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Risk Reduction of a Terrorist Attack on a Critical Infrastructure Facility of LGOM Based on the Example of the *Żelazny Most* Tailings Storage Facility (OUOW *Żelazny Most*)

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Abstract: This paper identifies the threats and risks of a terrorist attack on a critical infrastructure facility based on the example of *Żelazny Most* Tailings Storage Facility (OUOW). The threat analysis primarily took into account the threats of deliberate human actions. Identification of potential threats concerning the infrastructure surrounding the facility was conducted based on information that is readily available on the Internet. The reasons why it may be a potential target were also justified. Numerical calculations of the stress–deformation scale of the initial state of the reservoir, based on the Biot model with the Kelvin–Voight rheological skeleton, were presented as a starting point for in-depth research on the scale of threats and risks to the reservoir. The presented numerical model can be a starting point for calculating the stability of a reservoir subjected to explosives. The facility constitutes a major element of Lubińsko-Głogowski Okręg Miedziowy (Lubin-Głogów Copper District). OUOW *Żelazny Most* is the biggest such facility in Europe and is utilized to collect tailing waist. When expanded in its southern quarter, the facility will be the biggest in the world.

Keywords: *Żelazny Most* Tailings Storage Facility; threats; terrorist attack.

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1 Introduction

Advancement of civilization, along with the rapid scientific and technical progress in economic sectors such as electronics, energy production, communication, health care, education, and transport have led to wide access of the goods and services that are so essential for the efficient functioning and development of a modern state and its society. On the one hand, such fast development has amounted to an improvement of living standards, but on the other hand, it is potentially dangerous. The law defines critical infrastructure as systems that include functionally interrelated facilities such as civil structures, mechanical devices, and installations. It can also be defined as services that are crucial to the safety of the country and its citizens, and also those that ensure the smooth functioning of public administration institutions and businesses. Due to human activity, critical infrastructure may be damaged or destroyed. Consequently, continuity of key services may be jeopardized, as can the property, health and even life of the citizens. Taking into consideration the fact that such incidents negatively affect the economic growth of a country, it must be stated that critical infrastructure plays a key role in the functioning of a country and the life of its citizens, and therefore, the protection of this infrastructure can be seen as a priority.

While the threats of natural disasters have invariably remained unchanged since the dawn of time, the character and range of technical threats change with the advancement of technology.

At a time of pervasive terrorism, the biggest and most unpredictable threat should not be ignored – intentional human actions.

According to Aleksandrowicz (2016), Poland is under the same threat factors as the rest of Europe and the world. The only difference is their scale and intensity.

Considering the above, the authors decided to look into the problem of whether or not the risk of a terrorist attack on the critical infrastructure of Lubińsko-Głogowski Okręg Miedziowy (LGOM), based on the example of mining waste treatment *Żelazny Most*, may be lowered. According tothe authors, such threats are potentially real.

2 Exemplary Terrorist Actions on Critical Infrastructure Facilities

Threats that may trigger a crisis situation affect the safety and functioning of an entire country or any of its particular regions. They can be subdivided into three categories (Lidwa et al 2012). The first one – natural hazards – is connected to the forces of nature (floods, epidemics, tectonic movements). The second one – techno-logical threats – are caused by human activities. They usually concern citizens, their property, the environment, or critical structure facilities, and may be the result of malfunctioning of the following:

– industrial facilities, there may be a release of radioactive or biological products;
– municipal facilities, among which the most serious are malfunctioning in power plants, heating plants, water supply, and gas supply;
– buildings, where the most serious hazard includes the collapse of buildings and structures; and
– transportation devices (especially those used to transport hazardous cargo), which may be destroyed or damaged as a result of an accident involving road, railway, air, sea, or inland waterway transport.

The third category includes terrorism. Poland's engagement on the international arena may not only lead to perception of the country as an ally in the fight for democracy, but also as a potential target for terrorists.

In recent years, fake information about planted explosives, along with dummy bombs or decoys left in alleged places, has become an increasing problem. Such actions may be the result of both a desire to check the reaction of a state, or a wish to see a state's procedures and the efficiency of antiterrorist groups, as well as a wish to create chaos and panic. In many cases, such actions may lead to serious consequences for human health or life due to the potential swift evacuation of random people from the threatened area. Among others, such actions may be exemplified by a bomb scare in Rudna mine.

The increasing role of energy for a modern country makes critical infrastructure energy facilities more attractive as targets of attacks. A number of facilities may potentially be targeted: from gas and oil refineries, pipelines, and energy power lines, to other forms of energy-transporting carriers (e.g. tankers – hijacking of Sirus Star in 2008) or power plants (not excluding nuclear or hydroelectric plants that are located on dams). Such threats require the vigilance of energy-producing plants, as well as the services and authorities responsible for the safety of the country. Real and successful attacks on facilities of critical infrastructure in the world include the following:

