensive anthropogenic changes in relief. In this regard, InSAR data require comparison with the results of ground-based geodetic observations and other sources of information on the rock massif condition [[36], [38]].

Use of InSAR as a part of complex approaches allows for increasing the reliability of the studies of open pit slope stability due to the mutual complementation of spatial and point data, and refining of models of deformation behavior of massifs [[33], [38]].

Radar interferometry methods are widely used for spatial analysis of deformation processes related to the stability of open pit slopes. The greatest practical value of InSAR is manifested when it is used as a part of integrated digital stability research systems that provide for the joint use of satellite data, ground-based instrumental observations and computational geomechanical models, which creates prerequisites for the transition from deformation recording to analyzing and forecasting their development [[34], [35]].

A comparative analysis of the considered methods shows that they differ in terms of the nature of the data obtained, spatial coverage, and capabilities for analyzing deformation processes. Computational methods are focused on engineering assessment of slope stability and allow the analysis of loading scenarios; however, they do not reflect the actual behavior of the rock mass. Geodetic instrumental methods provide highly accurate measurements of displacements, but are limited by the point-based nature of observations. Terrestrial laser scanning and photogrammetry enable the acquisition of spatial data on slope geometry, although their applica-

tion depends on acquisition conditions and data processing. Satellite interferometric methods (InSAR) allow the analysis of deformation over large areas and long time periods; however, they require careful interpretation and comparison with ground-based measurements. The results of the comparative analysis of the methods are presented in Table 1.

Table 1 - Comparative Analysis of Methods

Method	Data type	Spatial coverage	Informational capability	Main limitation
Computational methods	Model-based	Full	Stability assessment	Assumptions
Geodetic methods	Point measurements	Local	Actual displacements	Limited coverage
TLS	3D spatial data	Local to near-full	Geometry and structure	Shadow zones
UAV photogrammetry	3D surface models	Areal	Surface deformation	Acquisition conditions
InSAR	Radar displacements	Wide-area	Deformation trends	Interpretation

Thus, none of the methods considered individually provides a complete and reliable description of the stability state of open-pit slopes, which necessitates their combined application within integrated approaches.

Integrated Digital Systems and Prospects for the Methods Development

Modern trends in the development of methods for studying open pit slope stability are characterized by the transition from the use of separate instrumental and computational approaches to the formation of integrated digital systems. Such systems combine data from geodetic observations, laser scanning, photogrammetry, satellite interferometry and computational geomechanical analysis, which allows for considering slope stability as a dynamic state of rock massifs [[26], [39]].

The integration of heterogeneous data sources significantly expands possibilities for studying the open pit slope stability. The joint analysis of geospatial and point measurements allows a more complete description of massif deformation behavior, while revealing the relationship between geometric changes, structural properties and stress-strain state of massifs [[40], [41]]. This approach contributes to improving the reliability of interpretation of the observed deformations and reduction of uncertainty in the stability assessment.

A separate innovative direction in the development of integrated systems is associated with the use of methods of data mining and elements of artificial intelligence. Approaches based on the application of neural networks and machine learning algorithms are increasingly used for predicting the stability indicators for open pit slopes based on a set of geological, geomechanical and monitoring parameters [42]. Use of such methods allows for identifying patterns in large amounts of data and more validated assessments of stability status.

Efficiency of the integrated digital systems is largely determined by the quality of the input data and correctness of the methodical organization of their joint analysis. The difference of spatial and temporal scales of observations, heterogeneity of measurement accuracy and lack of unified data harmonization procedures remain significant methodological limitations in the studied of the open pit slope stability [[26], [39], [43]].

The integrated digital systems represent a promising direction in the development of methods for studying open pit slope stability. Their use creates prerequisites for transition from isolated recording of deformations to complex analysis and forecasting of deformation behavior of rock massifs, which is the key task in ensuring the safety of open pit mining operations [[42], [43]].

Conclusion

The paper presents the analytical review of modern methods of studying open pit slope stability from the point of view of introduction and development of digital technologies. Computational geomechanical approaches, geodetic instrumental methods, terrestrial laser scanning technologies, photogrammetry based on unmanned aerial photography, and satellite radar interferometry methods are considered. The analysis performed shows that each of the considered approaches has specific capabilities and limitations that determine specifics of their use in the studies of the open pit slope stability.

It is shown that computational methods retain a key role in engineering assessment of slope stability, but under the conditions of complex geological structure and dynamic development of deformation

processes, their use requires mandatory comparison with instrumental observation data. Geodetic methods provide reliable information on actual slope displacements, but due to the point nature of observations, they have limited opportunities for spatial analysis of stability conditions. Digital methods based on laser scanning, photogrammetry and Earth remote sensing significantly expand the possibilities of stability studies due to the formation of spatial representation of slope geometry and the properties of deformation processes development.

Analysis of literature sources indicates that the greatest information content in the study of open pit slope stability is achieved by integrating data obtained by different methods. Formation of integrated digital systems allows for considering slope stability as a dynamic state of rock massifs, for taking into account spatial and temporal peculiarities of deformation development and for increasing validity of conclusions on the stability state.

