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ASSESSMENT OF STATE OF WATER-SATURATED MINE WASTE FOR THE JUSTIFICATION OF ENGINEERING STRUCTURE DESIGNS AT OPEN PIT MINES

The articles offers discussion of issues connected with slope stability of dumps, hydraulic fills and tailings ponds. The authors review regulatory documents concerned with the assessment of stability of hydraulic structures in open pit mining. It is found that the assessment procedure recommended by the actual standards is based on the analytical estimation and lacks modern methods of the numerical modeling.

After analysis of landslide processes at open pit mines, it is concluded that their scale and environmental damage has increased. The authors prove the need to study, predict, include in geotechnical design and monitor pore pressure in structures composed of mine waste and natural rocks. Facilities developed in participation with the present article authors for the pore pressure measurement in water-saturated rock masses exposed to loading are proposed. The difficulties connected with the facilities that generate loads comparable with the stresses in geotechnical structures are specified. The authors describe studies required in justification of optimal designs of geotechnical structures in open pit mineral mining.

Key words: *geotechnical structures, regulatory documents and guidelines, landslides, pore pressures, stability assessment, geotechnical and hydrogeological research procedure, safety monitoring, seepage-induced consolidation*

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Introduction

Safety in open pit mining is achieved through optimal design of engineering structures: slopes and pitwalls, dumps and different purpose embankments. In USSR the problem was solved by the mining industry institutions: VNIMI (Research Institute of Geomechanics and Mine Surveying, Saint-Petersburg) and VIOGEM (Research Institute on Drainage and Special Services in Mining, Geomechanics, Geophysics, Water Engineering, Geology and Surveying, Belgorod).

In VNIMI, the school of open pit mining geomechanics was founded in the early 1950s under the head of Prof G. L. Fisenko. For the recent 25 years, the school had been headed by T. K. Pustovoitova who deceased in August 2016. VNIMI's researchers accomplished many studies into stability of engineering structures at open pit mines of the country; the research findings made the basis for the development of regulatory documents and guidelines for the coal mining industry [1–6]. The latest documents being a summary of the 50 years-long research activities are the Slope Stability Practice for Open Pit Coal Mines published by VNIMI and approved by the Federal Environmental, Industrial and Nuclear Supervision Services of Russia—Rostechnadzor in 1998 [6]. Different expert teams were engaged in the slope stability assessment in mining but other regulations were not worked out. For this reason, all open pit mines in USSR used the regulatory documents and guidelines developed by VNIMI for the coal mining industry.

The review of the research findings on slope stability and the developed documents shows that the engineering approaches to calculations were based on the theory of limit equilibrium. In particular, the above mentioned Slope Stability Practice… by VNIMI offered the main calculation method as the geometrical and algebraic summation of forces, which allows the analytical models to account for the variety of geological features, geotechnical conditions and hydrogeological characteristics. Regarding hydraulic fills, watered dumps and stockpiles placed on weak water-saturated foundations, VNIMI proposed some instructional guidelines that accounted for hydromechanical processes in natural rocks and mining waste, including seepage-induced consolidation [4, 5].

In foreign literature, the issues different purpose slope stability and monitoring attract increasingly much attention of the researchers [7–12].

The current regulatory documents are at the level of geomechanics and soil mechanics of the 20th century when slope stability of natural and engineering structures was mainly assessed by analytical treatment. The attempts to the numerical modeling using different methods were made though enjoyed no widespread development. Onrush of computer engineering enables using numerical models in solving the most complex geomechanical problems connected with the assessment and prediction of the stability and stress state of rocks with regard to different natural and induced factors. Developed in recent years, software computer systems such as Plaxis, Abacus and other approved themselves in practical geomechanical calculations in solving two- and three-dimensional static and dynamic problems. Moreover, it is possible to select between various physical models of deformation behavior of rocks.

Open pit mines in Russia exercise hydraulic stripping and dumping. Mining industry uses tailings ponds, slime and sludge pits and other waterwork facilities. All such structures belong in the water engineering area and, therefore, fall within the regulatory framework of hydraulic engineering. The quality of hydraulic structure design and operation regulations in force in Russia is beyond admonition. In particular, slope stability of earth and hydraulic fills can be assessed using either engineering designs or numerical modeling. Different loads due to hydrogeological, geodynamic (including seismic) and other factors are accounted for in this case. It should be emphasized that the procedures offered for justification of stability of hydraulic structures include the requirement to account for pore pressure in weakly permeable water-saturated rocks exposed to loading [13–15].

