Variability of Accident Risk Level at Industrial Waste Landfills as a Result of Different Factors

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Abstract

Accident risk at industrial waste landfills depends on many factors – the quality of input data, expertise of the person carrying out the estimation, and flexibility of estimation techniques. The risk level of a landfill may vary from negligible to major risk only if, during estimation, factors that differently affect the degree of risk are taken into consideration. In this paper we analyzed how the particle size of the waste being disposed of at a landfill, the type of a potential accident whose scenario is modelled during estimation, and risk matrix size affect risk level. For the analysis of waste particle size, we took into consideration the recorded accident events at landfills in the past, while, in our analysis of the impact of accident scenario and matrix size, we carried out a brief risk estimation using a concrete example of a landfill and matrices of different sizes, so that we would be able to reach conclusions. The smaller the waste, the more material will leak during an accident; the faster the manifestation of an accident, the lesser the amount of time for the evacuation of endangered people;and the greater the number of cells in a used risk matrix, the more precise the evaluation of risk factors. Risk cannot be interpreted as an unequivocal category and, in order for it to be comparable, it is necessary to carry out the estimation in the same manner, bearing in mind the peculiarities of the rheological properties of waste, different accidents, and estimation technique sensitivity.

Keywords: risk, risk estimation, risk matrix, waste, landfill, accident

1. Introduction

Estimation of accident risk at industrial waste landfills has, over the past years, become a widely used practice in Serbia, as well as in the world. In many countries, the classification of landfills according to the level of risk is also a legal obligation, as is the case with Great Britain, Portugal, Slovakia, Sweden, Spain, etc. [European Commission, 2007], while, in Serbia, mandatory classification of landfills into the so-called A category (high-risk landfill sites) was prescribed in 2017 by means of the Decree on the conditions and procedure for issuing a permit for waste management, as well as on the criteria, characterization, classification, and reporting on mining waste ("Official Gazette of the Republic of Serbia" No. 53/2017). As landfills are "living structures", with the dimensions and characteristics of the waste disposed of at them and the ways of adding superstructures to them frequently changing during their service lives, so their accident risk changes and their classification may turn from negligible to extremely risky in a matter of years if they are not managed properly.

The risk is per se a variable unit whose values are determined by many factors, so it can move from one category to another for one and the same landfill only if different input factors that determine risk level are taken into consideration. Its level also greatly depends on the skills possessed by the person carrying out estimation, and also on the quality and availability of data on a landfill.

This paper will examine the impact of particular approaches and tools on the variability of risk level. The subjects of examination are as follows: the impact of the waste particle size disposed of at a landfill, of the type of an examined accident, and of matrix size on the estimated level of risk. These three factors are mutually independent, and they affect risk level either directly or indirectly.

For the purpose of analyzing the impact of waste particle size on risk level, the past recorded accidents at landfills will be taken into account, while, in analyzing the impact of the type of a potential accident on risk level, we will take into account a specific example of the ash and slag landfill belonging to the power plant "Nikola Tesla B" (TENT B) in Obrenovac, and we will also carry out a brief risk estimation according to different accident scenarios, so that we would be able to reach a comprehensive conclusion about their impact on the level of the resultant risk. The impact of matrix size on risk level will be examined through the application of different matrices and we will discuss this in the continuation of our discussion about the example of the aforesaid landfill.

1.1. Impact of waste particle size on risk level

When it comes to estimating risk at industrial waste landfills, one of the most critical parameters affecting risk level is the quantity of material that would leak in case of an accident. The flood wave that could potentially form defines the danger zone that would be threatened, and at the same time it defines the number of threatened persons, the area of threatened environmental substrates, and the number of material goods. The condition for the formation of a flood wave is the presence of water in waste. So, "wet" landfills, where waste is disposed of in the shape of a hydromixture, have the potential to form flood waves in the event of embankment failure or in the event of water flowing over the crown of an embankment. Flowing of the solid phase of waste in the shape of a hydromixture happens when part of potential energy turns into solid phase kinetic energy [Emerman, 2014]. Adequately estimated flood zone forms a basis for a realistic estimation of consequences, hence for the estimation of risk.

