Risk assessments for rockfalls taking into account the structure of the rock mass

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Abstract. The object of the study is the Far West quarry of Zhairemsky Mining and Processing Plant JSC. During the research work, the physical and mechanical properties of rocks at the Zhairem deposit were studied, an analysis of the correspondence between the actual and design parameters of the quarry was carried out, and field studies of rockfalls were carried out taking into account geotechnical domains. Due to an increase in the depth of development and a decrease in the width of the upper horizons of the Far West quarry, it is necessary to carry out an assessment of the risks of rockfalls and issue recommendations to reduce these risks. To achieve this goal, the following tasks have been identified: analyze previously performed studies; analyze the existing condition of the quarry sides; comparison of actual and design parameters of benches; division of the edge massif into geotechnical domains based on the results of structural zoning; field studies of rockfalls to determine the coefficient of normal and tangential recovery; analyze rockfalls in RockFall software; development of recommendations to reduce the risk of rockfalls.

1 Materials and methods

The barite-polymetallic deposit Zhairem is a typical representative of stratiform deposits of the Atasu type, a characteristic feature of which is the spatial combination of syngenetic sheet ferromanganese and lead-zinc ores with superimposed hydrothermal-metasomatic barite-lead-zinc mineralization. Mineralization of both types is associated with siliceous-carbonate strata of the Famennian stage of the Upper Devonian, composing the wings of the Zhairem brachyanticline.

Devonian system. Darya Formation (D3dr).

The rocks of this formation were exposed only at depth in the core part of the Zhairem brachyanticline and are represented by conglomerates, sandstones and multi-colored polymict siltstones.

Famennian Stage (marine facies)

Rocks of the Famennian stage are faunistically divided into 2 substages: lower and upper, which in turn are divided into packs. The lower substage is represented by packs (from

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bottom to top) of irregularly layered, rhythmically layered, flyschoid, and the upper one is gray-colored and red-colored.

Lower Famennian substage. Unconsistently layered member (D3fm1a)

The rocks of this member lie at the very bottom of the Famennian marine carbonate section; they form the core part of the Zhairem brachyanticline. The member is divided into five lithological horizons.

Horizon D3fm1a1 – light gray albite-calcareous rocks of unclear layered and indistinct nodular texture, which are facies replaced by greenish-gray and lilac polymictic siltstones. The thickness of the horizon ranges from 0 to 12 m.

Horizon D3fm1a2 – black carbonaceous siltstones and clayey-siliceous-calcareous rocks with interlayers of shell rocks. A distinctive feature of the horizon is the presence in individual layers (thickness up to 30-70 cm) of fragments of light gray limestone and abundant shells of brachiopods and pelecypods, which characterize the age of the host sediments as Lower Famennian. The thickness of the horizon is 5-8 m.

Horizon D3fm1a3 – thin-layered ribbon-layered siltstone carbonaceous calc-clay-siliceous rocks.

Horizon D3fm1a4 – dark gray, gray clayey-carbonate rocks of a thin lens-shaped and thin-layered texture. There are frequent small lenses enriched in carbonaceous matter, as well as lenses and nodular deposits composed of cryptogranular carbonate and albite, carbonate and chlorite. The content of these grains in the rock is 5-10%. The age of the Lower Famennian substage is determined by the leading form of cephalopods. The thickness of the horizon is 80-125 m.

Horizon D3fm1a5 – gray clayey-siliceous-carbonate rocks of microcrypto-grained, siltstone structure, unclear-layered, thin-layered texture with a large number of quartz-calcite, albite-calcite nodules. The rocks turn brown quite intensively, which is their peculiarity. The structural heterogeneity of the rock is due to the presence of unevenly distributed siltstone impurities (30-40% of the rock). The pigment of the rock is a carbonaceous substance. The thickness of the horizon is 60-160 m.

In the upper part of the horizon there is an accumulation of tuffs and tuffites of alkaline and acidic composition with a thickness of 0.8-1.2 m. In addition to them, in the same part of the horizon there are lenses of gray flints, thin layers (up to 20 cm) of low-grade magnetite and siderite ores.

The rhythmically layered member (D3fm1b) is one of the ore-bearing strata, which contains about 30% of the reserves of the Far West section. This member is represented in the field by 4 lithological horizons, which are quite clearly distinguished in the Western section and the eastern wing of the Zhairem anticline. In the Far West section, only the lower horizon (D3fm1b1) is quite confidently identified and therefore the three upper horizons are combined. However, for a better understanding of the structural features of the unit under consideration, it seems advisable to characterize all 4 of its horizons.

