Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Risk assessment for spontaneous soil liquefaction on dump sites

Évaluation des risques liés à la liquéfaction spontanée des sols sur les sites de décharge

Jörg Weißbach
State Reservoir Administration of Saxony, Germany, joerg.weissbach@ltv.sachsen.de

Wolfram Kudla
Freiberg University of Mining and Technology, Germany

ABSTRACT: On dumps of the former opencast lignite mines in Lusatia, spontaneous soil liquefaction events occur that pose a hazard to people on the dump. In the paper the spontaneous soil liquefaction with the present boundary conditions is briefly discussed. Since the occurrence of a soil liquefaction event cannot be predicted, the effects are considered. The effects depend mainly on the inclination of the terrain surface and the extent of the earth-moist cover. As an empirical measure for the morphology of the terrain the significance number m_h is introduced, on the basis of which hazard maps are created. These maps form the basis for calculating the risk for persons via the probability of occurrence of soil liquefaction events and the assumed number of persons per type of use. The determined risk is compared with everyday risks and an acceptable risk is proposed.

RÉSUMÉ : Lorsque l'ancienne mine de lignite à ciel ouvert du Lausitz a basculé, des événements de liquéfaction spontanée du sol se produisent, ce qui présente un risque pour les personnes sur la décharge. L'article discute brièvement de la liquéfaction spontanée du sol avec les conditions aux limites existantes. Puisque l'occurrence d'un événement de liquéfaction du sol ne peut être prévue, les effets sont pris en compte. Ceux-ci dépendent essentiellement de la pente de la surface du terrain et de l'épaisseur de la couverture terrestre humide. En tant que mesure empirique de la morphologie du terrain, le facteur décisif mh est introduit, sur la base duquel les cartes des aléas sont créées. Ces cartes constituent la base du calcul du risque pour les personnes en utilisant la probabilité d'occurrence des événements de liquéfaction du sol et le nombre supposé de personnes par type d'utilisation. Le risque déterminé est comparé aux risques quotidiens et un risque limite est suggéré.

KEYWORDS: Soil liquefaction, risk, open pit mine, hazard.

1 INTRODUCTION

In Lusatia, lignite was mined in opencast mines over a period of more than 100 years. The overburden was largely dumped loosely by use of an overburden conveyor bridge within the open pit. The main components of the dumps are fine sands and medium sands with different percentages of fine grains. In some areas the fine grains are almost completely missing. After mining was stopped, the open pits were recultivated and prepared for subsequent use. The planned and partly already implemented uses are e.g. agriculture and forestry, tourism and water management. The groundwater table, which was lowered during active open pit mining, has risen again in large parts of the area and is mostly close to the surface.

Figure 1. Consequences of the soil liquefaction event of 18.12.2017 in the former Schlabendorf-Süd open pit, photo of 21.12.2017.

Even during active mining, the miners were aware of the dangers of soil liquefaction. Therefore, after the closure of the opencast mines, especially the banks of the post-mining lakes were very successfully secured by compacted zones ("hidden dams") (LMBV 1998).

Less attention was paid to the dump areas away from the post-mining lakes. Since about 2006, spontaneous soil liquefaction events have occurred more frequently in these areas (Weißbach, 2020a). An example is shown in figure 1. Spontaneous means that without any visible external influence, the water-saturated soil below the groundwater level liquefies in an area of usually several hectares. Soil liquefaction events pose a hazard to people on the surface of the ground. That's why the dumps were explained to a large extent to forbidden areas. The hazard of soil liquefaction events for persons is the subject of the considerations presented here. Possible damage to property is not taken into account.

Up to now, attempts have been made to counter the danger of soil liquefaction in the subsoil by calculating a safety factor in earth static analyses (LMBV, 1998). However, soil liquefaction is a stability problem that is associated with brittle fracturing (Gudehus, 2016). For a proof of stability it is necessary to have a very precise knowledge of the properties of the soil, which is not possible due to the inhomogeneity caused by the fill.

A different approach to deal with the hazard is to consider the risk. In this context, not only the probability of the occurrence of a damage-triggering event is considered, but also the potential extent of damage. Figure 2 illustrates key terms of risk. To the right, the risk that refers to a hazard increases. The aim of risk assessment and risk management is to reduce the risk below the acceptable risk. Taking all measures into account, the residual risk can be achieved. A risk of zero cannot be achieved (Bründl, 2009).