Prediction of leaked quantities is, in practice, most often done based on the height of a landfill dam and the volume of the material disposed of inside the accumulation space, and based on historical data on the already recorded accidents [Tocher et al., 2014]. On average, the quantities of leaked material in the past were 26-40 % in relation to the total quantities of disposed of waste [Dalpatram, 2011, USCOLD, 1994, Rico et al., 2008, Azam & Li, 2010, Garga & Khan, 1995, Lucia et al., 1981, Larrauri & Lall, U., 2018]. A drawback of almost all of these analyses lies in the fact that landfills are examined in the same manner, primarily in terms of waste fluidity. With the application of established regular patterns regarding leaked material, the same quantities would be obtained in landfills where large-grain and small-grain material is disposed of, which may give a distorted picture of the flood zone.

If we take into account the recorded accidents that happened from 1915 to 2020, for which information is known regarding the quantity of disposed of material and the quantity of leaked material [Bowker & Chamber, 2020] and which are classified in accordance with the quantity and type of waste, it is possible to establish certain regular patterns.

A total of 28 landfills of different wastes were retrieved from the base, and clusters were formed, such as landfills of very fine waste (sludge resulting from iron ore processing), the landfill of coarse flotation tailings (copper ore tailings), and the landfill of ash and slag. These landfills were then classified according to size into, conditionally speaking, "small" landfills (landfills with a capacity lower than 2 Mm^3) and "big" landfills (with a capacity higher than 2 Mm^3) – Table 1.

***Table 1**. Examined accidents at landfills of different waste types retrieved from the base WTMF 1915-2020 [Bowker & Chamber, 2020]*

Quantities of disposed of waste	Type of waste	Locaton	Year	Ore	$V_{disposed\ of}$, m^3	V_{leaked}, m^3	$V_{leaked} \cdot 100 V_{disposed\ of}$ %
> 2 Mm^3	Fe sludge	Ukraine	1984	Fe	80,000,000	0	0
		Brazil	2015	Fe	56,400,000	43,700,000	77
		Russia	1981	Fe	27,000,000	3,500,000	13
		Brazil	2019	Fe	12,000,000	9,570,000	80
		Σ			**175,400,000**	**56,770,000**	**42.5**
	Coarse flotation tailings	Philippines	2012	Au Cu	102,000,000	13,000,000	13
		Canada	2014	Cu-Au	74,000,000	23,600,000	32
		Philippines	2002	Cu, Au	47,000,000	1,000,000	2
		Chile	1928	Cu	20,000,000	2,800,000	14
		Sweden	2000	Cu	15,000,000	1,800,000	12
		Chile	1965	Cu	4,250,000	1,900,000	45
		Σ			**262,250,000**	**44,100,000**	**17**
	Ash and slag	North Carolina	2014	Ash	155,000,000	334,000	0
		Serbia	2010	Ash	43,000,000	24,000	0.06
		Russia	2004	Ash	20,000,000	160,000	1
		Bulgaria	1992	Ash	52,000,000	500,000	1
		Σ			**227,000,000**	**994,000**	**0.5**
	Σ						**20.7**

≤2 Mm³	Fe sludge	China	2008	Fe	**290,000**	**190000**	**66**
	Coarse flotation tailings	New Mexico	1980	Cu	2,500,000	2,000,000	80
		Chile	1985	Cu	2,000,000	500,000	25
		Zambia	1970	Cu	1,000,000	68,000	7
		Chile	1985	Cu	700,000	280,000	40
		USA	1973	Cu	500,000	170,000	34
		Chile	1965	Cu	500,000	85,000	17
		Chile	1965	Cu	450,000	7,0000	16
		Chile	1965	Cu	350,000	350,000	100
		Chile	1965	Cu	43,000	21,000	49
		Σ			**8,043,000**	**3,544,000**	**44**
	Ash and slag	USA	1988	Ash	1,000,000	250,000	25
		USA	1988	Ash	1,000,000	250,000	25
		USA	2018	Ash	875,000	2,000	0,2
		USA	2018	Fe	185,000	123,000	66
		Σ			**3,060,000**	**815,000**	**29**
	Σ						**39.3**

The first thing one can notice based on data contained in Table 1 is that, percentually, the leaked quantities of waste in all three clusters of landfills are, in relation to the total disposed of quantities of waste, nearly two times higher in landfills with less than 2 Mm3 (∑39.3%) than in landfills with more than 2 Mm3 (∑20.7%). When observing individually per clusters, the same regular pattern can be established.