Primary section

The review of the state-of-the-art in slope stability justification for pitwalls, overburden dumps and hydraulic fills in open pit mining shows that the current method of engineering structure stability calculation comes considerably short of the procedure used in water engineering for geotechnical validation of calculated physical properties of rocks and the modern numerical modeling techniques. This backward slip is connected with the wider variety of geological, geotechnical and hydrological conditions in the mine engineering as compared with the water engineering. Furthermore, hydraulic structure design accounts for lower risk of destruction and involves higher reliability. For instance, depending on the class of a structure, the risks for dams and hydraulic fills usually make $5\cdot10^{-3}$–$3\cdot10^{-5}$, while the risks at pitwalls and dumps total 10^{-2}–$5\cdot10^{-2}$. The further advance in the hydrogeomechanics, mechanics of soils and computer engineering gives rise to a discrepancy between the potential and actual situation. It is necessary to eliminate the discrepancy at the earliest opportunity for the recent industrial environment of mineral mining experiences dramatic changes: unit capacity of open pit mining equipment grows, the depth and rate of mining operations increase, the geotechnical and hydrogeological conditions worsen with the depth of mining, and tectonic faulting and seismicity show themselves more pronouncedly (included induced events). In addition, the risk and scale of instability of engineering structures are elevated together with the material damage due to environmental, social and technological aftermath of their failure.

The aforesaid can be illustrated by the largest waterwork accidents in the last two years. For instance in 2015, at external dump no. 1 at Zarechensky open pit mine of SUEK-Kuzbass, landslide induced deformation in rock mass volume of 27 Mm^3. In the same year, landsliding of rock mass volume of 10 Mm^3 was recorded at a dump of Mikhailovsky Mining and Processing Plant. In 2016 Chernigovets open pit wall slid under load of dry overburden dumps in Kuzbass. The economic and environmental damage of the first two landslides made several billion rubles; in the third case, the material loss was aggravated by the death of three miners who turned out to be under the rock fall together with equipment.

These events add to a long list of landslides in the past. For example, at the edge of the 20th and 21st centuries, hydrodynamic accidents at waterworks deformed rock mass in volumes of 2.5 Mm^3 (dump at Bachatsky open pit mine, Kuzbass, 2005), 2 Mm^3 (tailings pond, Karamken Mining and Processing Plant, Magadan Region, 2009) and 5 Mm^3 (tailings pond, Kachkanar Mining and Processing Plant, Ural, 1999).

Such events took place even earlier: landslide 1.8 Mm^3 in volume at hydraulic fill no. 1, KMAruda in 1964, 1 Mm^3 landslide at hydraulic fill Balka Chuficheva, Lebedinsky Mining and Processing Plant in 1981.

Accidents at tailings ponds in different mining countries were reviewed in the bulletin prepared by the committee for tailings ponds and settling pits [7, 8] at the International Commission on Large Dams (ICOLD). An attempt was initiated toward integration and coordination of works in the field of prediction and monitoring of state of dumps in the most important mining regions of Russia (Kuzbass, Kola Peninsula, KMA) to be implemented by the Saint-Petersburg Mining University (Saint-Petersburg), College of Mining at MISIS (Moscow), VSEGINGEO (Moscow Region) and VIOGEM (Belgorod). The team-work results are presented in the form of a co-authored monograph [16].

Having addressed general aspects of mine engineering structure slope stability, the authors wish to focus on their vision and way outs regarding the problem of evaluation of dump and hydraulic fill designs as well as the analysis, prediction and monitoring of hydrogeomechanical processes in natural rocks and mining waste.

The prime hydrogeomechanical process that changes properties of dumped rocks with time is compaction (under external loading in case of foundations or under dead weight in case of dumps) or decompaction (in the influence zone of dump in front of a shaped slope). Depending on phase composition (water saturation) of dumps, the forward calculation of dump compaction uses the apparatus of the theory of seepage-induced consolidation or creep [17].