Figure 2. Key terms of risk assessment and risk management (according to (DGGT Arbeitskreis 4.6 Altbergbau, 2017)).

Risk assessment requires a deep understanding of the underlying process. Information on the process of spontaneous soil liquefaction considered here is given in (Gudehus, 2016) and (Weißbach, 2020a).

2 HAZARD ANALYSIS

2.1 *Event Analysis*

Figure 3 shows the former open pit mines of the Lusatian lignite mining district, which are under the administration of the Lausitzer und Mitteldeutsche Bergbauverwaltungsgesellschaft mbH (LMBV) and represent the investigation area. The Lusatian mining district is located in the area of the federal states of Saxony and Brandenburg in eastern Germany.

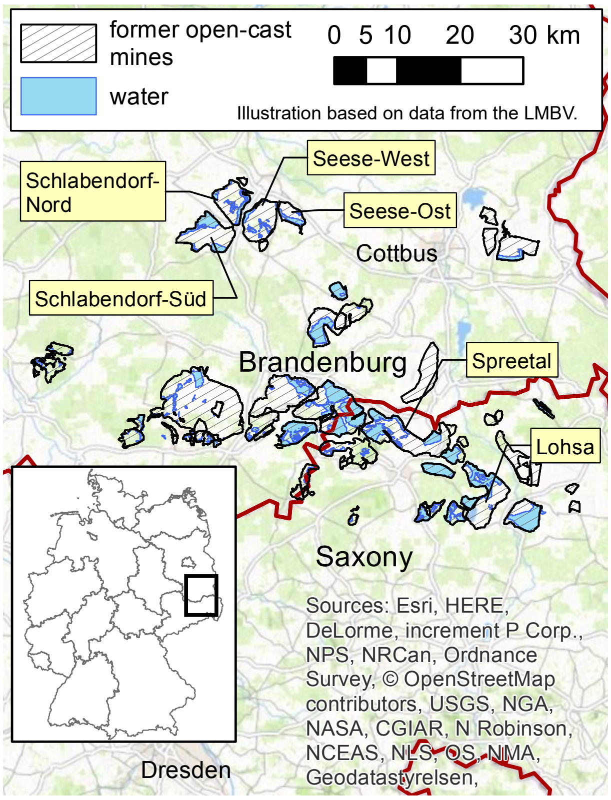

Figure 3. Location of the investigated open pits of the Lusatian mining district in Germany, marking of important open pits.

For the risk assessment, it was necessary to get as complete an overview as possible of the soil liquefaction events and to determine the exact location, extent and time. To localize the events and determine the boundary, digital terrain models were used, which were obtained by airborne laser scanning. These were first available for the investigation area in 2005 and were then periodically re-recorded. The measurement uncertainty of the terrain height was about ± 10 cm. The number of 125 soil liquefaction events in the period between 2006 and 2018 could be evaluated.

Figure 4 shows how an event can be detected and delimited by comparing digital terrain models. By forming a difference image, areas with subsidence and areas with uplift can be delimited. Typical changes in terrain height due to soil liquefaction are up to 8 m subsidence and up to 2 m uplift. On average, the terrain surface sinks due to the compaction of the liquefied soil. The average subsidence is about 50 cm ± 30 cm.

Care must be taken to exclude other causes for a change in terrain height, such as a change in the water level of open water areas. This can be done by considering orthophotos.

The time of an event was only approximately known until 2014. It could be narrowed down by observations on site or by remote sensing data. Since 2014, a seismic measurement network has been in place to detect soil liquefaction events, which are mainly characterized by surface waves, and to assign them to time and space (Kudla, et al., 2020).