The reason for this lies in the fact that landfills with less than 2 Mm^3 are usually temporary, unarranged structures which mainly include ancillary buildings close to facilities for the preparation of non-metallic raw materials and the filtration of waste water or they are used as temporary precipitators. Inside of such landfills, unstablilized waste with a large share of water is disposed of, so, as a result of an accident, there may be a leakage of percentually higher quantities of material in relation to the total disposed of quantities. Generally speaking, smaller landfills are less taken care of, so accidental situations are not a rare phemonenon. This is testified to by the fact that, in the past, the largest number of accidents occurred in small and medium-size landfills, with a capacity of up to 5 Mm^3 and a height of up to 30 m. Between 30 and 40% of all recorded accidents resulted in the leak of as many as 500,000 cubic meters of material, and given the fact that the largest number of accidents are associated with landfills whose capacity does not exceed 5 Mm^3, it may be roughly concluded that the largest share in that percentage belongs to them [Azam & Li, 2010].

Larger landfills, with a capacity that exceeds 2 Mm^3, are often divided into several fields that are exploited in turns, over a long period of time, so a higher percentage of waste is consolidated. Their exploitation is usually in the service of a facility with a large capacity, so they are managed with greater responsibility and accidents occur less frequently; hence the quantities of leaked waste in relation to the quantities of disposed of waste are lower.

Based on data from Table 1, although we are dealing with a small sample of landfills of sludge resulting from iron ore processing, it may be noticed that, upon the occurrence of an accident, a larger percentage of sludge leaked in relation to the total disposed of quantities at landfills than was the case with copper ore flotation tailings and landfills of ash and slag.

Generally speaking, if this waste is compared with other examined wastes, it is less solid and it has lower water permeability and lower resistance to cyclic impacts, as a result of the smaller granulation that characterizes it [Du et al., 2018, Fourie et al., 2001]. That makes it more fluid.

On the other hand, if we compare the percentual quantities of leaked waste in relation to the total disposed of quantities upon the occurrence of an accident in landfills of ash and slag with the quantities at other landfills, it is possible to notice that the former are lower than the latter, particularly in landfills with a volume above 2 Mm^3, where a leak of not more than 1% of disposed of quantities was recorded. This outcome can be ascribed to a larger particle size of ash and slag, which contributes to their greater shear strength, a smaller share of clay, and by that very fact, higher water permeability, and hence lower fluidity.

Recorded accidents at copper ore flotation tailings in relation to the remaining two samples are, from the viewpoint of the percentual quantities of leaked material in relation to the disposed of quantities, in the second place – Table 1.

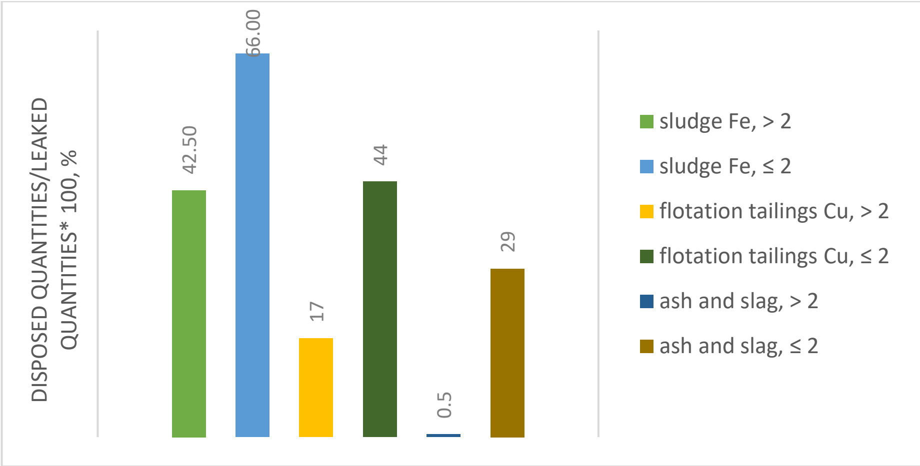

Figure 1 *Comparison of the quantities of leaked waste in relation to the total disposed of quantites inside landfills for different types of waste*

