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ARTICLE

EVALUATION OF OPERATING CONDITIONS OF FILTRATION COLUMNS OF RELIEF WELLS SITED WITHIN THE "ŻELAZNY MOST" MINING WASTE DISPOSAL FACILITY

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Abstract: Regardless of geological conditions, the drilling of deep wells always disturbs the original state of tension in the drilled rock mass. In the course of drilling, the stability of the borehole wall is maintained by the drilling mud, and afterwards by the installed casing or filtration column, which usually are steel or plastic pipes with appropriately designed diameter and wall thickness.

Casing columns in the wellbore should be sized so as to withstand the pressure of the rock mass without becoming deformed. Their strength parameters can be determined from the components of the primary state of stress in the rock mass and the magnitude of pressure occurring at the interface between the casing wall or filtration column wall, and the rock environment.

In this paper, an analytical method based on the Coulomb–Mohr model was used to calculate rock mass pressures around the filtration column of relief wells situated in the slope of the "Żelazny Most" Mining Waste Disposal Facility (MWDF).

Based on archival materials, a rock mass model was developed and was used for calculating undisturbed rock mass pressures at the filtration column wall and pressures coming from the gravel pack. The results obtained will be used for designing the filter pipe columns.

Keywords: borehole, borehole designing, rock mass pressure, strength of filtration columns, crushing of casing pipes

1. Introduction

Regardless of geological conditions, the drilling of deep wells always disturbs the original state of tension in the drilled rock mass. In the course of drilling, the stability of the borehole wall is maintained by the drilling mud, and afterwards by the installed casing or filtration column, which usually are steel or plastic pipes with appropriately designed diameter and wall thickness.

Casing columns in the wellbore should be sized so as to withstand the pressure of the rock mass without becoming deformed.

Their strength parameters can be determined from the components of the primary state of stress in the rock mass and the magnitude of pressure occurring at the interface between the casing wall or filtration column wall, and the rock environment. Apart from purely technological aspects, the proper operation of the well is determined by the strength of the casing, i.e. the applied casing column and filtration column.

If the compressive strength condition is to be met for the casing or filtration columns, a pressure distribution function around the drilled wellbore should be provided. Therefore, the geological and geotechnical conditions should be analyzed in detail and relevant factors affecting the behavior of the rock mass selected [1].

In rockmass mechanics, the analyzed phenomenon is described with mathematical equations. These are usually partial differential or ordinary differential equations defined in an area in which the analyzed phenomenon occurs. These equations supply the basis for developing a mathematical model of the studied phenomenon.

In the process of designing deep well structures implemented in formations having ground parameters, the Coulomb–Mohr model is most frequently used to calculate the rock mass pressures [2].

In this paper, an analytical method based on the Coulomb–Mohr model was used to calculate rock mass pressures around the filtration column of dewatering wells sited in the slope of the "Żelazny Most" Mining Waste Disposal Facility (MWDF).

2. Location and characteristic of the "Żelazny Most" MWDF

The "Żelazny Most" Mining Waste Disposal Facility is located in the Lower Silesia province, within the Lubin and Polkowice districts (Fig. 1). It was designed as a storing site for tailings from the processing and enrichment of copper ore provided by the Lubin, Polkowice-Sieroszowice, and Rudna mines. This facility is completely surrounded by earth embankments with a total length of 14.35 km. The area of the eastern dam, where the wells are planned, is located in the Rudna municipality [3].

