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GEOMECHANICAL ASSESSMENT OF MINERAL DEPOSITS BASED ON 3D MODELING

Protection of geological environment and safe development of mineral deposits is based on the data on their geological and geotechnical conditions. The research used the geological, experimental and mathematical methods and the modern computer technology. The deposit observations were carried out in underground mine workings, and geological documentation of exploration logs was carried out with appropriate testing and processing of the data obtained. With the intensification of mining operations, the volume of open mined-out space increases, the roof rocks disintegrate, and the support pillars get damaged and fail. These phenomena can lead to large-scale man-made disasters if geological and geotechnical conditions of mining are neglected. The quantitative and qualitative geological and geotechnical assessment of a mineral deposit is based on its 3D geological model. The research results were tested in an operating mine.

Keywords: *3D deposit model, geomechanics, geological and geotechnical conditions, rock mass, database, stability of mine workings*
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Introduction

Prediction of geomechanical behavior of rock mass in the course of mineral mining is an urgent problem. The geomechanical study of rock mass is especially important in underground solid mineral mining as it governs the safety of the open mined-out space and the rational implementation of mining operations. Such studies are usually carried out at the pre-project stage of mineral mining and accompany the production work of a mine. The behavior of exposed rocks in the roof, floor and sidewalls of mine workings, and the integrity of the safety and support pillars depends on the geological and geotechnical conditions of a deposit being developed. The need for geological and geotechnical study of a deposit arose from the practical requirements of mineral mining and creation of mining facilities during introduction of advanced technologies with automation and integrated mechanization of mining operations [1].

The timeliness, accuracy and reliability of geological and geotechnical assessment, and prediction of geomechanical processes and phenomena in mine workings are of great importance. The complex behavior of mineral deposits and the multifactorial nature of the processes that arise during mineral mining have some peculiarities. Most of the problems associated with assessing and predicting rock mass stability must be solved at the pre-project stage based on the geological exploration data, i.e. before the construction and operation of a mine. It is important to carry out targeted geological and geotechnical research not only during mineral exploration, appraisal and mine planning and design, but also during heading operations and preparation of mineral reserves for extraction. If such studies are synchronized with geological exploration and exploitation of a deposit, the achieved completeness and self-sufficiency of geological engineering provides a reliable prediction of the geomechanical behavior of rock mass during operation of a mine.

Research procedure

This scientific research involves various approved geological, experimental and mathematical methods and a modern computer technology. The governing methods of the research are the in-situ observations in underground mines, documentation of exploration logs, as well as the appropriate testing and digital processing of the data obtained. The experimental materials were obtained from the field studies during mine development and operation, and from the geological engineering research performed in exploratory drill holes and in stopes in gold mines of the Akbakai ore district. The main geomechanical studies were carried out at the Beskempir thin-vein gold deposit.

The choice of methodological techniques and research methods, and the analysis of the obtained full-scale and lab-scale test data maked it possible to implement a rational integrated field, laboratory and office research. The obtained results were used to [2–5]:

1) study mining conditions based on the special full-scale geological research and targeted processing of the geological database;

2) assess predicted parameters of geotechnical conditions and geomechanical processes during mineral mining.

Achieving this goal is based on 3D modeling of the geological environment, with the help of which the problems of quantitative geological and geotechnical assessment of a mineral deposit are consistently solved.

The methods of field and full-scale experimental research are used to study the behavior and properties of rocks, which can be assessed by quantitative and qualitative indicators. The significance of such research methods grows currently since only on this basis it is possible to assess the spatial variability of geological and geotechnical conditions of a deposit, which is required for the mine design and enables optimal and cost-effective engineering decision-making [6–9]. The geomechanical study of the rock mass was carried out in accordance with accepted international standard systems:

- RQD (Rock Quality Designation);
- Q system (Quality Index);
- RMR (Rock Mass Rating);
- GSI (Geological Strength Index).

These systems are recognized by international societies such as IAEG (International Association for Engineering Geology) and ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering).