The D3fm1b1 horizon is composed of dark gray thin-layered clayey-siliceous-carbonate rocks with a thin ribbon-layered texture, which quickly turn brown on the day surface due to the presence of divalent iron and manganese in the carbonate. Sometimes they contain lenses of flints, chlorite-carbonate rocks and low-grade hematite-magnetite and siderite ores up to 100 mm thick. Veined galena-sphalerite and chalcopyrite mineralization of non-industrial significance are also noted here. The thickness of the horizon is 30-40 m.

The D3fm1b2 horizon – massive dark gray clayey-siliceous-calcareous and clayey-siliceous-carbonate rocks of unevenly layered texture, alternating with microlayers of black carbonaceous-clayey rocks. Accumulations of globular pyrite form small intervals (1-3 m) of pyrite rhythmites in the upper and lower parts of the horizon. In the Far West section, industrial lead-zinc mineralization is also confined to the lower part of this horizon.

The D3fm1b3 horizon is a rhythmic alternation of massive siliceous-calcareous rocks (5-30 cm) and band-layered carbonaceous and pyrite rhythmites 1-5 cm thick and less often 10-20 cm thick. A distinctive feature of the rocks of this horizon in the central parts of the Far West and Western section s is their selective susceptibility to secondary hydrothermal alterations: bleaching, recrystallization, baritization.

The D3fm1b4 horizon – “tuff horizon” is the marker for all section s and deposits of the ore field. The predominant rock in the horizon is black tuffstones. The tuffs are predominantly ash, siltstone, less often psammosiltstone and coarse clastic, which alternate with clayey-siliceous-calcareous rocks. The total thickness is 1.3-1.4 m in the Far West and Western sections [1].

The thickness of the horizon in the Far West is 10-15 m, in the Western section it varies from 7-8 m to 18 m, in the Eastern section - 10 m.

In the Far West section, the horizon almost always contains ore bodies; in the Western section, it is usually less mineralized than neighboring horizons; and in the East, there is no industrial mineralization at this horizon. The undifferentiated horizon (D3fm1b2+4) is represented by dark gray unevenly layered and rhythmically layered clayey-siliceous-calcareous rocks in the lower part of which tuff formations are recorded.

The flyschoid member (D3fm1c) in all section s of the deposit is the main ore-bearing strata, which consists of 5 horizons. It contains about 70% of the industrial reserves of the Far West section.

Horizon – D3fm1c1 “nodule-bearing horizon” or “flysch” – a thickness of clayey-siliceous-calcareous rocks of flyschoid structure. Flyschoid rhythmicity is expressed in multiple repetitions of multilayers, each of which represents a complete rhythm. Carbonaceous and pyritic rhythmites are widespread in the horizon, and interlayers of psammosiltstone tuffs and sericite tuffopelites are also found.

The thickness of the horizon changes sharply over relatively short distances and depends mainly on the volume of the terrigenous component of the rocks: in the Far West section from northeast to southwest it increases from 70 to 180 m, in the Eastern section it is 50-60 m, in the Western section it varies from 46 to 80 m.

The horizon – D3fm1c2 – “marking horizon” – is composed of homogeneous massive black carbonaceous carbonate-kalifeldspar-siliceous rocks with unevenly distributed light calcite, pyrite-carbonate nodules (0.5-5 cm).

The thickness of the horizon in the Far West is 15-22 m, Western - 12-14 to 20 m, Eastern - 10-22 m.

Horizon – D3fm1c3, also having a flyschoid structure, is similar in composition and structure to horizon D3fm1c1, but less thick (6-20 m), thinner and rarer interlayers of detrital limestones and pyrite rhythmites. The horizon includes lenses of lead-zinc ores of small extent and thickness.

Horizon – D3fm1c4 is the “iron ore horizon” of the Far West and Western sections, characterized by lateral variability of facies and thickness. Within all three sections of the deposit there are independent centers with maximum ore accumulation, from which rich ores are replaced in the horizontal direction by facies of poor ores and nodular-layered limestones.

In the Far West section, the horizon is mostly eroded or located in the weathering crust. In the northeast, these are siliceous-carbonate rocks with interlayers and lenses of hematite-magnetite ores. In the southeast, the horizon is composed of gray and greenish-gray chlorite-carbonate rocks with a nodular-layered texture. The thickness of the horizon changes from northeast to southwest from 20 to 60-80 m.

Horizon – D3fm1c5 is characterized by a flyschoid structure with asymmetric layering. In terms of the composition of the rocks and their saturation with nodules, it is close to the “c1” horizon.

The predominant elements in the horizon section are dark gray concretion-bearing siltstones, which make up the middle part of the rhythm. Their thickness is from 0.5 to 2-3 m. The nodules are calcite, different in shape, ranging in size from 0.5-1 to 5-15 m. The thickness of the horizon in the Far West and Western sections is 30 m.

At the base of the horizon, well-preserved clusters of Lower Famennian shells were discovered.