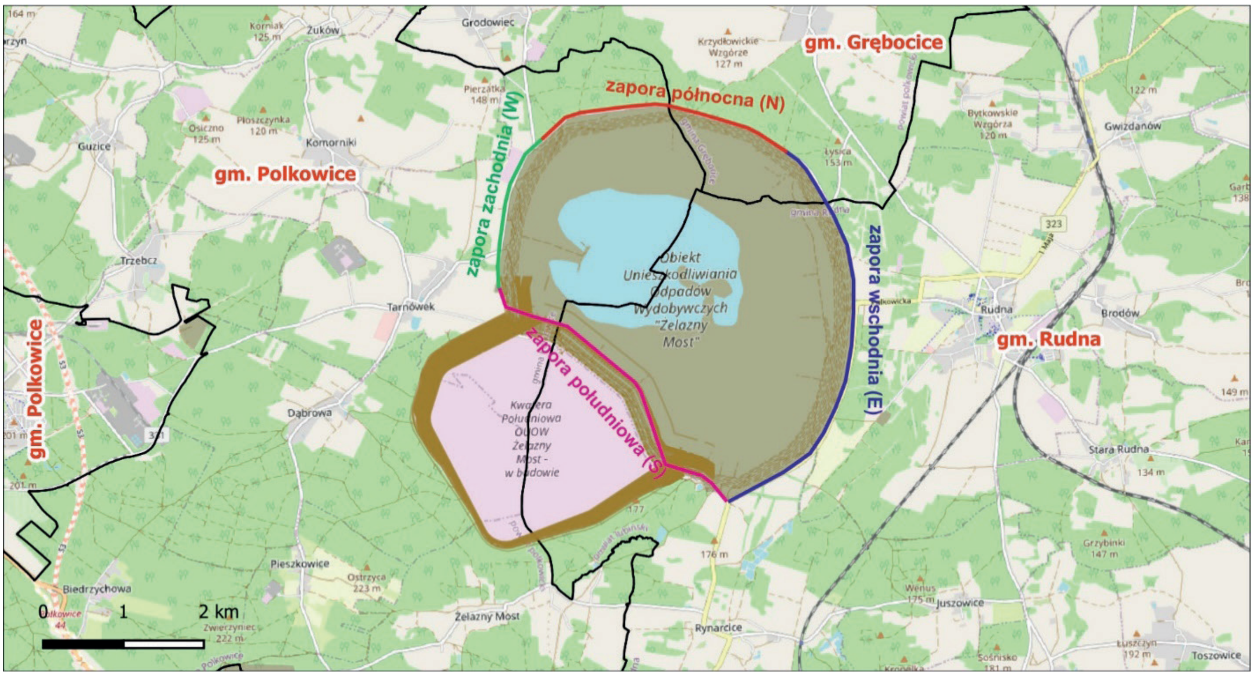

Fig. 1. Location of the "Żelazny Most" MWDF [3]

The embankments of the "Żelazny Most" MWDF are formed using the inward structure method in biennial cycles, at approximately 2.5-meter intervals within each of the 26 silted up sections. Silting up is carried out using a system of pipelines placed along the dam crown. Material from the deposited beach waste is used for shaping the structure, whereas landside slopes are protected with material from local deposits. Inside the reservoir there is a basin, filled with supernatant waters. The depth of the basin at its deepest point is about 3.0 meters. The supernatant water is captured by overflow towers and directed to a pumping station, from where it is pumped back to the Ore Enrichment Plant. After treatment, excess water is periodically discharged into the Oder River [3].

3. Characteristic of geological-engineering conditions

The general characteristics of the geological and engineering conditions in the area of the "Żelazny Most" MWDF are based on studies carried out in 2014–2023 [4, 5].

In the upper part of the subsoil of the analyzed area, Quaternary sediments with a thickness of several to several dozen meters occur. A zone of soils exhibiting the influence of periglacial processes taking place at the end of the Pleistocene are observed to a depth of several meters below the original ground surface. In places, in the near-surface part, young fluvial and stagnant Holocene formations with a large admixture of organic matter have also developed.

Pleistocene formations are mainly represented by sandy-gravel water glacial deposits, to a lesser extent morainic clays and silty clays or dust of stagnant origin. The deeper parts are mostly made up of Pliocene clays overlapped from the north and northwest, deformed glacitectonically several times during Pleistocene glaciations. They were subsequently severed and displaced as scales within the Quaternary sand and gravel deposits. These deformations also included overlays and interbeddings of silty and compact clays and lenses of sands and dusts within the clays. In some areas there are two overlaps and then they are separated by fluvioglacial deposits. The top surface of the overlap often forms outcrops under the sediments of the beach or the dam structure. The sediments of the Neogene are developed as dense gray-blue, blue-green and flame-green clays or spotted clays of the Poznan Pliocene series. Multiple, superimposed glacitectonic deformations have also led to a strong deglaciation of the clays, as well as the severing of smaller entrails and their secondary displacement [4, 5]. The geotechnical properties of subsoil of the "Żelazny Most" MWDF reservoir were recognized as part of a comprehensive and interdisciplinary research program, including both field and laboratory studies. Despite the very extensive research program, the geological model of the subsoil as well as the derived values of geotechnical parameters are still burdened with considerable uncertainty. The ground layers underlying the site as a result of the occurrence of many glacitectonic and periglacial processes, have been strongly deformed, displaced and shuffled, leading to a complex and hardly predictable arrangement of layers.

According to [4] the basic types of subsoil formations deciding on the stability of the site are solifluction silts and clays and Neogene silts occurring in the subsoil over the entire spectrum of variation in the values of index parameters. The soils with the highest plasticity, and therefore the weakest, can occur practically throughout the landfill area. Table 1 shows an exemplary profile of boreholes drilled to a depth of 350 m, along with the geomechanical parameters of the drilled rocks.