Results

Geological and geotechnical studies of rock mass have been carried out and structured in such a way as to ensure the analysis of all data represented by qualitative and quantitative indicators necessary for classifying rock mass according to an accepted system. Documentation exploration logs from exposed walls of underground mine workings and cores from exploratory boreholes made it possible to obtain the following geological and geotechnical indicators:

- representative interval of documentation of mine working walls and drill hole cores;
- rock quality index (RQD);
- condition of rocks (weathering, changes in structure and composition);
- water content of rocks;

• strength of intact rock mass;

• jointing (number of systems, intensity, orientation and other characteristics of joints), etc.

Afield geological parameters of rocks are determined when documenting exposed surfaces. The main purpose of documentation is to obtain information to determine the properties of rocks. The physical and mechanical properties of rocks are important indicators that govern the behavior and reaction of rock mass during mining. The data collected as a result of documentation are important for the design of stable rooms and pillars, for the assessment of collapsibility of hanging wall in rooms and for the heading and mine support design. Here it is important to collect information about all geological and geotechnical indicators that influence the strength and behavior of rocks in mine workings [10–13].

Assessing representative properties of rocks is a challenging task. For this purpose, the testing methods were developed to determine the strength, rigidity and other parameters of laboratory samples. The most difficult task is to assess the strength and the expected behavior of rock mass in the stress field. Today, to determine the rock mass strength and to assess geological and geotechnical conditions of a deposit toward the underground mine planning and design, empirical methods are developed based on application experience.

The geological and geotechnical assessment of a deposit, used later on for 3D modeling, involves studying the geological structure of the deposit, the composition and properties of ore and host rocks, the physical and mechanical properties of ore and host rocks, jointing and weathering of rock mass, a database creation and 3D modeling.

The studies of geological and geotechnical conditions of the Beskempir gold deposit made it possible to form an initial database and to build a three-dimensional models of the geological environment [4, 14, 15]. Processing of a large volume of initial data was carried out using the Micromine Mining and Geological Information System.

Geological structure. The Beskempir deposit is one of the deposits of the Akbakai ore district, which is located 3 km northeast of the Jambyl fault. It is one of the marginal faults of the Jalair–Naiman geosuture. The fault is clearly limited in space by the Kashkimbai fault from the southwest, the Kengir fault from the northeast, the Kyzyljartas fault from the north, and by the South Kengir fault from the south. The length of the Jambyl fault along its strike is about 15 km, and its width is about 3.5–4 km. In the northwest, the Akbakai ore district is overlaid by the Devonian volcanic formations which fill the Kyzyljartas graben–syncline structure. The ore-bearing rocks are igneous rocks represented by three intrusive and one dike complexes.

The Kyzyljartas (Early-Middle Devonian) gabbro-diorite complex is represented by rocks of several intrusive phases. The first phase of intrusion includes subconsonantal and less often secant bodies of small sizes. These bodies are composed of diabases, diabase porphyrites, conga-diabases and diorite porphyrites. A detailed study of the intrusive complex in the area of the deposit revealed that diabase porphyrites have a zone of temperature change at the contact with diorite porphyrites of biotite and biotite–hornblend composition. The formation of these small intrusions occurred in two stages. They clearly differ in their natural radioactivity. The second phase of intrusion includes gabbro-diorites of intrusive appearance, which compose the Kengir stock. The Kyzyljartas intrusion itself completes the formation of the complex. It is composed of rocks that vary in composition from gabbrodiorites through quartz diorites and granodiorites to adamellites and granites. The main part of the intrusion consists of granodiorites, on which, under the influence of granites of the Jeltau Massif, siliceous-potassium metasomatism was superimposed. According to the research data, Kyzyljartas granodiorites, compared to standard granodiorites, are characterized by a higher potassium content, and its content in the area of the Beskempir deposit is slightly higher than in the Akbakai deposit; this can be explained by the proximity of the granites of the Jeltau Massif (siliceous-potassium metasomatism).

The Beskempir deposit is located directly within the southern endocontact of the Kyzyljartas intrusion and is controlled by latitudinal dikes of diorite porphyrite–lamprophyres. The deposit is localized on the eastern side of the dike belt, on the hanging wall of the Beskempir fault. The ore bodies of the deposit, in their location, inherit the conditions of occurrence of lamprophyre dikes and melanocratic diorite porphyrites, and are localized mainly in the same faults as the dikes. These often turn out to be mineralized.