Upper Famennian substage. The gray-colored member (D3fm2a) is characterized by alternating horizons of gray nodular siliceous limestones and dark gray clayey-siliceous-calcareous rocks of flyschoid structure. The thickness of the pack is 30-95 m.

Red-colored tutu (D3fm2b)

The red limestones that make up the member are sharply different in color and appearance from all the rocks both in the ore field and in the area, thus being a good benchmark in the context of Famennian-Tournaisian deposits. It is characterized by a fairly uniform composition and structure, and only in the middle are organogenic-detrital limestones present. The thickness of the pack is 80-120 m [2].

2 Basic elements of ore field tectonics

The Zhairem ore field is located in the northwestern part of the Zhailma trough, complicated here by second-order folding – the Zhairem anticline.

The Zhairem anticline is a strip of outcrops elongated in the northeast direction on the erosional section of rocks of the Lower Famennian substage and partly of the Darya formation. In plan, this strip is arched with a convexity to the southeast. The length of this strip is up to 10 km, the maximum width is up to 1.5 km.

The southeastern wing of the fold, convex in plan, is composed of various horizons of the Lower Famennian substage. The average incidence angles in this wing are close to 45^0.

The core part of the Zhairem anticline has the shape of a narrow "scar" overturned to the west, complicated by tectonic sutures, along which intensive albitization, dolomitization and silicification of siliceous-carbonate rocks are developed.

The northwestern wing of the fold has a relatively simple structure and a gentle dip (up to $20\text{-}30^0$). In the center of the ore field, the wing is complicated by a series of additional folds with eastern wings tilted to the west and very flat western wings.

Within the Zhairem anticline, the main ore-bearing structures are the Far Western and Meridional brachysynclines.

The Far Western brachysyncline is the main ore-hosting structure of the Far Western area. Its wings are composed of rocks of the rhythmically layered and flyschoid members of the Lower Famennian substage, and in the core - weathered rocks of the upper part of the flyschoid member. The composing rock folds bear industrial barite-base metal mineralization.

The length of the fold along the soil horizon D3fm1c1 is 1200 m, the maximum width is 1000 m, the amplitude of folding is up to 300 m.

In the southern and northern wings, the rocks are relatively flat, from 10 to 45^0; in the eastern and western wings the dip angles are stable in the range of $30\text{-}45^0$.

The southern part of the brachysyncline is complicated by a latitudinally extended additional anticlinal fold, which has the shape of a narrow box-shaped protrusion with a vertical or steeply dipping ($55\text{-}70^0$) northern one. Towards the eastern and western wings of the Far Western brachysyncline, the described anticlinal complication, together with the fault, fades away. Its total length is 500m.

The structure of the Far Western brachysyncline is complicated by subconformable interlayer faults, which practically do not displace the host rocks and mineralization.

The meridional brachysyncline is also an ore-hosting structure and is separated from the Far Western fold by a gentle anticlinal swell 250-300 m wide, striking NW, ending at its NW continuation with a brachyanticlinal dome uplift, triangular in plan.

The brachysyncline is elongated in a north-south direction. The angles of incidence of its wings are gentle and range from 10 to 40^0 [2-4].

3 Analysis of geomechanical knowledge of the site

In 2015-2016 9 wells were drilled at the Far Western section in order to collect data necessary to carry out design work in accordance with international standards and the requirements of the Republic of Kazakhstan. The geomechanical data collection program included:

- Drilling wells using a triple core pipe and taking oriented core;
- Core orientation using the Trimble DeviCore BBT system of HQ diameter;
- Collection of data on the massif, including lithology (geological coding of Kazzinc LLP 2015), weathering, number of cracks, strength and classification of soils;
- Collection of structural data, including roughness, detailing, opening, weathering and fault fill;
- Geomechanical documentation of core according to the rating system of Bieniawski (RMR89) and Hook et al. (2013);
- Detailed structural documentation of oriented core;
- A comprehensive program of laboratory physical and mechanical tests of rocks to determine the strength of a monolithic sample;
- Plasticity index, classification of soils and shear testing of soils composing the overlying layer.

Table 1. Geomechanical wells (Far Western section).

Well No.	Longitude	Latitude	Horizon	Azimuth	Angle	Depth	Note
DAL-GT001	58565	122955	395	090	70	250	Crossing the western side from west to east.
DAL-GT002	58878	123506	350	150	70	200	Intersection of the NW side from NW to SE
DAL-GT003	59519	122768	350	330	70	200	The intersection of the SE side from SE to NW.