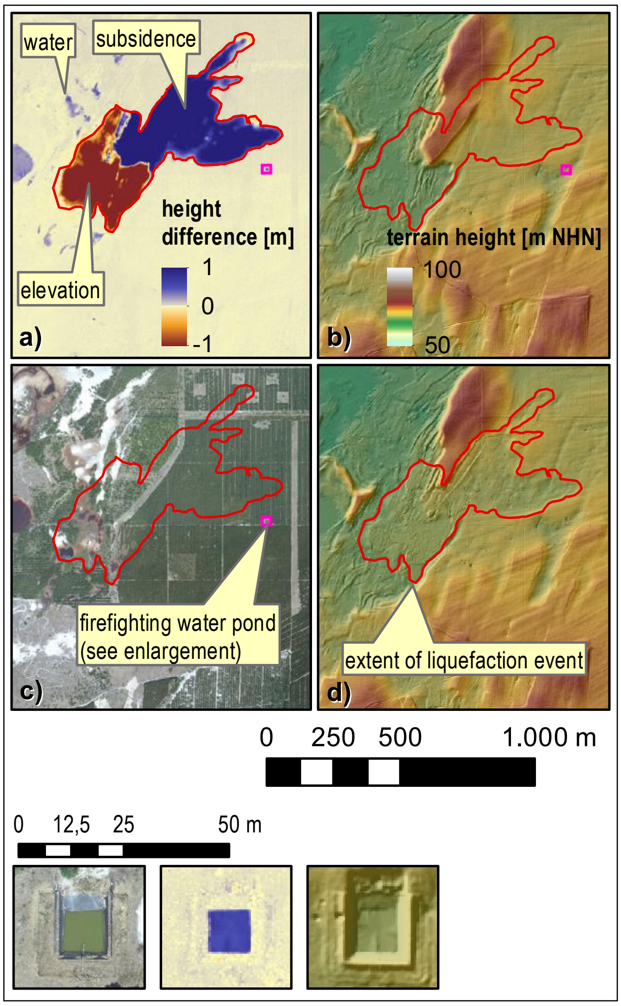

Figure 4. Methodology of delimiting an event area: a) difference image, b) digital terrain model before event, c) orthophoto, d) digital terrain model after event.

During the evaluation of the soil liquefaction events, it became clear that the terrain surface has changed very differently as a result of the events, which has an impact on the exposure of a person who is there at the time of an event. Soil liquefaction events in which the maximum horizontal displacement s_h at the terrain surface is less than 1 m, are called terrain collapses. The danger of such events is comparatively low, since essentially only depressions and cracks occur. If s_h is at least 1 m, then we speak of a flow slide. During these events the surface of the terrain can be completely destroyed. Strains, cracks, displacements occur and there can be areas of free suspension. Figure 1 shows the consequences of a flow slide. The danger for a person staying in the area of a flow slide is much higher than in the case of a terrain collapse.

Figure 5 illustrates the difference between terrain collapse and flow slide. The horizontal displacement s_h is determined by comparing orthophotos of the event area before and after an event. The displacement of characteristic landmarks on the level of the terrain surface (e.g. the edge of a path) is measured in the GIS.

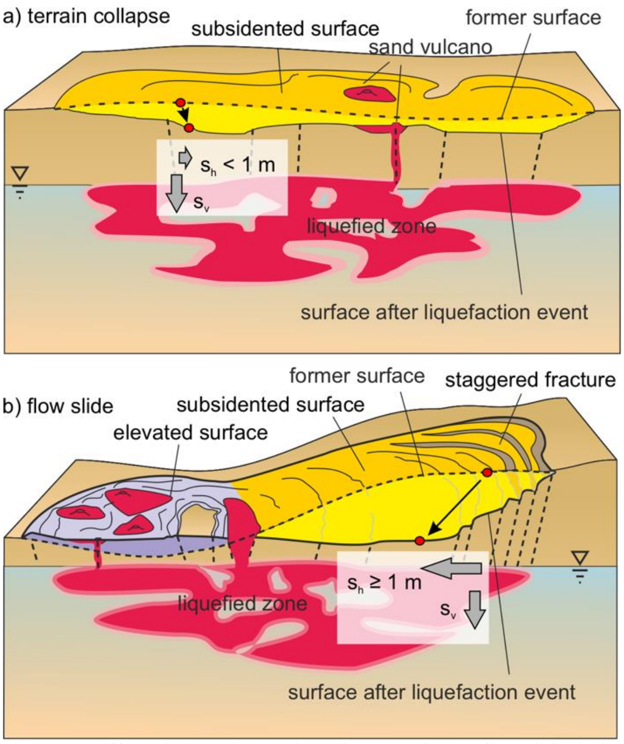

Figure 5. Differentiation of a terrain collapse (a) from a flow slide (b) by means of the horizontal displacement at the terrain surface.