The source information on the history of rock mass stress state to be used in the geomechanical forecast can be obtained from exploration. It is more rapid and reliable to obtain these data during full-scale investigation: probing with a piezo-cone and a penetrometer with an impeller, measurement of pore pressure in clayey rocks by special sensor, etc. [4, 5]. Aiming to have the objective source data at the design stage, it is advisable to use the method of geotechnical analogies to find characteristics of long-terms strength (inverse calculation of landslides of dump slopes at analogous objects) and compaction of dumps (from observations over deformation of embankments and hydraulic fill dams).

It is most convenient to find input parameters to calculate stress state of watered clayey rock mass using three-axial compression machines (stabilometers). Stabilometers assist in the determination of widely ranged strength and deformation characteristics of rocks under multiaxial stress. Stabilometers USV-2 and SVD-4 (axial pressure to 5 MPa) designed by VIOGEM (design engineer N. P. Vereshchagin) are worthy in this regard.

For many years, the Moscow Mining Institute, Moscow State Mining University, MISIS's College of Mining, VNIMI and the Saint-Petersburg Mining University have been engaged in research works at dumps and hydraulic fills of mining and processing plants of KMA [21] and at open pit coal mines in Kuzbass with a view to estimating slope stability of the mine engineering structures and justifying their optimal parameters. The created package of methods and means for hydrogeomechanical monitoring of mining waste was included in R&D rewarded by the Government of the Russian Federation in 2010.

The package includes instruments for periodic and stationary measurements of pore pressure in watered clayey rocks. Periodic measurements are carried out with special probes. In the 1960s–70s VSEGINGEO designed SPKT-1 system that determined density and moisture content of rocks using the radioisotopic technique. In the same years, the European countries (Netherlands, Sweden, Norway) developed instruments equipped with three-parameter probes that are recently used in Russia to study "soft" rocks.

For the control over state and properties of rocks, the Chair of Geology at the Moscow State Mining University jointly with DIGES company (water-power structure diagnostics) designed a probe combining a pore pressure sensor, impeller and a piezo-cone. The probe enables measurement of pore pressure and determines resistance to the cone squeeze and rotational shear of rocks within a depth interval under examination (RF Patents No. 1624093 in 1993 and No. 2025559 in 1994). The combination probing utilizes drill rig fluid power systems. For probing with such equipment in inaccessible areas (under dumps in the zones of protrusion and at hydraulic fills), VNIMI designed UGK-1 unit similar to a Netherland's penetrometer with the squeezing force up to 2 t.

Stationary hydrogeomechanical plants are used to monitor slopes of hydraulic fills and dumps; pore pressure in potential slide wedges is measured by sensors and deformation is recorded using surveying line plugs on the surface and in the foundations of dumps or fills. Such plants ensure pore pressure monitoring in slopes long before visible displacement of the plugs, which allows the prompt hydrogeomechanical control of a structure and well-timed prevention of hazardous instability of slopes [9]. A general flow chart of the hydrogeomechanical monitoring of slopes at dumps and hydraulic fills includes sensors at different locations; plugs in a dump or a fill; a system for accumulation, primary analysis and transition of data to a base computer via GSM connection [16, 18]. The system designed by KARBON Research and Production in 2005 is certified as a measurement device. It measures pore pressure simultaneously by 10 sensors with a period of 6 s and supports interactive mode. The system uses alarm mode to warn about reaching a limit pore pressure value.

It is found that the gathering speed displacements are preceded by a sufficiently long period of time when pore pressure gradually grows until maximum, the speed of displacements become disastrous, and a landslide takes place. Later on, the pore pressure lowers with time and deformation decays with the altered geometry of a slope [14].

Wireless datallogger Orfei-1 was designed at VSEGINGEO in 2013 and introduced in mines of KMA by the fellows of the Chair of Geology of the Moscow State Mining University. The system operates sensors that are installed in every hole. The system pickups, processes, stores and transfers data from the sensors with the analog outputs. Depending on the selected mode of operation, the datalogger allows for continuous or cyclic monitoring. In the first case, the datalogger performs realtime transition of the sensor data to the monitoring data base. Exchange with the remote server is via the same interface—wireless GSMGPRS. The power backup of the datalogger uses an inner power source. The cyclic monitoring is arranged based on the "black box" principle: the datalogger independently scans sensors at preset periods and keeps the readings in the nonvolatile memory. The memory contains the data and time of measurements, the measured ambient temperature and other service information. The data from the memory, via communication channel, are transferred automatically or upon an operator's enquiry. The system Orfei-1 is introduced into two checkup survey lines along the boundaries of dams bordering the tailings pond at Stoilensky Mining and Processing Plant.