At the same time, it was revealed that further development of methods for studying open pit slope stability is largely constrained by the lack of unified approaches to the coordinated interpretation of the data of different scales and complexity of their joint use within a single methodological scheme. In this regard, improvement of the analysis and interpretation the actual scientific and practical task remains for digital monitoring data remain a relevant scientific and practical problem, with the focus on the transition from the fixation of deformations to a reasonable analysis and forecasting of their development.

Therefore, the results of the review confirm feasibility of the integrated use of computational and numerical methods in the study of open pit slope stability and emphasize prospects for further research focused on the development of integrated digital approaches and improving the efficiency of safety of open pit mining operations.

Conflicts of interest. The authors have no financial or personal conflicts of interest related to this work.

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Тау-кен жұмыстарын цифрландыру жағдайында карьерлік беткейлердің тұрақтылығын зерттеу әдістеріне аналитикалық шолу

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<p>Мақала келді: 26 қаңтар 2026 Сараптамадан өтті: 22 сәуір 2026 Қабылданды: 8 мамыр 2026</p>	<p>ТҮЙІНДЕМЕ Карьерлік еңістердің тұрақтылығы ашық тау-кен жұмыстарының қауіпсіздігі мен тиімділігін айқындайтын негізгі факторлардың бірі болып табылады. Карьерлердің тереңдеуіне, жыныс массивінің геологиялық құрылымының күрделенуіне және тау-кен жұмыстарының қарқындылығының артуына байланысты цифрлық технологияларға негізделген карьерлік еңістердің тұрақтылығын зерттеу әдістерін қолдану қажеттілігі арта түсуде. Осы зерттеудің мақсаты — ашық тау-кен жұмыстары жағдайында қолданылу мүмкіндіктері мен шектеулерін ескере отырып, карьерлік еңістердің тұрақтылығын зерттеудің заманауи әдістерін жүйелеу және салыстырмалы талдау жүргізу. Жұмыста есептік геомеханикалық тәсілдерге, геодезиялық аспаптық әдістерге, жерүсті лазерлік сканерлеу технологияларына, ұшқышсыз ұшу аппараттарына негізделген фотограмметрияға, сондай-ақ спутниктік радиолокациялық интерферометрия әдістеріне аналитикалық шолу ұсынылған. Әдістерге деректер түрі, кеңістіктік қамту және деформациялық процестерді талдау мүмкіндіктері сияқты негізгі параметрлер бойынша салыстырмалы талдау жүргізілді. Әрбір әдістің қолданылу саласын айқындайтын өзіндік артықшылықтары мен шектеулері бар екені көрсетілген. Жеке қарастырылған әдістердің ешқайсысы карьерлік еңістердің тұрақтылық жағдайын толық әрі сенімді сипаттай алмайтыны анықталды. Ең жоғары ақпараттылық әртүрлі әдістерді кешенді тәсілдер аясында біріктіру кезінде қол жеткізіледі. Алынған нәтижелер карьерлік еңістердің тұрақтылығын зерттеудегі заманауи цифрлық әдістердің орны мен рөлі туралы тұтас түсінік қалыптастырып, олардың мониторинг пен бағалауға арналған интеграцияланған цифрлық жүйелерін дамытудың перспективасы екенін дәлелдейді.</p>
	<p>Түйін сөздер: беткейнің тұрақтылығы, есептеу әдісі, аспаптық әдіс, жердегі лазерлік сканерлеу, Жерді қашықтықтан зондтау, интеграцияланған цифрлық жүйе.</p>
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Аналитический обзор методов исследования устойчивости карьерных откосов в условиях цифровизации горных работ

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<p>Поступила: 26 января 2026 Рецензирование: 22 апреля 2026 Принята в печать: 8 мая 2026</p>	<p>АННОТАЦИЯ</p> <p>Устойчивость карьерных откосов является одним из ключевых факторов, определяющих безопасность и эффективность открытых горных работ. С увеличением глубины карьеров, усложнением геологического строения массивов и интенсификацией горных работ возрастает необходимость применения методов исследования устойчивости карьерных откосов, основанных на использовании цифровых технологий. Целью настоящего исследования является систематизация и сравнительный анализ современных методов исследования устойчивости карьерных откосов с учётом их возможностей и ограничений в условиях открытых горных работ. В работе представлен аналитический обзор расчётных геомеханических подходов, геодезических инструментальных методов, технологий наземного лазерного сканирования, фотограмметрии на основе беспилотной аэрофотосъёмки, а также методов спутниковой радиолокационной интерферометрии. Выполнен сравнительный анализ методов по ключевым параметрам, включая тип данных, пространственный охват и возможности анализа деформационных процессов. Показано, что каждый из методов обладает специфическими преимуществами и ограничениями, определяющими область его применения. Установлено, что ни один из методов, рассматриваемый отдельно, не обеспечивает полного и достоверного описания состояния устойчивости карьерных откосов. Наибольшая информативность достигается при интеграции различных методов в рамках комплексных подходов. Полученные результаты формируют целостное представление о роли современных цифровых методов в исследовании устойчивости карьерных откосов и подтверждают перспективность развития интегрированных цифровых систем мониторинга и оценки их устойчивости.</p>
	<p>Ключевые слова: устойчивость откоса, расчётный метод, инструментальный метод, Наземное лазерное сканирование, дистанционное зондирование Земли, интегрированная цифровая система.</p>
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