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DAL-GT004	59591	123286	380	250	70	250	Crossing the eastern side from east to west.
DAL-GT005a	58575	122606	375	270	70	250	Crossing the eastern side from east to west.
DAL-GT006	59154	122643	360	020	70	250	Crossing the southern side from SW to NE.
DAL-GT007	59636	123037	370	270	70	250	Crossing the eastern side from east to west.
DAL-GT008	59258	123446	375	200	70	250	Crossing the northern side from NE to SW.
DAL-GT009a	58099	122354	395	090	70	250	Crossing the western side from west to east.
						2150	Total linear meters

The given table and pie charts clearly demonstrate the proportional distribution of lithological differences in the contours of the quarries in the Western and Far Western sections [5-6].

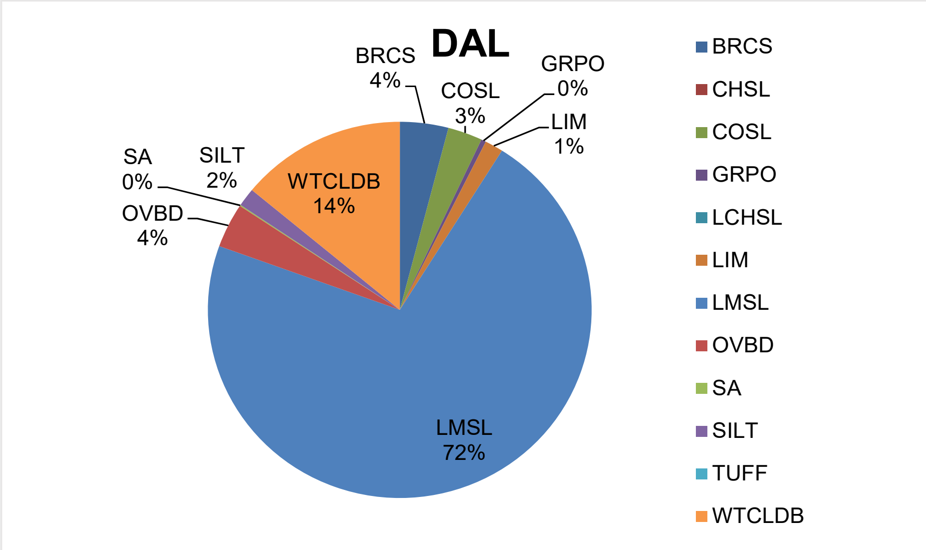

Fig. 1. Percentage distribution of rock types (Far Western section).

4 Conclusions

Based on the data provided, the actual and design parameters of the benches and sides of the quarries were compared and sections were constructed. Based on the results of the analysis, it was revealed that most of the quarries were opened in the Darya suite (D3fm1a). The rocks of this member lie at the very bottom of the Famennian marine carbonate section; they form the core part of the Zhairem brachyanticline. The member is divided into five lithological horizons.

Based on the results of the analysis, horizontal zoning was carried out along the width of the safety berm to identify dangerous areas due to rockfall processes. At the lower horizon below the horizon +324m, the width of the safety berm less than 7.0m is about 45%, the main part of this area is located in the northern part of the quarry. Higher up on the horizon +332m, the width of a berm less than 7.0 m is 45% and about 40% of the width of a berm more than 9.0 m.

An analysis of the angle of repose of the quarry side along the horizons every 5 m was also carried out. The value of the angle of repose of the ledge for each horizon was determined to assess the actual condition. At a horizon of 340-332 m, the share of sides with a bench inclination angle of 50-55 degrees was 5%. Below, on the horizon 332-324 m, the angle of repose of the ledge 50-55˚ is 7%. At horizons of 324-316 m and 316-308 m, 6% and 4%, respectively.

According to the developed methodology, full-scale studies of rockfall processes were carried out and 3 areas were selected to determine the initial data and calibrate the model in Rocfall software (Rocscience). The trajectory of the samples falling to the final point was recorded using slow-motion video recording and the final position of the piece was recorded using GPS to determine the tangential and normal restitution of surfaces for specific conditions.

During the full-scale experiment, the following values of the restitution coefficient were obtained for surfaces that are usually found in a quarry:

– berm - 0.0178; hard rock surface - 0.187; transport slope - 0.168. Using photo and video recording and modeling of the rockfall process, the parameters of tangential and normal restitution for each surface were determined

The value of the coefficient of normal restitution was determined experimentally by dropping samples onto the following surfaces: a safety berm in the weathering crust zone, the surface of hard rock, the bottom of a quarry and a transport slope.

According to the results of the analysis of the state of the massif and modeling, the average kinetic energy was up to 50 kJ, which, according to the Geobrugg classification (Switzerland), a mesh fence is recommended to protect objects from the effects of landslides and the fall of individual rock fragments. For inclined slopes made of clayey rocks, a trench is used, the parameters of which depend on the configuration of the ledge.

Based on the results of rockfall modeling on the design contour of the Dalnezapadny quarry, it was revealed that the width of the safety berm of 10 m with a bench height of 16 m in the host rocks is sufficient to contain rockfall from the upper horizons.

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