Table 1. Exemplary depth profile of ground layers with their geomechanical parameters for wellbore No. 1 [4]

Wellbore No. 1			ρ	$\boldsymbol{\rho}_{sat}$	ϕ	c'	y	E	ν
Depth interval [m]	Lithology	Name of geotechnic layers according to [30]	[kN/m^3]	[kN/m^3]	[°]	[kPa]	[°]	[MPa]	[–]
0.0–7.5	NN	1	19	20.5	34	1	9	80	0.2
7.5–17.0	NN	3	18	19.5	34	1	9	80	0.2
17.0–21.0	NN	4	17	18.5	34	1	9	80	0.2
21.0–68.4	NN	4'	17	18.5	34	1	9	80	0.2
68.4–71.2	Sandy clay	7n	16.06	20	18	1	1.8	96	0.25
71.2–73.6	Compact clay	14n	20.20	–	20	5	–	–	–
73.6–82.4	Silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
82.4–86.9	Fine sand	18n	15.86	19.8	30	1	5	240	0.2

Wellbore No 1			ρ	ρ_{sat}	ϕ	c'	y	E	ν
Depth interval [m]	Lithology	Name of geotechnic layers according to [30]	[kN/m^3]	[kN/m^3]	[°]	[kPa]	[°]	[MPa]	[–]
86.9–98.9	Silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
98.9–103.6	Fine sand	18n	15.86	19.8	30	1	5	240	0.2
103.6–111.8	Silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
111.8–112.3	Silt	10n	16.8	20	10	1	1	36	0.25
112.3–113.2	Lignite	10n	16.8	20	10	1	1	36	0.25
113.2–121.8	Silt	10n	16.8	20	10	1	1	36	0.25
121.8–128.8	Silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
128.8–133.9	Silty clay	9n	17.3	20.5	14.5	5	1.5	36	0.25
133.9–194.5	Silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
194.5–198.1	Coaly silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
198.1–208.3	Fine sand	18n	15.86	19.8	30	1	5	240	0.2
208.3–229.3	I; silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
229.3–240.5	Compact clay	9n	17.3	20.5	14.5	5	1.5	36	0.25
240.5–264.0	Silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
264.0–273.8	Compact silty clay	9n	17.3	20.5	14.5	5	1.5	36	0.25
273.8–286.6	Dusty sand	18n	15.86	19.8	30	1	5	240	0.2
286.6–292.1	Dust	15n	17.97	21.3	24	3	2.4	96	0.25
292.1–313.1	Silt	9n	17.3	20.5	14.5	5	1.5	36	0.25
313.1–319.9	Fine sand	18n	15.86	19.8	30	1	5	240	0.2
319.9–329.1	Sandy clay	9n	17.3	20.5	14.5	5	1.5	36	0.25
329.1–333.0	Sandy dust	15n	17.97	21.3	24	3	2.4	96	0.25
333.0–350.0	Silt	9n	17.3	20.5	14.5	5	1.5	36	0.25

Explanations:
ρ – density
ρ_{sat} – density saturated
ϕ – friction angle of soil
c' – cohesion
y – dilatancy angle
E – Young's module
ν – Poisson's ratio

4. Hydrogeological conditions

The "Żelazny Most" MWDF is located in the area of Uniform Groundwater Body (JCWPd) No. 78 in which one or two aquifers exist in the Quaternary beds. There are 1 to 4 Miocene levels in Neogene sandy formations. The fractured-zone waters in the Triassic formations are highly mineralized. The area of the Uniform Groundwater Body JCWPd includes the Oder River drainage basin, and within its boundaries there is a Major Groundwater Reservoir (GZWP) 314 – Oder River Valley (Głogów). This reservoir is present in permeable sand and gravel formations filling erosion depressions of a Neogene series [3].

Quaternary aquifer formations in the area of the "Żelazny Most" MWDF occur in the form of extensive layers of sandy and sandy-gravel deposits, directly underlying the body of the dams and beach tailings, or occurring at greater depths under glacial till or Pliocene clays. The total thickness of Quaternary formations in the area of the eastern and northern dams is small, and the aquifers are built up by sand and gravel layers with thicknesses of 5 to 40 m. The filtration coefficients of these formations range from 2.7 to 79.6 m/day, averaging 24.1 m/day. The water table in the near-surface layers of the Quaternary level has a free character in the foreground of the dams and a tense character under the filling sediments of the "Żelazny Most" MWDF.

Three levels are distinguished within the Paleogene-Neogene floor: supracoal, intercoal and subcoal.