This kind of data justifies the attitude that the smaller the size of waste particles, the higher percentually are the quantities of leaked waste in relation to the total disposed of quantities. These data directly affect the increase in the significance of consequences and indirectly to the increase in risk level.
A unique justification of the attitude that a smaller waste particle size means higher leaked quantities as a result of an accident, and thereby a higher risk, is the linear percentual increase in leaked quantities in relation to the decrease in waste particle size in Figure 2.

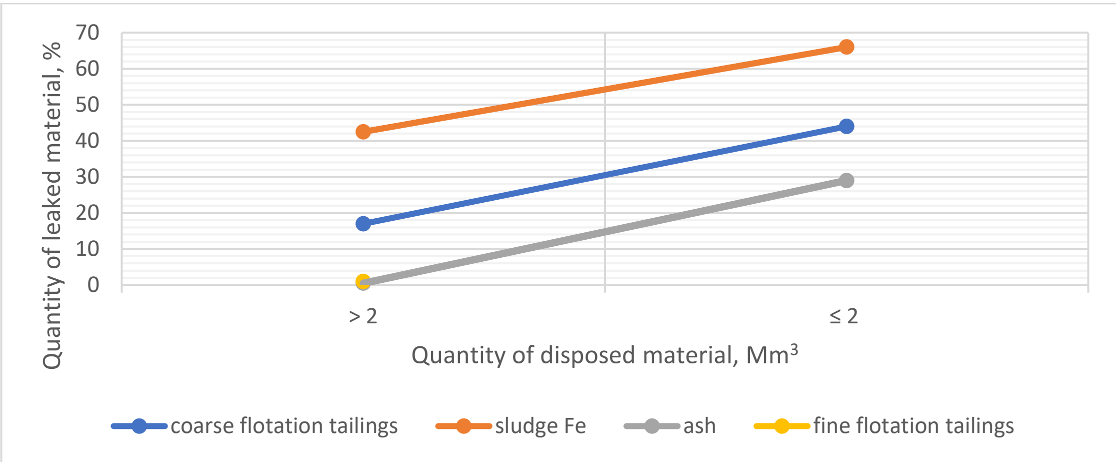

Figure 2. *Summary data on leaked quantities of waste in relation to disposed of quantities of waste inside landfills*

2. Impact of the type of scenario on risk level

When estimating risk level, it is necessary to model the scenario of an accident, to determine its probability, and then to estimate the consequences arising from such an accident. The most frequent accidents that happened at landfills in the past are accidents due to liqufeaction, erthquake, inflow of large amounts of precipitation that resulted in water flowing over the crown of a dam or dam failure, static instability of slopes, internal erosion, etc.
All accidents do not begin at the same time and they do not have the same consequences. Some accidents may happen almost instantly, without any warning, like liquefaction, whereas others, like water flowing over the crown of a dam or static instability of slopes, announce their onslaught for up to several days or even months in advance, which allows for the possibility of alarming and evacuating the locals, so that they may initially yield less severe consequences compared to other accidents. Figure 3 shows a gradation of the most frequent types of accidents according to the speed and time of occurrence.