2.2 *Effect analysis*

2.2.1 *Significance number m_h as parameter for the description of the terrain morphology*

In the evaluation of the soil liquefaction events, a significant slope of the liquefied area before the liquefaction was determined for each event, for which the following criteria apply (for the definition of the parameters, see Figure 6)

- large angle of inclination of the slope β
- large difference in height of the slope Δh
- low distance between ground water table and ground surface at the foot of the slope $z_{w,1}$

The selection was done manually and not with an algorithm.

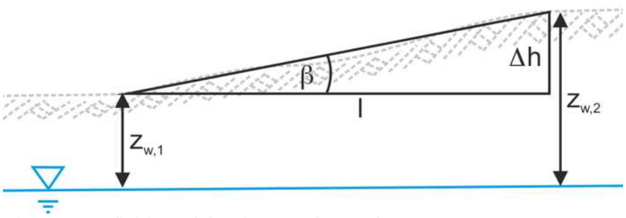

Figure 6. Definition of the sizes used on a slope.

Afterwards the determined values were plotted in a diagram. In order to consider the influence of the terrain morphology, the significance number m_h is defined.

$$m_h = \frac{\Delta h^2}{l} = \Delta h \cdot \tan\beta \qquad (1)$$

Figure 7 shows the distance between water table and ground surface $z_{w,1}$ at the foot of the slope above the significance number m_h for all evaluated significant slopes. Within the diagram, the data of the significant slopes are separated into clear areas, depending on the type of event. There are explanations for some exceptions. For example, the horizontal shift can be inhibited by various special features. For soil liquefaction events, which are characterized as flows slides, $m_h > 0{,}2\ m$ is always valid. Terrain collapses occur at $m_h \leq 0{,}2\ m$ and usually at $4\ m \leq z_{w,1} < 11\ m$. For distances between water table and ground surface $z_{w,1} \geq 11\ m$ no events have occurred so far.

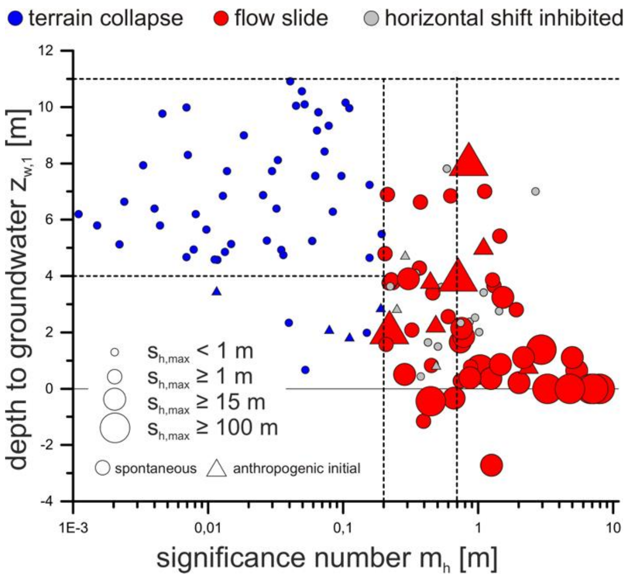

Figure 7. Type of event as a function of significance number and groundwater level at the foot of the slope.

The behaviour shown in figure 7 can be explained by a 2D-soil mechanical model as shown in figure 8.

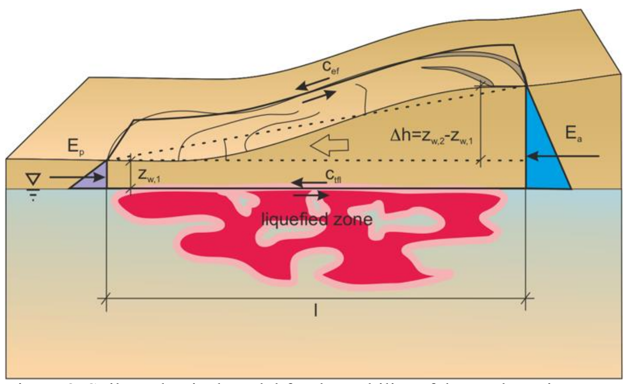

Figure 8. Soil mechanical model for the stability of the earth-moist cover.