In the immediate subsoil of the MWDF, there is a level of supercoal, composed of fine and medium sands in the form of lens. In natural conditions, this level, like its deeper Tertiary counterparts, is characterized by subartesian pressure, lower than the placement of the Quaternary water level.

The groundwater of the Cenozoic floor is strongly influenced by the post-flotation water accumulated in the sediments of the "Żelazny Most" MWDF reservoir. The depth of water in these sediments depends on the water level in the sedimentation pond and the distance from the water reservoir. The occurrence of suspended waters stabilizing at different ordinates is a common phenomenon.

Water penetration from the settling pond takes place continuously and is dependent on the water level in the landfill and the extent of the boundary line. Infiltration of water from the tailings pond into the ground caused hydrodynamic and hydrochemical changes in the groundwater around the landfill. The hydrated layers of waste in the sand and gravel bedding zone are locally in contact with waters of the Quaternary horizon [3, 4].

5. Scope of planned drilling operations

It is planned to drill 4 dewatering wells of 250 and 350 m b.s.l. as part of the designed drilling program. All the wells will be drilled in the slopes of the "Żelazny Most" MWDF in adapted cavities. All the boreholes will be drilled with a drill of 0.56 m in diameter, after which a surface casing ϕ 0.508 m will be tripped down. The borehole will then be drilled to the planned depth with a drill ϕ 0.444 m and a 0.280 m diameter filtration column will be installed. An appropriately sized gravel pack will be introduced into the annular space.

6. Methodology for calculating rock mass pressures according to Coulomb–Mohr theory

The basis for determining the strength parameters of the filtration columns in the designed boreholes is the knowledge of components of the primary state of stress in the rock mass and the magnitude of pressure occurring at the interface between the wall of the casing column or the filtration column and the rock environment [1, 2, 6].

Apart from purely technological considerations, the proper operation of the well is determined by the strength of the casing, i.e. the casing column and filtration column tripped into it.

If the compressive strength condition is to be met for the casing or filtration columns, a pressure distribution function around the drilled wellbore should be provided.

6.1. Determining the highest vertical and horizontal pressures in the intact rock mass by the analytical method

In this paper, only the method used to determine the state of stress in a loose medium having internal cohesion will be addressed. The original state of stress in such a medium is determined based on the Coulomb–Mohr method with the following equation [5, 7, 8]:

$$\delta_2 = \frac{1+\sin\phi_i}{1-\sin\phi_i}\,\delta_1 + 2k_i\frac{\cos\phi_i}{1-\sin\phi_i} = \sum_{i=1}^{n} g h_i \rho_i \tag{1}$$

where:

δ_2 – the highest principal stresses acting vertically at the bottom of a given layer,
δ_1 – the lowest principal stresses acting horizontally,
g – acceleration of gravity,
h_i – thickness of i-th layer,
ϕ_i – angle of internal friction of the i-th layer,
ρ_i – density of the i-th rock layer,
k_i – cohesion of the i-th layer.

If veritical stress δ_2 is denoted as p_z, and horizontal stress δ_1 is denoted as p_x, then equation (1) will assume the following form:

$$p_z = \frac{1+\sin\phi_i}{1-\sin\phi_i}\,p_x + 2k_i\frac{\cos\phi_i}{1-\sin\phi_i} = \sum_{i=1}^{n} g h_i \rho_i \tag{2}$$

The physicomechanical parameters of rocks appearing in equation (2) were assumed in compliance with materials presented in [4] and given in Table 1.

The horizontal pressure of rocks at a given depth in the top of the i-th layer was determined from the transformed equation (2).

$$p'_x = \left(\sum_{i=1}^{n-1} g h_i \rho_i - 2k_i\frac{\cos\phi_i}{1-\sin\phi_i}\right)\frac{1-\sin\phi_i}{1+\sin\phi_i} \tag{3}$$

whereas the horizontal pressure in the bottom of the i-th layer equals to:

$$p''_x = \left(\sum_{i=1}^{n} g h_i \rho_i - 2k_i\frac{\cos\phi_i}{1-\sin\phi_i}\right)\frac{1-\sin\phi_i}{1+\sin\phi_i} \tag{4}$$

6.2. Determining pressure in the immediate vicinity of a casing pipe

The theoretical principles of calculating pressure in the immediate vicinity of a casing column have been described in detail in [1, 9–11] and literature [12–16].