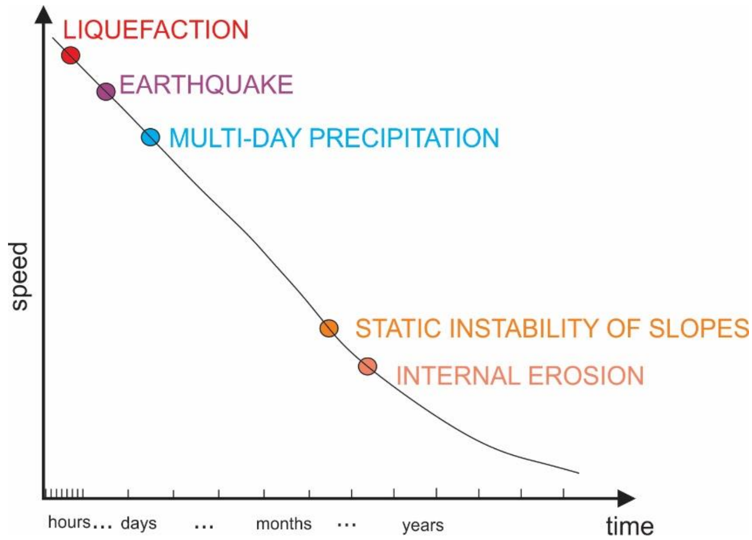

Figure 3. *Speeds and times of activity for different types of accidents at landfills*

Based on the previously presented facts, it may be assumed that the risk for one and the same landfill is not the same if it is separately examined for each respective type of accident.

In order to check this claim, we will use a concrete example of a landfill to carry out a quick risk estimation for the fastest type of accident – liquefaction, and the slowest – static instability of slopes. As a well-designed landfill, without any accident situations in the course of its service life, and as one of the best arranged landfills in Serbia, we chose the landfill of ash and slag "TENT B" in Obrenovac.

This landfill is made up of three cells that are exploited in turns. Currently, the second cell is active and the volume of disposed of waste is around 35 Mm^3, while the designed capacity for all the three cells is over 100,000,000 m^3. The current height of the perimeter embankment is around 20 m, while the maximum designed height is 28 m. Waste is disposed of in the form of a thick hydromixture, with a 1:10 ratio of solid to liquid, and the accumulation lake has a volume of around 4 Mm^3. In the vicinity of the landfill there are no settlements, apart from workmen's barracks which are partially displaced, and of larger waterbodies, 3 km to the north of it flows the river Sava. As far as infrastructure buildings are concerned, in its immediate vicinity, on the right bank of the river Sava, is the power plant "Nikola Tesla B" and the trunk road Belgrade-Šabac. So, this is initially a low-risk landfill.

For a quick estimation of liquefaction potential, we chose the so-called Japanese criterion [Iai et al, 1986] emphasizing waste particle size and the degree of grain uniformity, while, apropos of accident estimation according to the scenario of static instability, we used a semi-probabilistic method which takes the certainty factor and the degree of landfill maintenance into consideration [Silva et al, 2008].

Based on the granulometric composition of ash and slag and the degree of grain uniformity of the waste that is disposed of at the landfill of ash and slag "TENT B" (Cu=5.3-7.5) [RI, 2018], it was established that this landfill falls into the category of "the most liquefiable environment", Figure 4. If we bear in mind that the landfill is well-arranged in hydrotechnical terms, without any recorded liquefaction events in the past, the probability of this accident may be evaluated as "medium". So, in spite of highly positive liquefaction potential, with good maintenance and conscientious landfill management, the initiation of this accident can be kept under control.

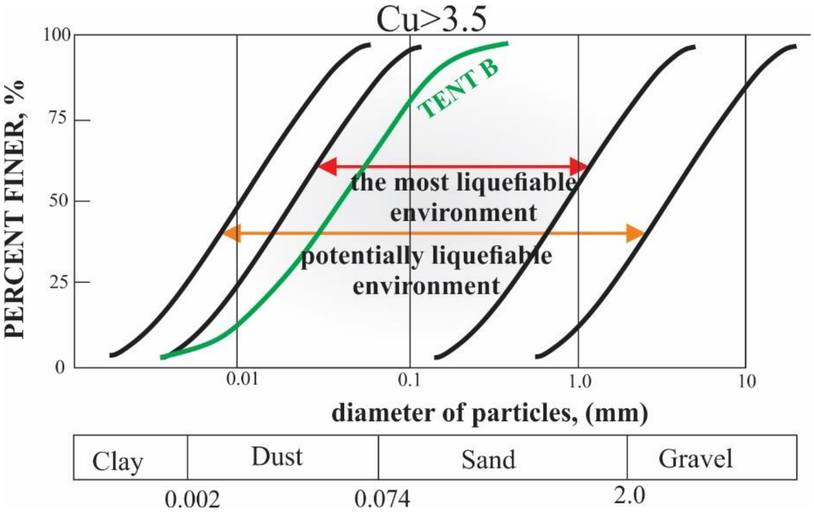

Figure 4. *Evaluation of liquefaction potential according to the "Japanese criterion" [Iai et al, 1986]*

For estimation of the annual probability of an accident according to the scenario of static instability, we took into consideration the certainty factor of profile 11 which has the worst results – Table 2. Since this is a well-arranged and maintained landfill, it belongs to the first category (curve I) according to the method suggested by Silva et al, 2008.