Dikes are of decisive importance in controlling the placement of ore bodies and in deciphering the genesis and age of mineralization. Based on the previous research data, it is found that:

• gold–quartz mineralization is superimposed on latitudinal lamprophyre dikes, which intersect granodiorite-porphyry dikes, and are themselves intruded by diabase porphyrite dikes;

• lamprophyre dikes of variolitic structure are intra-ore (they cross and metamorphose quartz veins, and are overlaid by productive sulfide mineralization);

• age of lamprophyre dikes of the north–northeast strike is 241–256 Myr, which corresponds to the Permian period. The listed dikes contain xenoliths of vein quartz, which contain about 0.2 g/t gold.

The dikes of the north-northeast strike are represented by lamprophyres and diabase porphyrites; they are characterized by a relatively fresh appearance. These dikes cut through ore bodies and release thin apophyses into them. These, in turn, are superimposed on late ore quartz–calcite–antimonite and quartz–calcite mineralization. These facts make it possible to unambiguously determine the age of intrusions, ore formations and dikes.

The rocks of the igneous complex of the deposit area form a relatively large intrusive body; by nature, it is a fractured intrusive massif. In terms of the size and form of occurrence, intrusive rocks make up the area which accommodates all engineering structures of the Beskempir mine field.

Gold mineralization and sulfides are associated with vein quartz, linear beresite zones and mineralized dike areas. Quartz veins and beresites are developed in both footwalls and hanging walls sides of the dikes. The contacts of the quartz–beresite veins, the intensely mineralized dike and silicified granodiorites with each other and with the host granodiorites and the unevenly mineralized dike are clear. There is practically no gold observed in the host granodiorites. The division of dikes into nonmetallic and unevenly mineralized strips is possible at intervals of a limited length. And when the ore body passes from one side of the dike to the other, uneven mineralization is observed. It is developed to the full capacity of the dike and is completely included in the contour of the ore body. In some intervals, the ore body lies at a small (1–3 m) distance from the dike contact and is represented by a thin quartz–beresite vein, and in isolated cases, on the contrary, at short intervals (up to 10 m). The ore body is represented by an unevenly mineralized dike without quartz–beresite fringing.

There are two main and two minor ore veins known at the deposit. The main veins of the deposit include: Beskempir (gently dipping), Surprise (steeply dipping) and the minor Surprise-2 vein (steeply dipping). The ore veins are controlled by dikes. The secondary Berezitovaya vein (has a gentle dip) is not associated with dikes and has poor gold contents. It was impossible to delineate blocks with commercial metal content along it.

The block structure of the deposit somewhat complicates the alignment of veins. However, the transverse faults (displacements) identified within the mine workings are sufficiently geometrized to depth according to exploration drilling data using geological core documentation data and a set of logging diagrams.

Physical and mechanical properties of rocks. The physical and mechanical properties of rocks which compose the above-listed geological structures in the test ore field were studied on selected samples using laboratory testing methods [16–18]. It should be noted that the prospects for studying the physical and mechanical properties of rocks based on the geophysical analysis of exploration logging data are promising.

Jointing. In the conditions of the Beskempir deposit, the study of rock jointing was carried out by visual inspection and using special tools (measuring tape, mining compass, special laser protractor, etc.) both on the walls of mine workings and on the cores from production and exploration drill holes.

The rock mass is assessed as moderately jointed, with crushed intervals in places. The rock mass is composed of rocks with rigid structural bonds, and belongs to the class of very strong and fairly strong rocks. The spatial variability of the properties of the rock mass should be considered relatively stable both along the strike and in depth. Tectonic faults determine the degree of the rock mass disintegration and jointing intensity, as well as development of systems of joints and their spatial orientation in the rock mass. The ore bodies are characterized by varying degrees of intensity of jointing, and hosting granodiorites are generally characterized by the lowest jointing intensity. The main determinants of jointing, its intensity and orientation in the enclosing rock mass of the study deposit are the ore-forming processes and tectonic faults across the strike of the ore bodies. In the study rock mass, there are three main systems of joints, which are located along the dip and strike of the ore bodies, and across the strike. It is found that joints are most intensively developed near faults [19, 20].