The values of pressure on the contact of casing and gravel pack contact can be calculated from the below equation [8, 19]:

$$\delta_a = p_x \left(\frac{a}{R} \right)^{C-1} \tag{5}$$

where:

δ_a – pressure on the contact of gravel pack and a casing pipe,

p_x – horizontal pressure of rock is in the intact rock mass, described with equations (3) and (4),

a – outer diameter of a casing pipe,

R – diameter of the drilled wellbore,

$$C = \frac{1 + \sin\phi_{zw}}{1 - \sin\phi_{zw}}$$

ϕ_{zw} – angle of internal friction of gravel pack after thickening in the wellbore.

Having assumed that the angle of internal friction for gravel $\phi = 36^0$ is $C = (1 + \sin\phi_{zw})/(1 - \sin\phi_{zw}) = 3.852$, then the ultimate form of equation (5) will take the following form:

$$\delta_a = p_x \left(\frac{a}{R} \right)^{C-1} = p_x \left(\frac{a}{R} \right)^{3.852-1} = p_x \left(\frac{a}{R} \right)^{2.852} \tag{6}$$

If the pressure acting on the casing equals to the pressure evoked by the weight of the gravel pack, then the pressure can be determined from the equation:

$$p_x^* = p_z^* \cdot \frac{1 - \sin\phi_{zw}}{1 + \sin\phi_{zw}} = g \cdot \rho \cdot h \cdot \frac{1 - \sin\phi_{zw}}{1 + \sin\phi_{zw}} \tag{7}$$

No cohesion parameter was assumed in above equation.

7. Results of calculations of rock mass pressure distribution around dewatering well No. 1

Calculations of rock mass pressures were performed for the planned dewatering well No. 1 with a depth of 350 m and a filter column of 0.28 m diameter installed within the slope of the "Żelazny Most" MWDF. Figure 2 graphically shows the distributions of vertical and horizontal pressures in the rock mass and gravel pack and in the immediate vicinity of the filtration column in well No. 1.

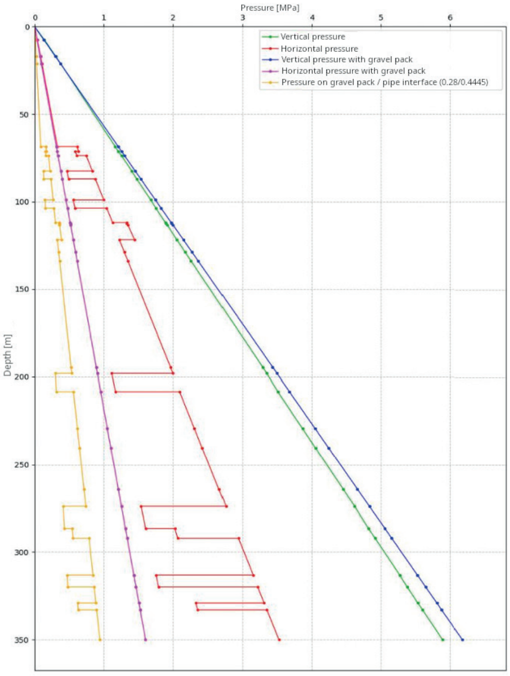

Fig. 2. Collective plots of vertical and horizontal pressures evoked by the rock mass and gravel pack in the dewatering well No. 1

8. Summary of the results of rock mass pressure calculations according to Coulomb–Mohr theory

The analysis of the calculated values of horizontal components shows that the lowest values of stresses acting on the walls of the filtration columns at a given depth are obtained when the pressures are assumed to come from the gravel pack loaded with rock mass. In contrast, the highest pressures result from calculations of the original state of stress in the rock mass.

In line with the widely discussed principles of wellbore design and the calculation of casing strength to the outer crushing pressure [5, 11, 18–22], a less favorable case should be selected from the strength point of view, i.e. the value of horizontal pressure exerted by the rock mass. Accordingly, the dimensions of the casing and filtration pipes, as well as their strength characteristics, should be so designed in dewatering wells that horizontal pressures from the rock mass in the interval of layers with soil properties do not crush the columns.

The analysis of the rock mass pressures calculated by the Coulomb–Mohr method reveals that the maximum values that can lead to the crushing of the filtration columns appear at different depths in individual wells, in their lower intervals.

Taking into account the results of calculations of rock mass pressures in the immediate vicinity of the designed dewatering wells within the “Żelazny Most” MWDF and the experience gained while designing and drilling wells for various purposes, it should be concluded that filter columns with a crushing pressure strength of at least 3.5 MPa should be used for the wells in question.

When adopting such a value for the crushing pressure of the filter pipe columns, account was also taken of the variable geological structure and the very different (but also very low) geomechanical parameters of rocks encountered in the profiles of the planned wells.

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