Table 2. *Results of stability factor calculation for static static loads of the landfill "TENT B" [RI, 2018]*

Profile	Fs
11	1.48
14	2.30
16	2.12
18	1.72

According to Figure 5, the annual probability of an accident according to the scenario of static instability is close to 10^{-6}, which may be qualitatively interpreted as "low".

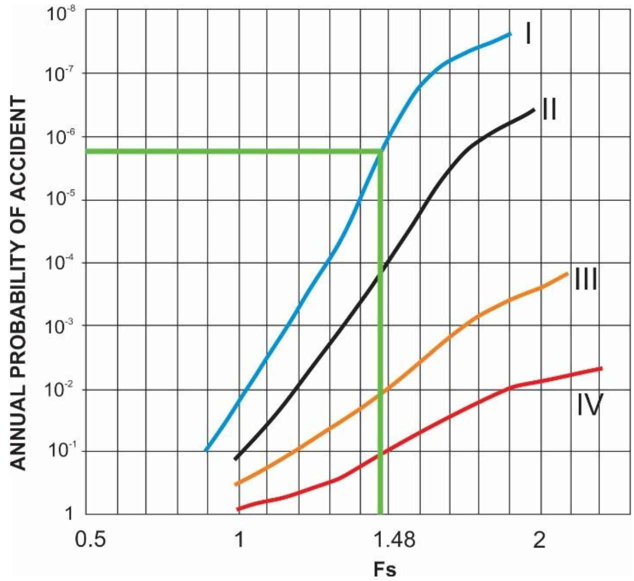

Figure 5. *Evaluation of the annual probability of an accident according to the scenario of the static instability of slopes [Silva et al, 2008]*

For the evaluation of consequences, only one factor was taken, one that differentiates between these two examined types of accident – the time sufficient for the evacuation of people. In case of liquefaction, the times for alarming the workers and the people who happen to be there, in the vicinity, is not sufficient and there may be human casualties, which automatically classifies the consequences into the high, that is, extreme category. In case of an accident due to static instability, the coming accident leaves enough time to alarm and evacuate the people who happen to be in the surrounding area of the landfill.