Weathering. Typically, rocks outcropped on the surface of the Earth or exposed by mining rarely preserve their initial characteristics in the length of time and deteriorate physically. In the near-surface zone, in the other thermal and physicochemical conditions, rocks undergo various changes — weathering. As a result, a weathering zone, where rocks lose their original properties and quality, appears and grows. When solving engineering geology problems, assessing the degree of weathering of rocks is of great importance, since rock disintegration intensifies as weathering increases.

At the Beskempir deposit, based on the degree of weathering, zones of weakening are identified on the sides of tectonic faults. Weathering and its intensity govern some practical problems of geomechanics to be solved in mine planning and design, for example: a) selection of the most favorable locations for engineering structures (taking into account quality of weathered rocks); b) determination of thickness of weathered rocks to be removed or reinforced in open pits; c) assessment of weathered rock stability in underground workings; d) prediction of possible adverse events such as rock falls, landslides and other types of rock deformations; e) assessment of engineering class of weak weathered rocks, as well as their cutting conditions and methods; f) selection of necessary engineering measures to ensure stability of mine workings, protect them from hazardous deformations of weathered rocks or protect rocks from further exposure to weathering agents [5, 6, 8].

Database creation. In three-dimensional modeling of a deposit, the fundamental basis is a database of geological and geotechnical indicators, which must be replenished and checked in terms of consistency. The obtained data should reflect the actual condition of rock mass in three-dimensional space using quantitative and qualitative indicators. The results of our research served as the database of geological and geotechnical indicators to be estimated using canonical and interval data tables.

Canonical data tables include files *collar* (coordinates) and *survey* (inclinometry); using the data from these files, the trajectory of the mouth (beginning) and end of the geological documentation interval is visualized in space.

Interval tables are documentation files *geotech drive* (walls of underground mine workings) and *geotech drillhole* (core of drill holes).

These files are needed to visualize the results of documentation of geotechnical indicators in a rock mass, which are the initial data for interpolating quantitative parameters into a block model (evaluation of indicators in a three-dimensional environment) on the platform of modern computer technologies. To generate *geotech drive* and *geotech drillhole* files, it is necessary to obtain data on such important geological and geotechnical parameters as:

- Lithological and petrographic code (ROCK);
- Water content of rock mass (Jw), Rat;
- Strength of rocks (UCS), MPa;
- Rock strength category;
- Rock Quality Designation (RQD);
- RQD (Rat);
- Number of joint systems (Jn);
- Number of joints in a system (NJ);
- Spacing of joints (SD);
- Spacing of joint systems (SDOO) Rat;
- Joint roughness;
- Joint alteration (Ja);

The data on each geological and geotechnical indicator is entered into a form developed by the authors. After the database of the Beskempir deposit was created, it was checked for integrity, constant errors, etc. in the Micromine Mining and Geological Information System. Then, possible errors were eliminated using software. As a result, the reliable database was created and served the basis for modeling and interpolation of quantitative indicators in three-dimensional space [4, 21, 22].

3D modeling and geological and geotechnical assessment of the deposit. 3D modeling of the deposit included the features of its geology and structure, its previous study level and the geological survey methodology. The modeling used specific methods and techniques in Micromine software. The modeling sequence consisted of a few stages.

Data handling. The database of geological and geotechnical indicators was imported into the software and visualized. The data were checked in three-dimensional space in order to verify their availability for interpolating quantitative geological and geotechnical indicators of the deposit into a block model.

Structural geological model. 3D models of ore bodies and host rocks in the ore footwall and hanging wall were built. This stage ended with the creation of a geological model of the deposit. Next, the geotechnical mapping results were visualized. 3D models of faults were built. As a result of this work, a structural model of the deposit was created.

Block modeling. At this stage, a block model was created within the contour of the deposit, and its elementary cells were encoded based on the structural geological model (ore bodies, host rocks, faults, etc.). The accomplished work was a preparatory stage for assessing the geological and geotechnical conditions of the deposit on the 3D modeling basis.

Structural trend. In the contour of the deposit, there is a clear structural control of both mineralization and tectonic faults. The breakdown by geological–structural domains was carried out only by geological criteria. Then, a structural trend was created in the Micromine software pursuant to the above domains (**Fig. 1**). When filling out the attributes of the block model, the search ellipsoid will search for the necessary data with regard to the geological and structural features of the deposit [23, 24].