– A cyber-attack in Germany in 2014, which resulted in physical damage of a huge blast furnace in steelworks. It was the first such type of attack conducted in the West. According to the report of the German Federal Office for Information Security (BSI) regarding cyber terrorism, the attackers used the sophisticated techniques of spearphishing and social engineering in order to gain access to the steel mill's IT network. Industrial control systems were also connected to this network to facilitate remote production management and the collection of real-time statistics. Using their knowledge of the systems, the hackers forced one of the blast furnaces to uncontrollably shut down. Big blast furnaces (up to 40 m) in steelworks operate in a continuous mode, very often for several years nonstop. In the case of the cyber-attack, the uncontrollable shutdown of the furnace led to the destruction of many elements of the steel smelting control process, in turn causing great damage to the infrastructure of the steelworks. The report, keeping in mind the safety of the company, did not reveal the exact date of the attack or the name of the steelworks.
– An attack on Tiguentourine gasworks in In Amenas, Algeria in 2013 is an example of new threats to critical energy production infrastructure and to the homeland security of a country. The attack in In Amenas may be assessed as the most complex and professionally planned attack of this type on energy production infrastructure on the African continent. The attack lasted for 4 days, posing a real threat of destroying the major gasworks and location of gas extraction in Algeria (about 10% of the total production of the country) and caused the death of 38 hostages. As a result of the attack, the refinery in In Amenas had to be temporarily closed and the operations of similar facilities were reduced (among others, British BP and American Conoco). Additionally, a significant number of foreign workers were temporarily evacuated in fear that they could become targets of similar attacks. Two hundred and fifty workers of the Hassi Moumene oil refinery in the south of Algeria (BP, Statoil, Sonatrach, Petrofac) left their workstations. They demanded safety

guarantees due to an attack conducted by an armed group in January 2013, who stole equipment such as off-road vehicles.

3 Determining the Type of Data Needed to Plan a Terrorist Attack on Critical Infrastructure

Determining the type of data needed to plan a terrorist attack on critical infrastructure is the first step in carrying out an attack, and the data needed depends on the target of the attack. After determining the area, type of data, as well as the time and space scale comes the stage of assessing the possibility of obtaining qualitative data (Tomlinson 1986, Burrough and Mark 2003, Longley et al 2005, Kowalski et al 2010, Kang-Tsung 2019).

Modern spatial data retrieval methods are not based solely on traditional methods, but instead on advanced sources of data that are created using modern technologies. Geodata (spatial information) consists of:

- location data (coordinates on the reference frame),
- geometric properties,
- the spatial relation of objects, which can be identified in relation to Earth, and
- a physical model of the facility allowing both the impact and scale of the influence of external factors to be determined.

Currently, data may be obtained directly from outer space (from satellites), as well as from the satellite systems that are indirectly used on Earth. The impact of modern technologies is best observed in current surveying methods and in the example of multispectral imaging aerial and satellite photography and automated measuring stations. However, we should not ignore traditional measuring methods, which are still of significant importance in terms of data acquisition, e.g. maps, plans, and field measurements.

Consequently, it is possible to have an overview of the most important measuring methods, as well as the methods of spatial data acquisition that can be used when planning a terrorist attack (Król 2019, Shejja et al 2018, Haney 2017, Weimann 2016, Audu 2014, Asmat 2010, Chandrakar and Thomas 2010):

- reconnaissance, field measurement, and observation;
- measurements utilizing GNSS (Global Navigation Satellite System) receivers;
- radio interferometry InSAR (In Specific Absorption Rate) (aerial and satellite);
- laser scanning (aerial);
- satellite imagery;
- aerial photography – taken from the altitude of manned aircrafts and unmanned aircrafts (UAV – Unmanned Aerial Vehicle), as well as nanosatellites;
- ground photographs – metric and non-metric photographs;
- vector conversion – raster/raster–vector;
- the photogrammetric method (obtaining and presenting metric and non-metric photographs);
- the cartographic method (processing already existing maps);
- national archives, e.g. geodetic and cartographic materials, maps, and local zoning plans; and
- analog and digital materials, the geographic database (readily available in the Internet) – free and paid.

The geoportal Google Earth, the social network Open Street Map, as well as many others make it possible to download information and geoinformation (information about a particular localization), which in the form of special information are collected in the Geographic Information System. Readily available and free of charge satellite and radar images, aerial pictures taken from drones, and analog and digital maps are popular sources of information that can be used for various purposes. Geoportals of the national geodetic and cartographic services allow us to find any given place and to obtain 3D information about its topography, land cover, and buildings. Photography cataloging may come in useful for detailed analysis, whereas a series of photos (even taken with a phone) in readily available programs may be useful for generating a relatively detailed 3D model.

Such an example of using geoinformation from readily available sources can be seen in a terrorist attack in Bombay in 2008, where the terrorists utilized the information in Google Earth to organize their attack plan and learn the topography of the city.

4 A Critical Infrastructure System Composed of Facilities that Make Up LGOM

Facilities of the critical infrastructure that make up LGOM are interconnected, where the final product of one technological phase is an intermediate product utilized in the next facility.

The degree to which the LGOM facilities are interconnected can be presented in a simplified description of the integrated course of the technological process that is involved in the production of KGHM Polska Miedz S.A.: copper ore is excavated in the mines of ZG Lubin, ZG Polkowice-Sieroszowice, and ZG Rudna. It is then transported to the ZWR facilities of Lubin, Polkowice, and Rudna for flotation processing. The process results in copper concentrate, which in turn is delivered to the steelworks. The process of ore flotation is one of the elements of mineral dressing. The process requires large amounts of water, estimated to amount to about 4–5 m^3/t of the fed ore.

The copper concentrate obtained in the process of mineral dressing makes up about 4%–6% of the ore excavated. Thus, it is obvious that most of the excavated rock (94%–96%) ends up as waste stored on the surface. Flotation waste is in the form of liquid slurry, in which solid particles take up 6.5%–8.7% of its volume. The waste is then transported via pipelines to OUOW *Żelazny Most*, which is located in the Dolnośląskie voivodship on the border of Lubin county, within the area of three communities (Zielinski et al. 2013).