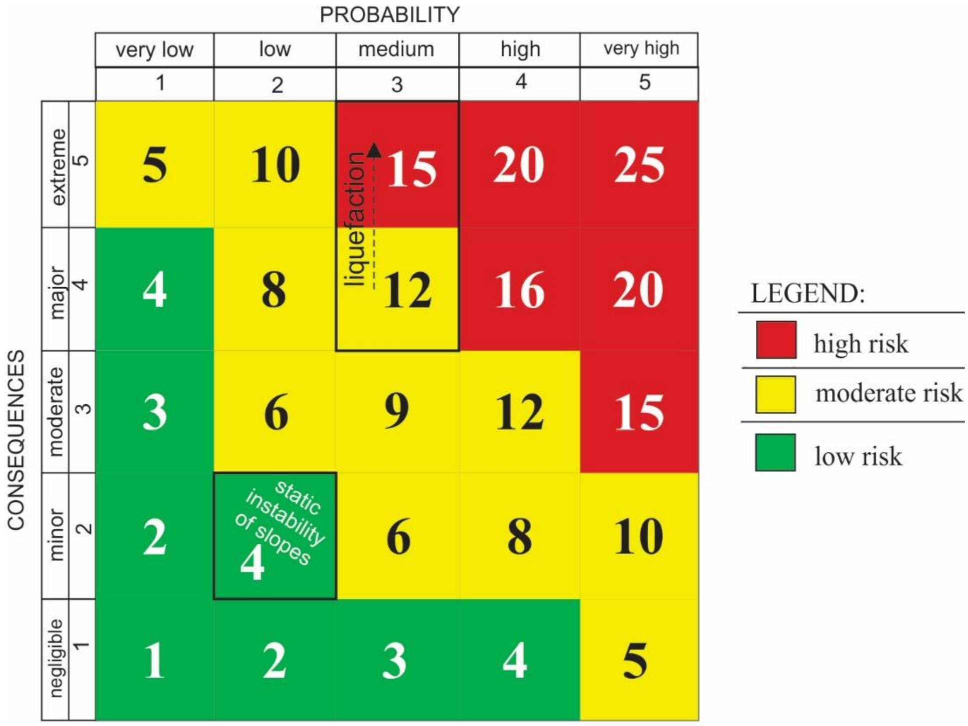

Figure 6. *Analysis of accident risk at the landfill of ash and slag "TENT B" according to the risk matrix 5x5*

According to the risk matrix 5x5, Figure 6, we can see that the risk analyzed for the same landfill according to the scenario of liquefaction falls into the category of high risk, whereas, according to the scenario of the static instability of slopes, it falls into the category of low risk. From the aforesaid it may be established that risk is a variable category for the same landfill and that it is wrong to take for granted that it is an unequivocal category. One landfill's risk must necessarily be examined on the basis of several scenarios, at least those for which there is a reasonable doubt and potential that they may happen, and, in accordance with this, it is necessary to take measures for the prevention and mitigation of consequences. Accordingly, one landfill may at the same time have several levels of risk, depending on the accidents examined, and, for the purpose of comparison with other landfills, it is vital to take the same accidents into consideration.

3. Impact of risk matrix size on risk level

Risk matrix is one of the most desirable techniques for risk estimation because it is easy to apply and allows for a clear interpretation of results. It has two dimensions – the probability of event and the severity of consequences, so it fits perfectly in the probabilistic nature of risk, which is then calculated as the product of probability and the severity of consequences. Risk levels in the matrix are marked with adequate colors, because colors "speak" and visually position the level of risk.

It may be of different sizes, with an even or odd number of cells: 3x3, 3x4, 4x4…12x12. The greater the number of cells, the wider the selection of the scores of individual risk factors. Although the matrices with an even number of cells are used as much as those with an odd number of cells, a small advantage is always given to odd matrices. The reason for this lies in the easier manner of determining median parameter values. The selection of matrix size is in itself a matter of taste. The smaller the matrix, the easier the interpretation of results, but on the other hand the possibility of a realistic and precise evaluation of risk parameters is limited.

A landfill's risk can be evaluated with a 3x3 matrix as well as a 12x12 matrix, and whether the risk score will be in the same zone in both cases is a dilemma.

If, for the demonstration of this problem, we bear in mind the previously examined case of the ash and slag landfill "TENT B", it is possible to perceive certain variations in the level of risk. The risk of this landfill

was previously analyzed using a 5x5 matrix, and for the purpose of this examination we will use a 3x3 matrix as well as a 7x7 matrix.
According to the 5x5 matrix, the probability of a statistic instability accident was evaluated as “low”, the consequences in case of this accident as also “minor”, and the risk was evaluated as low risk, its score being 4 (Figure 6). If thus evaluated risk parameters are mapped onto the 3x3 matrix, what we reach is a negligible, score-1 risk (Figure 7.a). However, according to the 7x7 matrix, minor consequences and low probability yield a score-9 risk, which is not negligible any more, but moderate (Figure 7.b). So, a change in matrix size automatically resulted in a change in risk level.