Geological and geotechnical assessment of the deposit. To carry out the assessment, the inverse distance weighted interpolation method was used (IDW). This method is most suitable for the geological and geotechnical assessment of a mineral deposit. Unlike other methods, the weighting coefficient in IDW is calculated not only to the nearest indicator but also to all neighboring indicators. In this case, the weighting coefficient is inversely proportional to the distance raised to a power of the starting point to the neighboring indicator. The indicator located nearby have the greatest weight, and the influence of other indicators is also taken into account. The next step is to study each domain and assess geological and geotechnical conditions of the deposit in the software. The results are illustrated in **Fig. 2**.

Thus, the 3D block model of the Beskempir deposit displays geological and geotechnical conditions of the deposit in real time in three-dimensional space. The quantitative and qualitative geological and geotechnical indicators enable rock mass stability ranking.

The geological and geotechnical assessment of the Beskempir deposit made it possible to categorize the rock mass stability in three-dimensional space in accordance with international systems (**Table**):

- host rocks — stable, moderately stable and sometimes unstable;
- ore — unstable;
- faults — very unstable;
- crushed rock zones — unstable, in some places moderately stable and sometimes very unstable.

Conclusions

The observations in mine workings reveal the following geomechanical phenomena and processes: deformation of sidewall rocks in mine workings and at the bottom of mine shafts, swelling of floor rocks, displacement and various-type deformation of roof rocks (rock fall, doming, caving), outbursts of rocks and minerals, rock falls and collapses in areas of low stability and at interfaces of different stability classes, etc.

To prevent negative geological processes, it is necessary to use effective methods that ensure safe and rational underground mining. In general, prediction of geomechanical processes and phenomena during mineral mining in certain geological conditions, at a limited amount of available information, is a difficult task due to the ambiguity and versatility of mutually influencing factors.

To solve the above problems, the geological and geotechnical assessment of the Beskempir gold deposit was carried out using 3D modeling of the geological environment of the mine in a computer software. During the work implementation, the criterial data were determined from the analysis of geological structure and composition of ore and host rocks, as well as the structural and tectonic indicators of geological and geotechnical conditions of the deposit. The resultant 3D geological and geotechnical model of the deposit at the mine is the requisite material for the safe and efficient mine planning and design.

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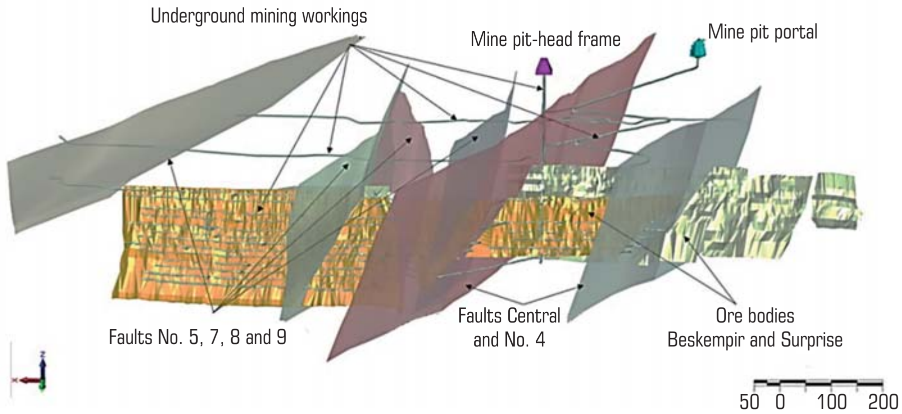

Fig. 1. Structural trend with regard to structural geology of the deposit. Axonometric view