Fig. 1 presents the interdependence of LGOM facilities and visualizes the importance of the studied facility.

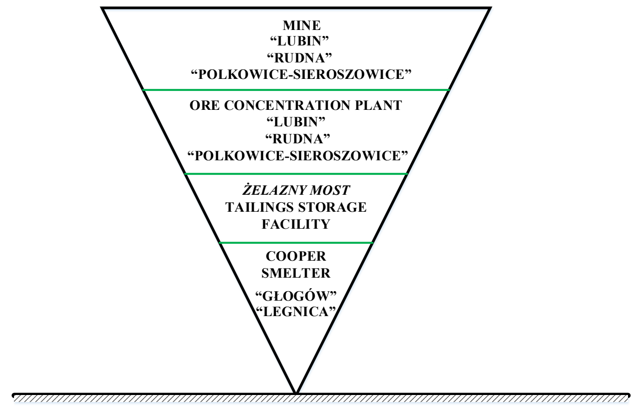

Figure 1: Location of OUOW *Żelazny Most* within the system of the critical infrastructure of LGOM (source: own elaboration).

5 *Żelazny Most* Extractive Waste Disposal Facility

The facility is located in the southwestern part of Poland and is 80 km from Wroclaw on the territory of LGOM near the town of Rudna. Its localization has enforced the elimination of three villages: Barszów, Pielgrzymów, and Kalinówka. It is Europe's largest waste pond and one of the biggest in the world.

The construction of the waste facility began in 1974, and its operation and simultaneous expansion has been ongoing since 1977. In its initial stage, it was locked by two starter dams: in the east and west, both of which enclosed the natural valley. Currently, after the construction of the north and south starter dams, its combined length amounts to 14.3 km. In its central part, there is a reservoir of overlying water.

Current expansions of the waste pond may be subdivided into the following phases:

– phase I (1974–1985) – construction of the waste pond of about 130 million m^3 and elevation of the dams amounting to 134.50 MASL;
– phase II (1985–1995) – expansion of the waste pond to about 230 million m^3 and elevation of the dams amounting to 150 MASL;
– phase III (1995–2002) – expansion of the waste pond to about 350 million m^3 and elevation of the dams amounting to 160 MASL; and
– phase IV (2005–2009) – further expansion of the waste pond to the crest elevation of 180 MASL.

Fig. 2 presents the consecutive phases of expansion of OUOW *Żelazny Most*.

Due to the constant storage of waste and the ongoing expansion of the waste pond, its parameters underwent continuous change, and as of December 2014, they are:

– total surface of the facility – 1394 ha,
– beach area – 462 ha,
– area of the water body – 777 ha,
– dams' elevation – 174 MASL, and
– waste volume – 557.6 million m^3 (Czaban et al. 2015).

6 Threats to OUOW *Żelazny Most*

Due to threats resulting from malfunctioning of the dams, the OUOW pond is categorized as being a class 1 hydrotechnical structure, as non-functioning or incorrect functioning may lead to a serious accident.

An extensive system encircling the entire facility has been developed in order to monitor the impact on particular elements of the environment: ambient air, water, soil, and crops. Moreover, a series of protective measures have been introduced against the mentioned impact, among others: systematic stabilization of the beaches and embankments,

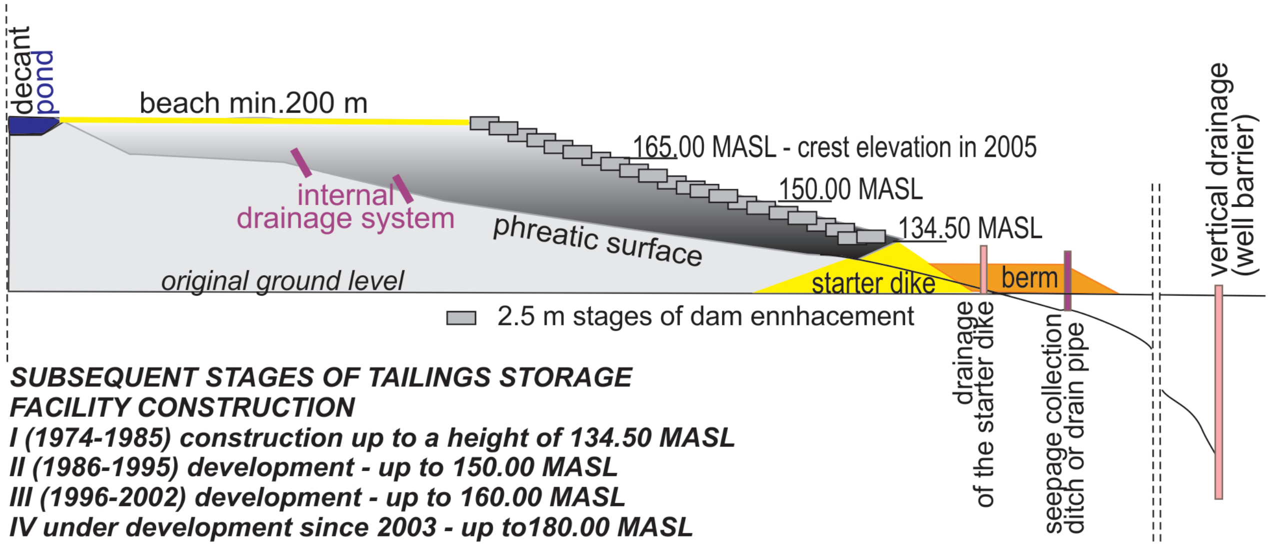

Figure 2: Consecutive phases of expansion of OUOW *Żelazny Most* (based on *http://www.dhvhydroprojekt.com.pl/download,process,xy_800_600,file,132/Zelazny-Most-1.jpg, access: 20.04.2018 r*).

overhead irrigation of the beaches, grass sodding of the embankments, drainage ditches (ring system), a vertical drain barrier, an alarm system for emergencies, and sealing of the reservoir dome with low-fraction aggregate.