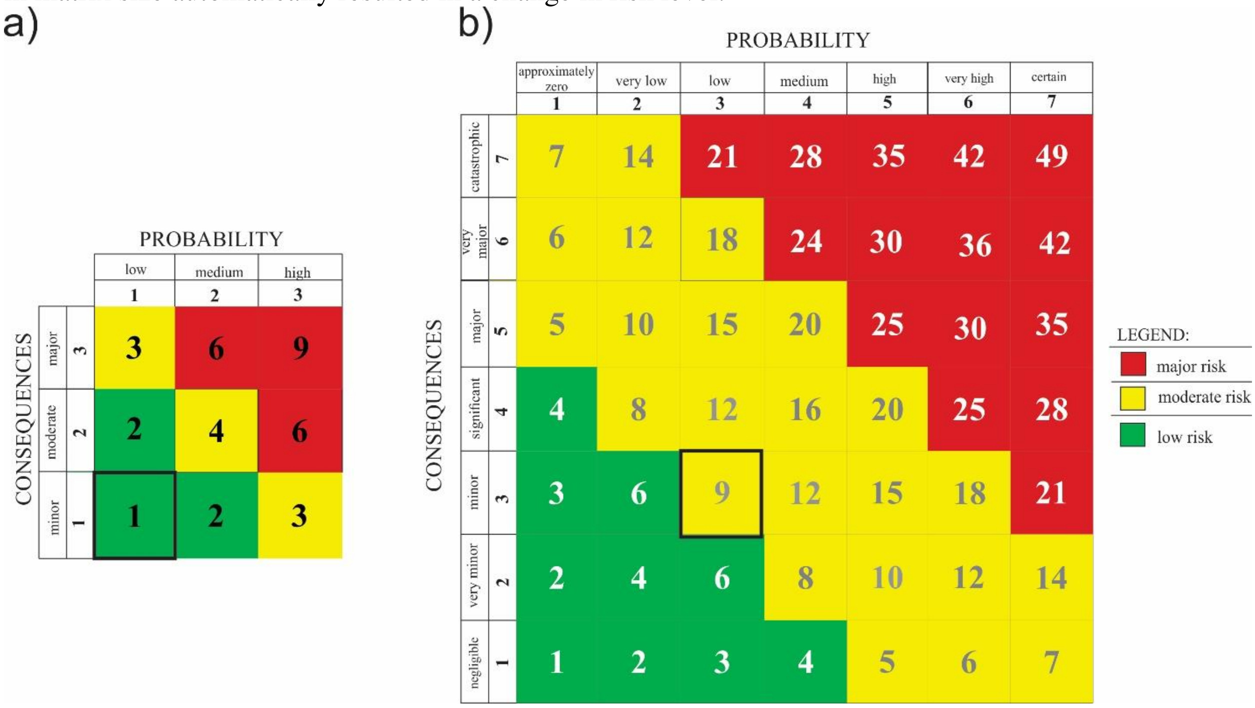

Figure 7. a) Analysis of accident risks at the landfill of ash and slag “TENT B” according to the risk matrix 3x3, b) Analysis of accident risk at the landfill of ash and slag “TENT B” according to the risk matrix 7x7

In accordance with such observations, the estimation scale of accident probability and consequence severity should be harmonized with the matrix scale. Most definitely, the recommendation remains that the risk of one and the same landfill should always be analyzed with one and the same matrix, so that the results would be comparable and in order to avoid dysharmony of results.

4. Conclusion

How complex the process of estimating accident risk at industrial waste landfills is, is told by the great number of factors partaking in it. In accordance with the sensitive stability of landfills, it is of utmost importance to approach the estimation with responsibility and objectivity. In this paper the following was established:

- Landfills of all types of waste cannot be unequivocally examined during risk estimation. When forecasting the quantities of leaked material, it is necessary to take into account the hydrodynamic properties of waste which, as it has been proven, are greatly affected by waste particle size [Jing et al, 2019]. The smaller the waste disposed of at the landfill, the more material there will be leaking out of the dam in case of dam failure, and therefore the level of risk, at that moment, will be higher compared to landfills with the same dimensions but larger waste;
- The risk of one landfill for different types of accident cannot be unequivocally evaluated. One landfill may be simultaneously a high-risk one, for instance, as a result of liquefaction, and a low-risk one, if the accident resulting from the static instability of slopes is examined. In order for the landfill risk to be comparable, it is necessary to estimate it based on the same input data and by modelling the same scenarios;
- The risk of one landfill is not the same if the analysis is carried out with matrices of different sizes. The larger the matrix used, the more precisely the risk parameters (probability and consequences) will be

estimated. The scales of estimation of risk parameters must be adequately harmonized with the scale of the matrix so that the estimation of risk would be more realistic.

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