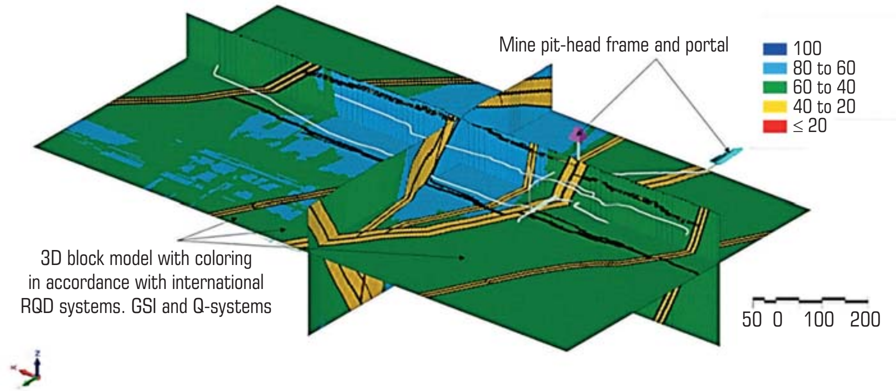

Fig. 2. Axonometric 3D block model with stability categories as per international systems

Rock stability categories by international systems

Rock stability category	RQD	RMR/GSI rating	Barton's Q index	Category	Legend
Very stable (Very good rock)	90–100	81–100	40–1000	I	
Stable (Good rock)	75–90	61–80	10–40	II	
Medium stable (Fair rock)	50–75	41–60	4–10	III	
Unstable (Poor rock)	25–50	21–40	1–4	IV	
Very unstable (Very poor rock)	<25	<21	0–1	V	

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STUDY OF GEODYNAMIC PROCESSES IN MINERAL MINING USING QUASI-GEOID BASED ON WAVELET ANALYSIS

This article offers proposals on the geoid model grid output format to ensure convenient application of the data in investigation of geodynamic processes during underground mining. With a view to improving the national geoid model, it is proposed to use the data of the detail general coverage gravimetric survey of the area of the country. These data are obtained within a reasonable time using the airborn gravimetry technology.

The research findings allow creating a set of computer programs to implement the developed procedure in terms of the experimental data processing and to prove the usability of the procedure for the preliminary modeling of the geoid for the area of the Republic of Kazakhstan.

Keywords: *geodynamic processes, physical geodesy, coordinate systems, gravitational field, geoid, quasi-geoid, gravimetric height, modeling, coordinate transformation, regulation method*
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Introduction

Global models of the Earth's gravitational field play an important role in constructing artificial Earth satellites trajectory theories and in modeling geodynamic processes and the internal Earth structure when solving various problems in the manmade and natural environment. These studies are possible by obtaining an integral picture of the processes occurring in the subsoil and on the Earth surface. Therefore, in mining, the use of a quasi-geoid is being studied in the field of rock deformations that occur during open-pit and underground mining [1, 2].

On the other hand, such height determination methods and vertical control using an accurate geoid model represent one of the most complex research topics in geodesy. Since the 1980s, this problem attracts a growing attention due to the wide spread and intensive application of the methods of the Global Navigation Satellite System (GNSS). Many of the strategies used in gravity field modeling were developed at a time when the goal of the geoid height accuracy was 10 cm or less. Currently, to determine geoid and quasi-geoid heights, it is necessary to carefully evaluate accuracy in centimeters or better, and, if necessary, adjust the approaches inherent in the methods and techniques used.

It is very important to be able to divide geodetic observations into planimetric and alimetric, and to introduce three-dimensional geodesy elements into geodetic practice at the national scale in the Republic of Kazakhstan.

In this regard, this article proposes a new technique of gravimetric quasi-geoidal (geoid) modeling for converting GPS ellipsoidal heights to normal ones, since orthometric heights do not always provide accurate results compatible with local vertical databases [3]. To improve the conversion, a gravimetric (quasi) geoidal model can be linked to GPS levelling data. The new composite surface (which is no longer a classical (quasi) geoid) can then be used to more accurately convert elevations.

Problem formulation

In the Republic of Kazakhstan, the geodetic support of critical decision-making consists of state geodetic, levelling and gravimetric networks that determine the quality and accuracy of coordinate systems, heights and gravity, including three main interconnected parts such as the state coordinate, altitude and gravimetric bases.

For many years, GPS levelling was used to validate gravimetric geoid models on land, but as geoid calculation methods improved, the data often had discrepancies (i.e., non-zero e and e′). Therefore, numerous studies focused on integration of gravimetric quasi-geoid, geoid and GPS levelling data. Many scientists used a trigonometric four-parametric surface to minimize data biases and extreme long-wavelength differences between geoid and GPS levelling data [4]. One of the most important methods is the use of