The newest achievements of science and technology were used during the design stages. A team of international experts was called together to work in cooperation with the designers. Very thorough geological research and a high number of geotechnical laboratory and field tests were conducted. An extensive system of control and measuring instruments allowing constant monitoring of occurrences taking place in the body and the base of the dams was set up.

All of the elements are being utilized by the designers for the execution of phased executive designs for building the embankments, which take into consideration the necessary drainage, strengthening by loading berms, drainage discharge, and surface discharge. Since the facility was designed and constructed in accordance with such rigorous norms, one may ask whether or not the research problem mentioned at the beginning of this paper is still up to date.

According to D. E. Krzysztof Wrzosek, general designer, engineer Jerzy Matuszewski, general designer of water and slurry installation, and D. E. Jacek Stasierski, general specialist for monitoring from Hydroproject Ltd., this would call for unheard of amounts of explosives, a time-consuming and professional setup, followed by detonation in a precisely selected sequence. Anyone willing to undertake such an action would be detected, not to mention the fact that the potential saboteur would need to obtain the detailed and strategic documentation of the facility in advance. Even the planning stages of a terrorist attack of such a scale could not remain undetected by the hydrotechnical company or the authorities ensuring the safety of Poland (Wrzosek et al. 2011).

Objects that were considered by their designers in 2011 to be impossible to destroy can be destroyed now, according to specialists in the field of destruction and tactics of terrorists.

The result of such an incident could be the release of overlaying water amounting a little to about 15 million m^3, along with partially liquefied sediments amounting about 6 million m^3. The consequence of such an event could be the flooding of several towns.

According to the Operations Manual of OUOW *Żelazny Most*, in order to safeguard against the outflow of overlaying waters, a minimum beach width of 200 m has been applied. In practice, the width of the beaches is anywhere from 300 to 1200 m. In relation to the opinion of ZEM (Zespół Miedzynarodowych Ekspertów), which is presented in expertise concerning the expansion of OUOW *Żelazny Most* (February 2013), the most recent geotechnical research indicates that in situ sediments, even in the most extremely unfavorable conditions, and in the state of full saturation, are not susceptible to spontaneous and broad destruction due to liquefaction, and thus even the most pessimistic scenario assumed in the emergency plan is not likely to occur.

To sum up, the expert opinions cited by the authors do not mention deliberate human actions – terrorist attacks – as a threat to the investigated facility.

During the 90s of the past century, an increased speed of the surface displacement of the eastern dam was observed. After conducting the necessary tests and analyses, ZEM suggested introducing the observational method as the official method of construction and functioning of OUOW. This allowed the introduction of necessary remedial actions that aim to ensure the stability of the mentioned section of the eastern dam.

The analysis of the obtained results allowed the instability of the shear zones, especially in the transformed tertiary cohesive formations, to be identified.

Backward analysis, which allowed measures to be determined for improving stability, was conducted in accordance with the observational method. The measures included:

- shifting of the embankment crest (above the elevation of 165 MASL) in the most vulnerable sections of the silt toward the water pond in order to create the so-called cord;
- installation of a relief wells system, which lowered the pressure in tertiary cohesive soils and subsequently increased the effective stress in these soils; and
- phased construction of a loading berm at the base of the dam.

Shifting of the embankment crest and construction of the loading berm turned out to be effective, as indicated by the readings of control and measuring apparatus. Among others, the Geomos system of automatic measurements of surface deformation, which was installed in 2009, noted a reduction in the increase of horizontal displacements in the area of the wash sections E1 and E2. The obtained results coincide with the geodetic observations of the traditional control points (surface benchmarks), which also indicated lowered displacements of the eastern dam downstream. Significant results were obtained by the installation of the relief wells. These wells were equipped with a long continuous screen that enables pumping from numerous layers of permeable soil that occur in cohesive layers in the entire profile.

7 Numerical Calculations for the *Żelazny Most* Tailings Storage Facility

As mentioned above, it was necessary to use both theoretical and practical methods to solve the assumed problem. The research subject itself is extremely important and complex. A physical model, presenting the cause and effect chain, plays an important role in predicting how the examined facility will behave under the influence of external factors such as the threat of a terrorist attack. A properly constructed model can provide necessary information concerning prevention and protection against such a threat. From this point of view, it thus fulfills a strategic role in planning comprehensive protection for the facility. It should be emphasized that the more data we provide to the model, the better it reflects reality – and this is why the methods indicated in the article, both theoretical and practical, are mutually complementary. In the context of the explosion hazard, the analysis of loads in the dams of the tailings pond may indicate the presence of significant dynamic impacts affecting the stability of the repository. A potential explosion may cause a strong impact on the structure of the tailings pond. The presented landfill consolidation numerical model is a base model showing the impact of both internal and external loads on deformations taking place in the facility. The model, after being extended in a specific research direction, may enable the formation of the basic parameters of a potential explosion. Moreover, it may also indicate the zones that exceed the yield point of the material, which directly translates into its loss of stability. Therefore, the modeling of dynamic interactions may provide information that is necessary in the design process to recognize the existing hazards related to the stability of the landfill. Laboratory tests carried out on material taken from the landfill *Żelazny Most* (Bartlewska 2009, Strzelecki et al 2011, 2014, 2015) allowed the effective parameters of the model of Biot consolidation with the rheological skeleton to be determined. The obtained measurement results allowed a numerical model of consolidation of the *Żelazny Most* reservoir to be created and the process of its deformations over time to be analyzed. The results of calculations can be used to analyze the state of stress and deformation of the landfill under the influence of its own weight, and also the process of water filtration through this tailing pond. The conducted analysis of plasticity potentials may be the starting point for the analysis of stability or its loss, e.g. as a result of deliberate human activity, on this important, and the largest, hydrotechnical construction of this type in Europe.