The horizontal equilibrium of the earth-moist covering in the state of failure is considered under the condition that only a small residual strength c_{tfl} is left due to liquefaction of the water-saturated subsoil. The degree of utilization μ corresponds in a two-dimensional view to the ratio of the active earth pressure E_a on the impact side of the slope shoulder and the passive earth pressure E_p at the foot of the slope as well as a residual strength expressed as cohesion in the area of the water table (equation 2).

$$\mu = \frac{E_a}{E_p + c_{tfl} \cdot l} = \frac{\frac{1}{2} \cdot K_a \cdot \left(z_{w,1} + \Delta h\right)^2 \cdot \gamma_k}{\frac{1}{2} \cdot K_p \cdot {z_{w,1}}^2 \cdot \gamma_k + c_{tfl} \cdot l} \tag{2}$$

Written out with the earth pressure coefficients for active and passive earth pressure K_a and K_p, the weight of the dumped soil γ_k and the slope length l a proportionality according to equation 3 is obtained, whereby the empirical quantity signify-cance number m_h is justified. This proportionality also applies if in the three-dimensional case a lateral residual strength c_{ef} is considered.

$$\mu \sim \frac{\Delta h^2}{l} \tag{3}$$

In a parameter study (Weißbach, 2020b) it could be shown that the soil mechanical model in figure 8 and equation 2 is closely linked to the boundary area between the characteristics of flow slide and terrain collapse. However, a distinction of the characteristic is possible.

2.2.2 *Creation of hazard maps*

Using an algorithm described in (Weißbach, 2020a) a hazard map was derived from a digital terrain model and a model of the groundwater surface (state before a soil liquefaction event occurs). For this purpose, the significance number m_h is calculated with a viewing radius of 100 m. The radius of 100 m corresponds approximately to the 95 % percentile of the probability density function of all considered slope lengths of the relevant slopes. Furthermore the distance between water table and ground surface was calculated in the same grid.

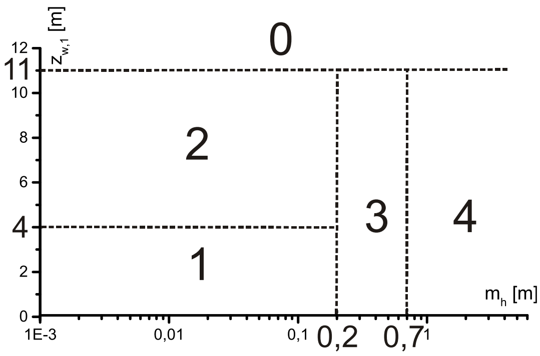

Figure 9. Definition of hazard categories.

Table 1. Hazard categories.

Hazard category (GK)	*Meaning*
0	Soil liquefaction events unlikely (yet not observed)
1	Soil liquefaction events can be triggered by anthopogenic activity or external events
2	Terrain collapses
3	Flow slides
4	Flow slides with large horizontal displacements

The raster data of the significance number m_h and the distance between water table and ground surface $z_{w,l}$ were classified according to the limits in Figure 9. In this way, a comprehensive assignment to hazard categories could be made. Their meaning is described in table 1.

In addition to the classification into hazard categories, the hazard maps also took into account areas on the open pit dumps that certainly cannot liquefy. These are e.g. dump areas with a high fine grain content or compacted areas. Water areas have been identified separately, as it is not possible to stay on the surface for these areas.

The hazard maps were produced for each year between 2006 and 2018. The fact that the groundwater level is variable was taken into account. Furthermore, the changes of the terrain surface e.g. due to previous soil liquefaction events were taken into account. The soil liquefaction events in the past for the respective status of the hazard map were shown separately, since separate considerations are necessary for the hazard on these areas (see figure 10).