It is noteworthy that Russian and foreign practitioners use considerably different approaches to systematic measurement of pore pressure in dams (for the first turn, at hydraulic fills and tailings ponds). ICOLD issued special Bulletin 104—Monitoring of Tailings Dams Paragraph 3.4 of which described the in-site pore pressure measurement and data interpretation procedure [7]. The domestic regulatory and instructional documentation governs the pore pressure measurement in watered hydraulic structures but involves no issues connected with the justification of sensor patterns or measurement procedures and rules for some types of the structures. In case of hydraulic fills in the coal mining industry, VNIMI bridged that gap [4, 5]. For other types of industrial hydraulic structures, pore pressure sensors are "beyond the law" despite the height (more than 100 m) and water saturation of the dams. The current ludicrous situation should be changed. Pore pressure measurements in dams, hydraulic fills and waterwork foundations, as well as in wet dumps and their bases are to be provided (included) in the actual safety monitoring systems, particularly in view of R&D on automated remote control over such hydraulic engineering structures.

At the present time, owing to the absence of vacant land for dumping, high engineering structures are being shaped at open pit mines. In particular, at open pit mines in Kuzbass, the dumps under planning have the height of 200 and even 250 m. The loading on the foundations of such dumps will reach 5 MPa. The current classifications of the methods used to determine design performance and strength and deformation characteristics of dispersed soil neglect the real range of loads on dumps [19, 20]. No determination of strength of the planned dumps under such loading was undertaken. In the 1960s–80s VNIMI comprehensively studied properties of dumps at different mineral deposits in the USSR using a large shearing test machine with an area of 550 cm^2. The maximum possible load with that machine was 1 MPa, which confirmed with the load of a dump 60 m high. Thus, the strength characteristics obtained by VNIMI and specified in the related regulations disagree with the loads exposed on the currently planned dumps. The review of the documents developed by different expert organizations involved in stability calculations for specific dumps shows that the majority of the experts have no knowledge on the strength determination methodology. Most of them erroneously think that each type of dumped rock has a constant internal friction angle and cohesion irrespective of the normal loads in the dump. For this reason, stability calculations use values of strength characteristics tabulated in specifications. The outcome of such calculations is illustrative. Suffice it to recall the accident at Zarechensky open pit mine in Kuzbass, where the dump designs were based on the overestimated parameters of strength of overburden rocks and foundation loams.

The overview of the issues connected with the analysis of physical properties of dumps, hydraulic fills and their foundations allows concluding on the lack of equipment and methodology for strength determination in mining waste under loads relevant to stresses in the body and foundation of dumps. The absence of test equipment and procedure for coarsely clastic rocks resulted in a considerable gap in the geotechnical knowledge on the mechanisms of change in physical properties of mining waste under high stresses. The inverse calculations of landslides at 100 m-high dumps at Zarechensky and Bachatsky open pit mines (Vostochny dump) showed that the landslides took places at the same characteristics of strength at the foundations of these structures: internal friction angle =12 deg and cohesion C=25 kPa. The strength characteristics of these Quaternary loams according to the geotechnical research undertaken before dumping over these foundations yielded much higher values of the internal friction angle and cohesion.

Conclusion

There is a discrepancy between the earlier obtained dependences of the cohesion increase with the load on a dump, and the equipment to determine physical properties of natural rocks and mining waste under higher loading due to dump weight. The methodology of geotechnical and hydrogeological investigation of high dumps, justification of optimal designs of dumps under conditions of hydrogeomechanical and induced lithogenetic processes as well as the safety monitoring calls for updating. It is proposed to form a council based on the Center for Geomechanics and Mining Problems at the Saint-Petersburg Mining University and the Chair of Geology and Surveying of the College of Mining at MISIS with a view to working out a regulatory document for safe hydraulic fills and for the purpose of geotechnical study of overburden dumps and hydraulic fills.

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