7.1 Consolidation calculations – the state of plane strain

The physical and strength parameters obtained in the laboratory tests and presented in Bartlewska's (2009) work were used in order to generate a numerical 2D consolidation model for the landfill site and also a home-based model

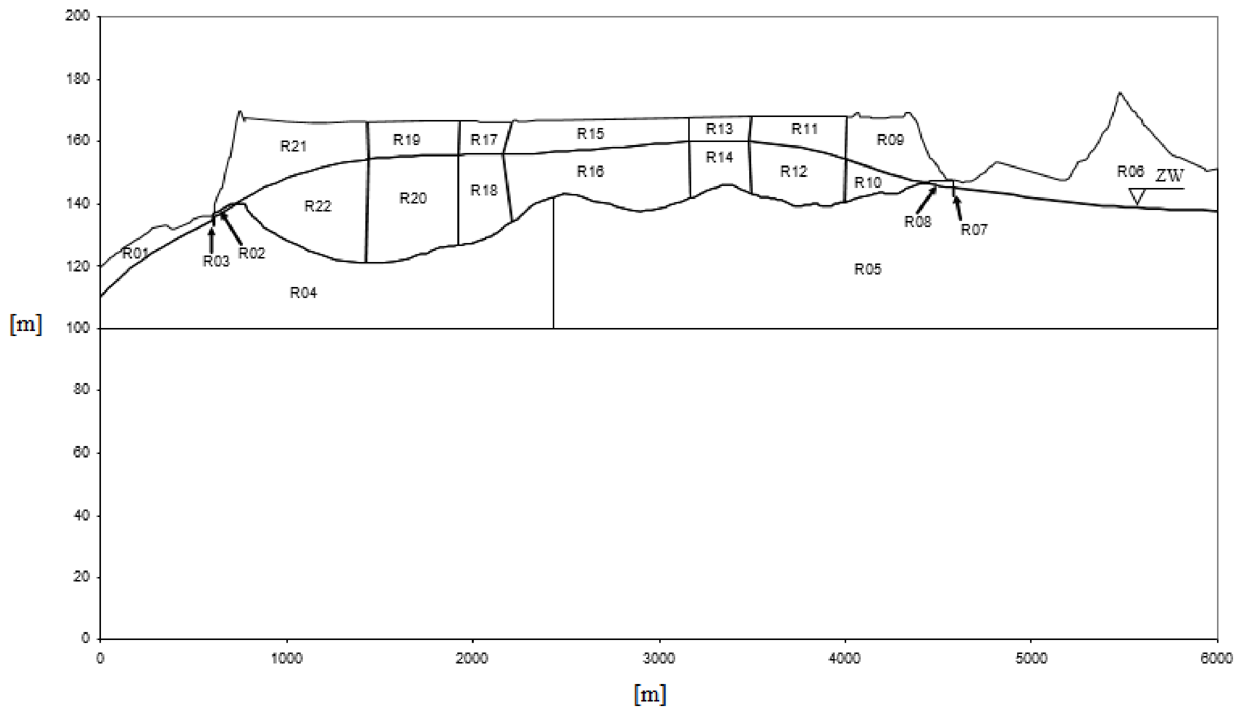

Figure 3: Division of the 2D computational domain into regions (Bartlewska 2009).

based on the Biot analytical model with the Kelvin–Voigt rheological skeleton. In the presented chapter, there is a numerical simulation of 2D consolidation of the object and the natural terrain in the state of plane strain based on the equations of the Biot analytical model and with the Kelvin–Voigt rheological skeleton. This model was created for a vertical north–south section through the center of the landfill. Direction was selected arbitrarily as the construction of the tank is similar in all directions. The entire area subjected to computer simulation of the consolidation process was built from smaller areas with different parameters of sediments that are stored within.

The equations of the Biot consolidation model with the rheological skeleton Kelvin–Voigt were used in accordance with Bartlewska (2009) and Strzelecki et al. (2011) as follows.

Physical relationships of the Biot model with the Kelvin–Voigt rheological skeleton have the following form:

$$\begin{gathered}\sigma_{ij} = 2N\varepsilon_{ij} + 2\eta^{p}\dot{\varepsilon}_{ij} + \left(A\varepsilon + Q\theta\right)\delta_{ij} + \eta^{o}\dot{\varepsilon}\delta_{ij}\,, \\ \sigma = Q\varepsilon + R\theta\end{gathered} \tag{1}$$

In the work of Biot-Willis (1957), constants from the presented constitutive relations were interpreted as follows:

– N is the shear modulus of the skeleton,
– A is the modulus of the volumetric skeleton filled with liquid,
– Q is the coefficient of the impact of liquid volume deformation on the stress in the skeleton or vice versa – the coefficient of the impact of the skeletal volume deformation on the stress in the liquid, and
– R is the module of volume deformations of the liquid filling in the pores of the Biot's medium.