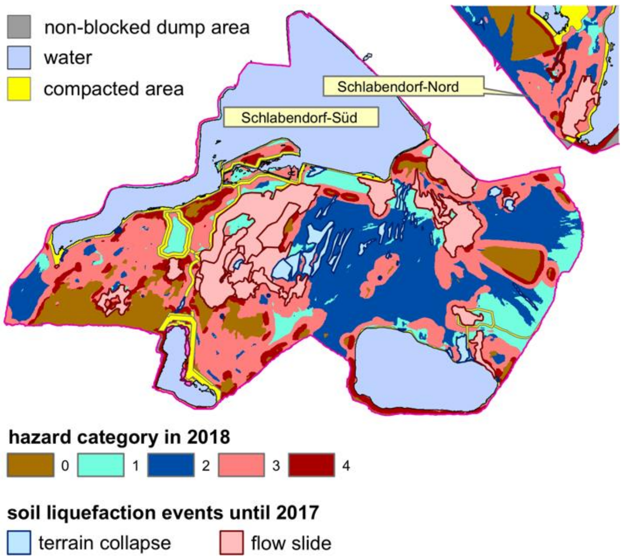

Figure 10. Hazard map for the year 2018 (example opencast mine Schlabendorf-Süd).

The hazard map shows what the effects of a soil liquefaction event would be if it occurred. It does not give any indication of the probability of a soil liquefaction event occurring.

3 CONSEQUENCE ANALYSIS

To calculate the risk, the general equation 4 was used.

$$R_{S,O} = P(S) \cdot P(O|S) \cdot G_O \cdot v_{S,O} \tag{4}$$

The risk R, related to a scenario S and an object O is the probability $P(S)$ that the scenario occurs, multiplied by the probability $P(O|S)$ that the object meets the scenario, multiplied by the value G_O of the object, multiplied by the vulnerability $v_{S,O}$ of the object in the scenario.

In table 2 it is shown, how the generally valid equation 4 was converted in the concrete case. First, the probability $P(A_t)$ of occurrence of a soil liquefaction event was determined. This was done by determining the relative frequency (related to area units) of soil liquefaction events. For this purpose, the events that actually took place in one year were related to the area that could be affected by soil liquefaction in that year according to the hazard maps (equation 5).

Table 2. Implementation of the risk calculation.

Parameters	*Implementation*	*Source*

$P(S)$	Probability of occurrence of soil liquefaction event $P(A)$	own calculation (see below)
$P(O\|S)$	Probability of residence $P(B)$	Acceptance on the basis of planned use
G_O	Value 1, as personal injury is considered	-
$v_{S,O}$	Letality λ	Assumption depending on the event type

The relative frequency determined was averaged over the years due to strong fluctuations and determined the probability of occurrence of a soil liquefaction event. The evaluation of the relative frequency $h_n(A)$ described in equation 6 was made separately for the event types (index t) and event years (index j). In addition, a subdivision into the affected open pits was made.

$$h_n(A_{t,j}) = \frac{\sum F_{t,j,actual}}{F_{t,j,potential}} \tag{5}$$

$$P(A_t) \equiv \overline{h_n(A_t)} = \frac{1}{13} \sum_{j=2006}^{2018} h_n(A_{t,j}) \tag{6}$$

For the probability of residence $P(B)$ the planned types of use were used. Since there are no settlements on the dump, the stay on an area depends on the respective use. A distinction was made between forestry use, agricultural use, other high-quality use and succession areas. Each type of use was assigned a probability of stay in persons per unit area, which corresponds to an average value estimated on the safe side. As no marked temporal accumulation could be proven for the soil liquefaction events, the probability of residence applies equally over the day and over the year, although in reality the probability of residence varies greatly over time.

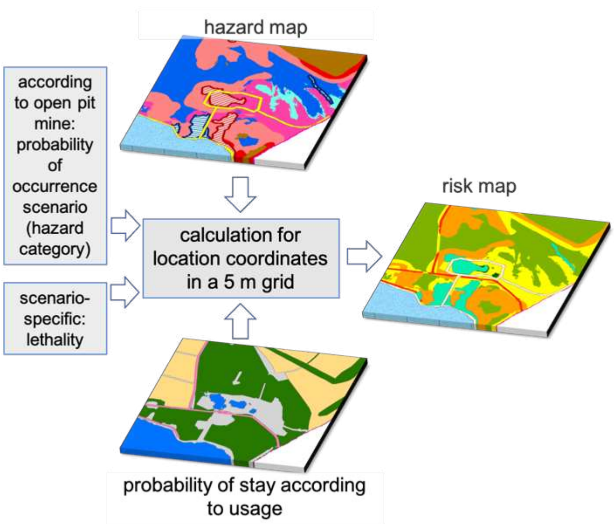

Figure 11. Procedure for calculating the risk.