The parameter M is expressed as $M = A - \frac{Q^2}{R}$.

Biot's constants M and N correspond to the elastic medium of Lamé constants. Taking into account the physical relationships for the Biot's medium with the rheological skeleton of the Kelvin–Voigt body in the equations of motion, according to Strzelecki et al. (2015), the following system of consolidation equations was obtained:

$$\begin{gathered}N\Psi_k\nabla^2 u_i + (M + N\Psi_k)\varepsilon,_i = -\frac{H}{R}\sigma,_i + \rho_{11}\frac{D^s v_i^s}{Dt} + \\ + \rho_{12}\frac{D^s v_i^l}{Dt} + \rho_{12}\frac{D^l v_i^s}{Dt} + \rho_{22}\frac{D^l v_i^l}{Dt} \\ \frac{c}{f^2}\nabla^2\sigma = \frac{1}{R}\dot{\sigma} - \frac{1}{R}\dot{\varepsilon} + \rho_{12}\frac{D^l v_i^s}{Dt} + \rho_{22}\frac{D^l v_i^l}{Dt}\end{gathered}$$

Table 1: Values of the medium parameters (Bartlewska 2009).

Index	1	2	3	4	5	6	7
Area	**R01, R02, R04**	**R05, R06, R08**	**R09, R10, R21, R22**	**R11, R12, R19, R20**	**R13, R14, R17, R18**	**R15, R16**	**R03, R07**
j (°)	35	32	25	12	18	16	
c (Pa)	1.00E+03	1.00E+04	1.00E+04	1.00E+04	1.00E+04	5.00E+03	
k (m/s)	1.00E-06	5.00E-07	2.00E-07	8.00E-08	5.00E-08	1.00E-08	1.00E-04
N (Pa)	9.50E+08	8.55E+07	9.50E+06	7.60E+06	4.75E+06	2.85E+06	
A (Pa)	2.20E+09	1.98E+08	2.20E+07	1.76E+07	1.10E+07	6.60E+06	
R (Pa)	5.00E+09	4.50E+08	5.00E+07	4.00E+07	2.50E+07	1.50E+07	
H (Pa)	2.50E+09	2.25E+08	2.50E+07	2.00E+07	1.25E+07	7.50E+06	
n_0 (–)	0.25	0.22	0.35	0.33	0.30	0.30	
G (N/m³)	2.50E+04	2.40E+04	2.40E+04	2.35E+04	2.35E+04	2.35E+04	
W (N/m³)	1.00E+04	0.00					
α (–)	1.00	1.00	1.00	1.00	1.00	1.00	
η_s	2.20E+06	1.98E+05	2.20E+04	1.76E+04	1.10E+04	6.60E+03	
λ_s	1.00E+07	9.00E+05	1.00E+05	8.00E+04	5.00E+04	3.00E+04	

In the case when the process can be treated as quasi-static, the above system of equations can be represented by the formula

$$\begin{cases} N\Psi_K\nabla^2 u_i + (\Psi_l M + N\Psi_k)\varepsilon,_i = -\frac{H}{R}\sigma,_i \\ \frac{k}{f^2}\nabla^2\sigma = \frac{1}{R}\dot{\sigma} - \frac{H}{R}\dot{\varepsilon} \end{cases}$$

where $\Psi_k = 1 + T\frac{\partial}{\partial t}$ and $T = \frac{\eta^s}{N}, \eta^s$ are the shear viscosity of the skeleton.

7.2 Boundary conditions for a 2D model

The whole area of the consolidation process that is subject to computer simulation consists of areas with different parameters of deposits stored in them. Therefore, the whole area was divided into smaller areas with known parameters. In this way, 22 subregions were created and are shown schematically in Fig. 3. Table 1 shows the numbering of the center parameters for these regions and their corresponding values.

7.3 The results of numerical calculations for a plane model

The results of numerical calculations performed using the finite element method in Flex PDE 6 software for a plane model, after completing the consolidation process in the form of 2D charts, are given below.

Fig. 4 shows the vector field of the material displacement of the landfill and ground. The obtained maximum size of subsidence occurs in the central part of the repository and amounts to approximately 1.1 m.

Fig. 5 shows the graph of horizontal displacements. It can be seen from the graph that the maximum values of horizontal displacements occur in the vicinity of the landfill slopes and are of the order of 10 cm.

A graph for vertical displacement is shown in Fig. 6. The figure shows that the largest vertical displacements occur in the central part of the landfill, which is consistent with the observations in the field. The maximum calculated vertical displacement is of the order of 1.10 m.

Fig. 7 shows the behavior of the stability potential, which is expressed in the following formula:

$$\Psi = \frac{\partial H}{\partial y} + \frac{\gamma_s - \gamma_w}{\gamma_w}$$

When the value of Ψ is positive, there is no loss of stability. As can be seen in Fig. 7, there is no loss of filtration stability in the examined cross-section.

Fig. 8 shows the distribution of stresses in the liquid (pore stresses) after the consolidation process – fp_α ss. According to the accepted boundary condition, the stresses at the groundwater level and above are equal to, where *f* denotes porosity and p_a the atmospheric pressure.