The calculation of the risk was carried out under the assumption of lethality (small for terrain collapse, large for flow slides) according to the scheme in Figure 11, taking into account specific features in the equations used for each scenario (each hazard category). Details are given in (Weißbach, 2020). The result of the calculation is a map showing the area-related risk. For the evaluation of the risk, however, it is important to know to which area the risk is related.

4 RISK ASSESSMENT

Whether or not a risk is accepted by society depends largely on the perception of risk. Many everyday risks, such as road traffic, are greater than the risks from soil liquefaction identified here (Proske, 2008). The following statements on risk perception for a person apply to areas used for mining:

- The risks are not under its own control.
- There are no clear advantages to taking risks.
- The risks are difficult to understand or unknown.
- The risks cause fear.
- The consequences of the realization of the risk are irreversible.
- These are risks with a technical origin.
- In the realization of the risks, there may be a spatially and temporally concentrated number of victims.

In order to be able to evaluate whether the risk calculated in section 3 is acceptable or not, a acceptable risk depending on the extent of damage was proposed (see (Bowles, 2011)). For this purpose, it was calculated how many people on average would be affected by a soil liquefaction event. The calculation was done according to equation 7.

$$N_{Nu,t} = B_{Nu} \cdot F_t \cdot \lambda_t \tag{7}$$

with N Extent of damage [persons]
B Occupancy [persons/hectare]
F Area of an event (assumed: 1 hectare for terrain collapse, 10 hectare for flow slide)
λ Letality
Nu Index for the type of use
t Index for the type of a soil liquefaction event

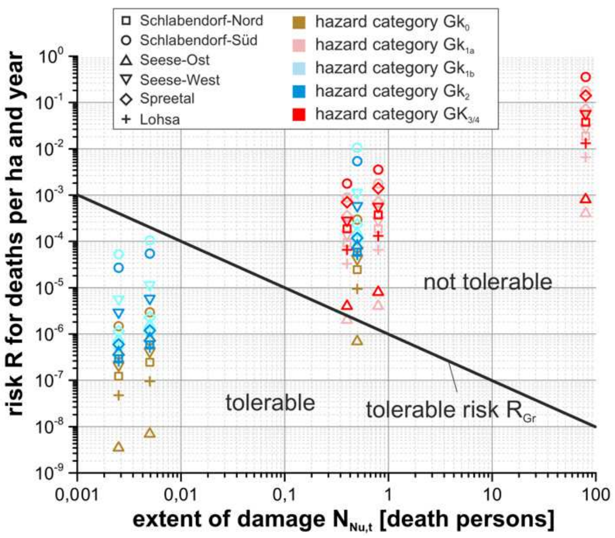

Figure 12. Calculated risks and proposal for a limit risk.

Figure 12 compares the extent of damage and the risk of death per hectare and year. Both values are dependent on each other due to the probability of residence and lethality. Following the principle that a lower risk is assumed for a large extent of damage, a acceptable risk was proposed. This takes into account the perception of risks resulting from mining activities. Essentially, the result means that the risk of soil liquefaction events cannot be tolerated for areas on which flow slides can occur and for areas with high-grade use. For these areas measures have to be provided.

The proposed acceptable risk was compared with the hazard map and planned uses. Figure 13 shows for which areas in the example of the Schlabendorf-Süd opencast mine measures are necessary and in which areas they are not.

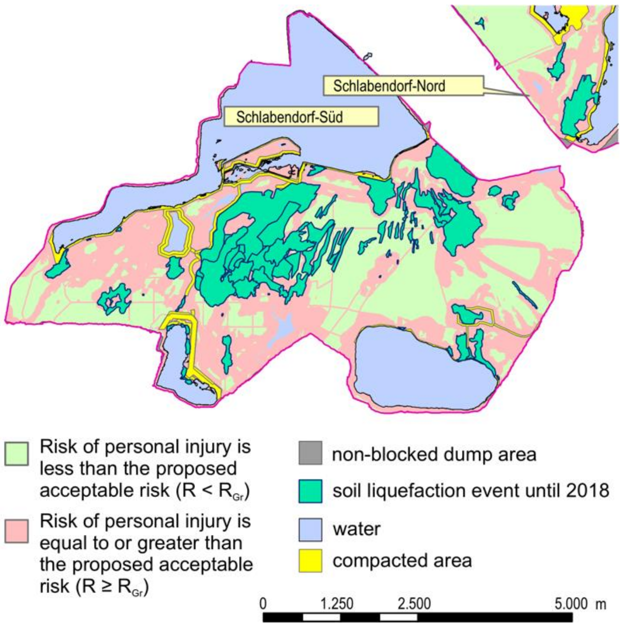

Figure 13. Map for exceeding the proposed acceptable risk (example opencast mine Schlabendorf-Süd).