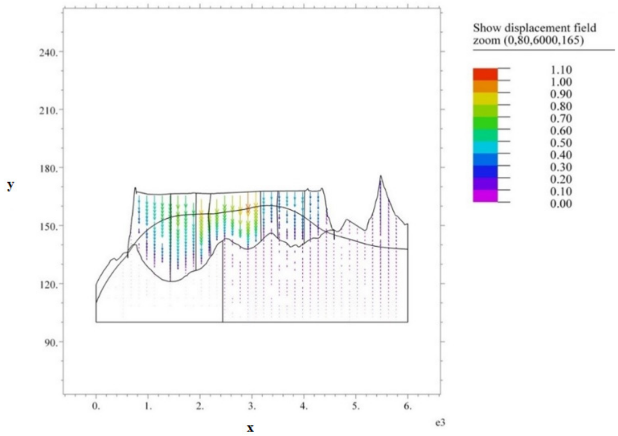

Figure 4: Results for the 2D model – land dislocations.

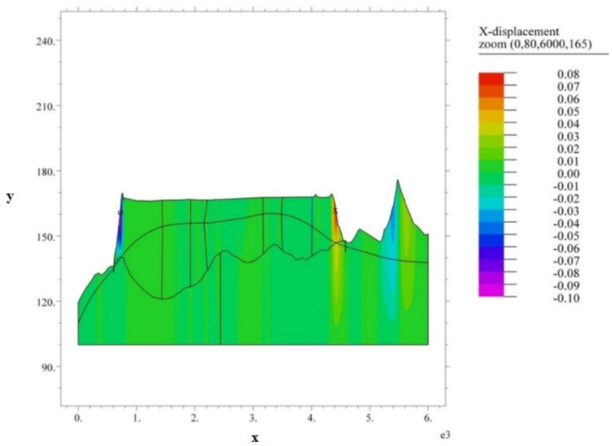

Figure 5: Results for the 2D model – displacement in the x direction.

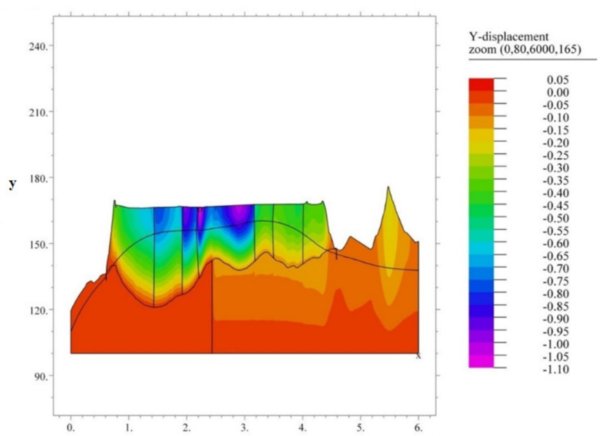

Figure 6: Results for the 2D model – displacement in the y direction.

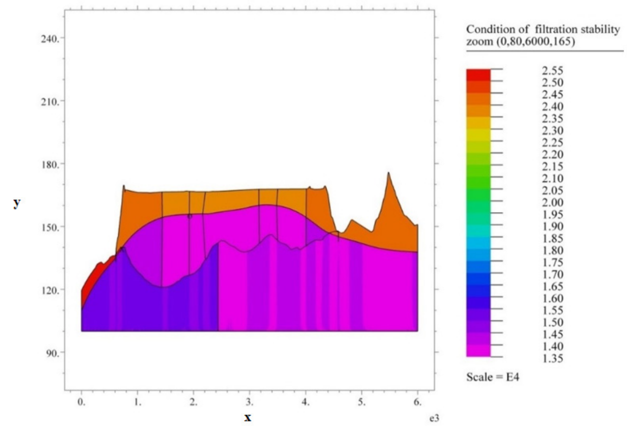

Figure 7: Results for the 2D model – stability condition.

The highest pressure values in the liquid occur in the ground below the repository.

Determination of the center plastic zones based on the Coulomb–Mohr potential is shown in Fig. 9. The negative value of the potential determines the areas where the area is stable. Where the potential assumes a positive value, the shear strength is exceeded with the adopted parameters of the internal friction angle and cohesion. It can be seen from the graph that there are such areas in which the medium may be in a plastic state. The propagation of waves caused by the explosion of the load may cause the formation of large sub-areas in which the porous medium will pass into a plastic state and may cause the tank's stability to be lost. However, detailed research in this direction requires selection of places of loading, analysis of the propagation processes of vibrations that were caused by the explosion, and determination of possible zones of loss of stability.

7.4 Conclusion of the correctness and application of the numerical model

The presented solution of the creeping problem at the *Żelazny Most* landfill site under the influence of its own weight and the filtration flow process is a demonstration of the practical application of the mathematical model of the Biot body consolidation with the Kelvin–Voigt rheological skeleton. Despite the complexity of the model and the complex procedure of determining the elastic and viscosity parameters of the repository material, it was possible to build a numerical model of landfill consolidation and to calculate the process of its deformation over time. The presented example shows that at the current stage of knowledge, we can use more and more complex process models in engineering calculations

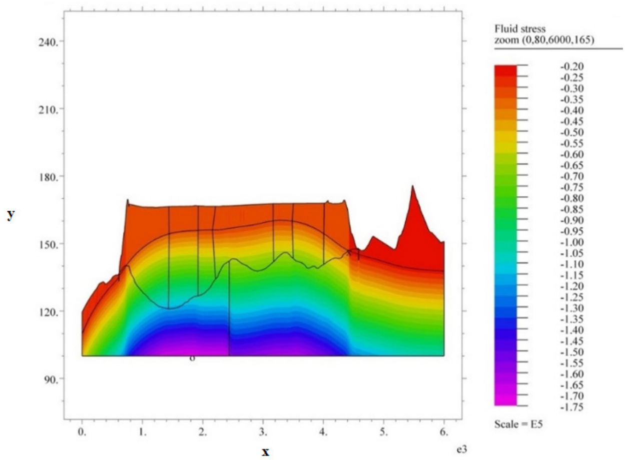

Figure 8: Results for the 2D model – stresses in liquid.

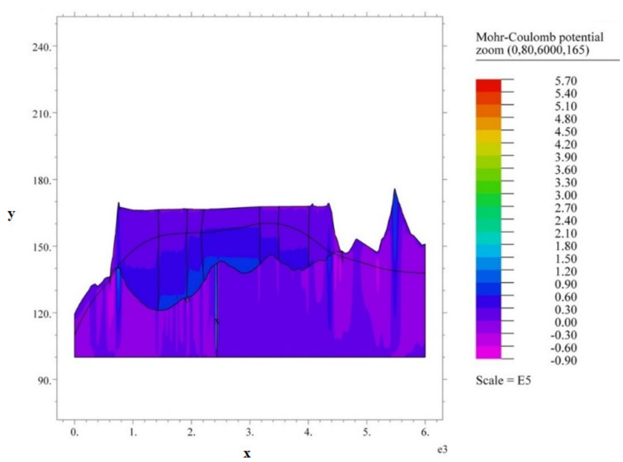

Figure 9: Results for the 2D model – Coulomb–Mohr potential.

to strain the deformation of porous media filled with compressible liquid. The calculation process takes into account the significant variability of the mechanical and hydrogeological parameters of the landfill and substrate, as well as their anisotropy. It is, therefore, possible to try to solve complex engineering problems using mathematical models that are more and more similar to reality. It should be emphasized that the presented results were obtained on the basis of Biot constants and strength parameters obtained from laboratory tests (including the numerical estimation of parameters), which means that the obtained results very likely (with accuracy limited primarily by the accuracy of the model) comply with real processes occurring in the modeled area. The main reason for non-compliance is the fact that the proposed model does not take into account the plasticity of the soil with which we are dealing with in the case under study. However, the application of the methodology, and also the obtained results, offer enormous opportunities in the context of the further development of the model, and thus the forecasts for extending the tank stability. This seems to be an extremely important element in the prevention of terrorist attacks. It is worth noting that even in the initial state, there are observed areas in which the plasticity potential changes, which means that viscous plastics are present in these areas. Propagation of the shock wave in the event of a charge explosion can seriously jeopardize the stability of the tank.

8 Conclusion

When considering a potential terrorist attack on OUOW, it is shocking how much sensitive information is both free and readily available on the Internet. The most important are satellite pictures, as well as articles on the installed measuring apparatus, which also pinpoint its location. The apparatus can easily be recognized and located in the photographs, and the information could be used to interfere with the functioning of the facility. Damage of the pipeline over a long distance in several places may be set as an example – the pipelines are monitored using the system Wonderware (in some places, the system PRO2000 is still in use) that monitors the parameters of hydro transport and the transfer of recovery water. It does not indicate the exact place of damage and requires the entire length of the pipeline to be inspected. Smaller leaks (few dozen dm^3/min) are detected by the staff during routine inspections – the inspections include the facility and the surrounding area. Damage to the pipelines may be done in several ways – from the inside or the outside (it is not the intention of the author to give specific guidelines, but to show the potential threat that may lead to malfunctioning of the facility).

Another crucial piece of information for potential terrorists may be the account of how the flow of the western embankment can be stopped and how the elements of the installed infrastructure that were used to obtain stability could be utilized.

However, the most important and dangerous threat to OUOW is its accessibility and ease of penetration. This is mainly connected to the fact that the facility is the biggest in Europe and is used as a testing ground for a number of institutions, scientists, and students alike, who in an uncontrollable way explore the entire facility. The only formality they need to fulfill is to request an access pass from the director of Oddział Zakładu Hydrotechnicznego for research. Once the pass is granted, they are able to conduct research and are undisturbed by the staff of the facility – this fact may be easily used by potential terrorists to conduct a thorough penetration of the facility. The biggest threat appeared in recent times when KGHM Polska Miedź announced the expansion of *Żelazny Most* Tailings Storage Facility.

An investment of 578 million zlotys is being carried out by Budimex, the company which won the tender. Works on adapting the reservoir to the expansion began last year. *Żelazny Most* will be expanded in its so-called Southern Quarter. KGHM announced in the press that a building permit was issued in March of this year, and the construction works will begin in the upcoming days.

The beginning of such a big investment, where a large number of suppliers and subcontractors are engaged, always involves uncontrollable chaos connected to the movement of vehicles and people and the transport of materials being delivered to the site. A high intensity of human traffic, beginning with KGHM managing staff, supervisors of various subcontracted companies, along with scientists and students observing the progress of the constructions will mean that reconnaissance of the entire facility by potential terrorists is easy. In-depth reconnaissance, along with the attention being paid to the expansion, will make it easy for any potential terrorist to conveniently plan a terrorist attack.

The eastern embankment seems to be the "best" element for inflicting damage, as the highest material losses would potentially be caused on this side of the facility, especially high human losses among the staff of branch of the hydrotechnical plant (Oddział Zakładu Hydrotechnicznego) and the citizens of the town Rudna. The inevitable extensive media coverage would enable the terrorists to reach their goal, which after all is publicity.

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