Measures may be taken for areas where the risk of soil liquefaction cannot be tolerated:

- Measures to demonstrate that the risk present is less than the acceptable risk, e.g. demonstration of safety (LMBV, 1998), demonstration of limited effects and test loading
- Measures to reduce the probability of soil liquefaction events, e.g. compaction
- Measures to reduce the likelihood of people being present, e.g. change of use or blocking
- Measures to reduce lethality, e.g. behavioral requirements, personal protective equipment.

The results of the risk assessment support the efforts of the LMBV to implement the final operational plans for the rehabilitation of the dumps.

4 CONCLUSIONS

As has been shown, the risk for soil liquefaction events on dumps of the Lusatian lignite mining area can be calculated. From this basis, measures can be derived and compared with each other. The basis for the determination of the risk is a deep understanding of the process and the most complete possible recording of the essential data of the events.

By knowing the risks, costly measures can be avoided, e.g. through changes of use. Furthermore, the knowledge gained offers the opportunity to improve risk perception.

5 ACKNOWLEDGEMENTS

The presented results are the result of many years of research projects on behalf of the Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV) and the mining operator Lausitz Energie Bergbau AG (LEAG). The authors would like to thank for the financial support and the good cooperation.

6 REFERENCES

Bowles, D. S. (2011). Tolerable risk guidelines for dams: principles and applications. 3rd International Week on Risk Analysis, Dam Safety and Dam Security, Valencia.

Bründl, M. (Hrsg.). (2009). Risikokonzept für Naturgefahren - Leitfaden. Bern: Nationale Plattform für Naturgefahren PLANAT.

Chowdhury, R., Flentje, P., & Bhattacharya, G. (2010). Geotechnical slope analysis. Boca Raton: CRC Press.

DGGT Arbeitskreis 4.6 Altbergbau. (2017). Empfehlung „Geotechnisch-markscheiderische Untersuchung, Bewertung und Sanierung von altbergbaulichen Anlagen“. In 17. Altbergbaukolloquium, 16. bis 18. November 2017. Freiberg: TU Bergakademie Freiberg.

Gudehus, G. (2016). Mechanisms of partly flooded loose sand deposits. Acta Geotechnica, 11(3), S. 505-517.

Kudla, W., Lucke, B., Rosenzweig, T., Buske, S., Schicht, T., & Reinhardt, K. (2020). Entwicklung eines komplexen seismischen, hydraulischen und geotechnischen Monitoringsystems zur Früherkennung der Bodenverflüssigungsgefährdung am Beispiel von Innenkippen des Lausitzer Reviers (SHGM) – Zusammenfassender Abschlussbericht. TU Bergakademie Freiberg, BIUG, K-UTEC, Freiberg, Sondershausen.

LMBV (Hrsg.). (1998). Beurteilung der Setzungsfließgefahr und Schutz von Kippen gegen Setzungsfließen. Senftenberg.

Proske, D. (2008). Catalogue of Risks: Natural, Technical, Social and Health Risks. Berlin Heidelberg: Springer.

Robertson, P. K. (2010). Evaluation of Flow Liquefaction and Liquefied Strength Using the Cone Penetration Test. Journal of Geotechnical and Geoenvironmental Engineering, 136(6), S. 842-853.

Weißbach, J. (2020a). Risikobeurteilung von Bodenverflüssigungsereignissen auf Innenkippen des Lausitzer Braunkohlereviers. Dissertation, TU Bergakademie Freiberg, Institut für Bergbau und Spezialtiefbau, Freiberg. https://nbn-resolving.org/urn:nbn:de:bsz:105-qucosa2-708562

Weißbach, J. (2020b). Zur Herleitung der Maßgeblichkeitszahl m_h. Vortrag 27.08.2020, Freiberg.