Quantitative landslide risk analysis and risk evaluation for publicly accessible geosites

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Abstract: Risk analysis and risk evaluation are increasingly used tools for mitigating geohazards. It is commonly accepted that risk is basically a function of likelihood and consequence. However, the quantification of the likelihood of a geohazard occurring, as well as the prediction of its consequences, is a difficult task. Therefore, it is important to develop structured geohazard risk management frameworks. Even if the results produced with such frameworks might be considered as rough estimates, they will certainly be useful tools to identify areas of potentially higher risk.

This paper presents a quantitative landslide risk evaluation framework for a publicly accessible geosite which is declared an UNESCO World Heritage. A risk evaluation for this frequently visited geosite is necessary since it is affected by landslide hazards. The types of landslides were classified by their geometry (shallow and deep landslides), their mechanisms and their triggering events. Spatial extent, volume, velocity and travel distance of existing deep landslides were investigated by intensive geotechnical monitoring. The probability of landsliding was estimated using formal probabilistic analysis. Additionally, the historic occurrence of landsliding was related to rainfall intensity and antecedent rainfall.

Consequence analysis includes property damage (roads, visitor tracks, viewing platform) and injury/loss of life for both visitors and scientists. Since some elements at risk are mobile (visitors etc.) a temporal probability had to be introduced which takes also into account the varying occupancy of buildings and visitor tracks. By integrating the different hazard models, frequency analysis and consequence analysis, risk levels for annual loss of property and annual loss of life at different locations were computed.

Résumé: L'évaluation et l'analyse des risques sont des outils de plus en plus utilisés pour atténuer les dangers géologiques. Il est généralement accepté que le risquer est fondamentalement une fonction de la probabilité d'occurrence et de conséquence. Cependant, tant la quantification de la probabilité d'occurrence d'un risque géologique, que la prévision de ses conséquences, sont difficiles. Par conséquent, il est important de développer des cadres structurés de gestion des risques géologiques. Même si les résultats produits au sein de tels cadres pourront être considérés comme des évaluations grossières, ils seront certainement des outils utiles pour identifier des secteurs à risque potentiellement plus grand.

Cet article présente un cadre quantitatif d'évaluation de risque d'éboulement pour un site géoloqique accessible au public et classé comme Héritage du monde par l'Unesco. Une évaluation du risque pour ce site fréquemment visité est nécessaire puisqu'il est affecté par des éboulements. Les types d'éboulements ont été classifiés par leur géométrie (éboulements peu profonds et profonds), leurs mécanismes et leurs événements déclencheurs. L'ampleur, le volume, la vitesse et le parcours des éboulements profonds existants ont été étudiés à l'aide une surveillance géotechnique intensive. La probabilité d'éboulement a été estimée en utilisant l'analyse probabiliste formelle. De plus, les événements d'éboulements passés ont été corrélés à l'intensité des précipitations concommitantes.

L'analyse des conséquences inclut les dégâts matériels (routes, sentiers de visite, plateforme de visionnement) et les dommages corporels et décès des visiteurs et des scientifiques. Puisque quelques éléments en danger sont mobiles (visiteurs, etc.), nous avons dû présenter une probabilité temporelle qui prend également en considération l'occupation variable des bâtiments et des sentiers de visite. En intégrant les différents modèles de hasard, l'analyse de fréquence et l'analyse des conséquences, les niveaux de risque pour les pertes annuelles de propriété et de vies humaines à différents endroits ont été calculés.

Keywords: landslides, risk assessment, slope stability, safety, preventive measures.

INTRODUCTION

The development of risk analysis and risk evaluation strategies has advanced to such a state, that these methods are now practical tools in multidisciplinary geohazard risk management concepts and guidelines. However, the quantification of the likelihood of a geohazard occurring as well as the prediction of its consequences is a difficult task. Therefore it is important to develop structured geohazard risk management frameworks. Even if the results produced with such frameworks may be considered as rough estimates, they will certainly be useful tools to identify areas of potentially higher risk.

At first sight developing a risk evaluation methodology for geosites or geotopes may seem uncommon. However, local authorities, research facilities and tour operators actually discover the possibility for geotourism or geotope tourism to become a popular niche for the travel industry. Unfortunately, geotopes or geosites are often particularly geohazardous areas like quarries or steep faces etc. Thus, an increasing attendance requires an increasing implementation of geohazard risk management procedures to avoid human casualties and economic losses.

This paper presents a quantitative landslide risk evaluation framework for the publicly accessible Messel pit which is declared an UNESCO World Heritage. A risk evaluation for this frequently visited geotope is necessary since visitors, scientists and infrastructure are affected by landslide hazards. The objective of this contribution is to present a generally applicable, structured and transparent procedure providing guidance for the risk management of geotopes as such.

Study area

The area under investigation is the ancient opencast Messel pit, located about 20 km south of Frankfurt am Main, Hesse, Germany (Figure 1). The lacustrine sediments of the Eocene Messel Formation accumulated inside a volcanic crater lake (Franzen & Haubold 1986), which was formed in Carboniferous igneous rocks and sediments from the Lower Permian (Harms et al. 2003). Lithostratigraphically, the Messel Formation deposits are subdivided from top to bottom into three units (Matthess 1966; Weber & Hoffmann 1982): Upper Messel Formation (*UMF*, clay, sand and lignite), Middle Messel Formation (*MMF*, Messel oil shale) and the Lower Messel Formation (*LMF*, breccias, sand-, siltstones, and clays with pyroclastic fragments).

The Messel oil shale (MMF) has become famous through the discovery of vertebrate fossils of Eocene age. Since 1995, the Messel pit is placed on the UNESCO list of World Heritage sites, because "…it provides unique information about the early stages of the evolution of mammals and includes exceptionally well-preserved mammal fossils…" (The World Heritage Newsletter, 10, p. 4).

In 1991 the federal state of Hesse acquired ownership of the Messel pit and assigned its duties and responsibilities to the "World Heritage Messel Pit GmbH". Since 1992 the "Forschungsinstitut und Naturmuseum Senckenberg" is the operating authority and responsible for conservation and security of the Messel World Heritage site. An ever increasing number of visitors reflect the public interest in Messel. Between 1992 and 2003 more than 60000 (5100 visitors/a) people attended guided tours. In the year 1996, a viewing platform was erected so that people can get a better overview of the pit itself. Between the years 2000 and 2003, this platform has been visited by approximately 200000 people (50000 visitors/a). It is expected that the opening of a nearby information centre will increase the number of visitors up to 100000 per year.

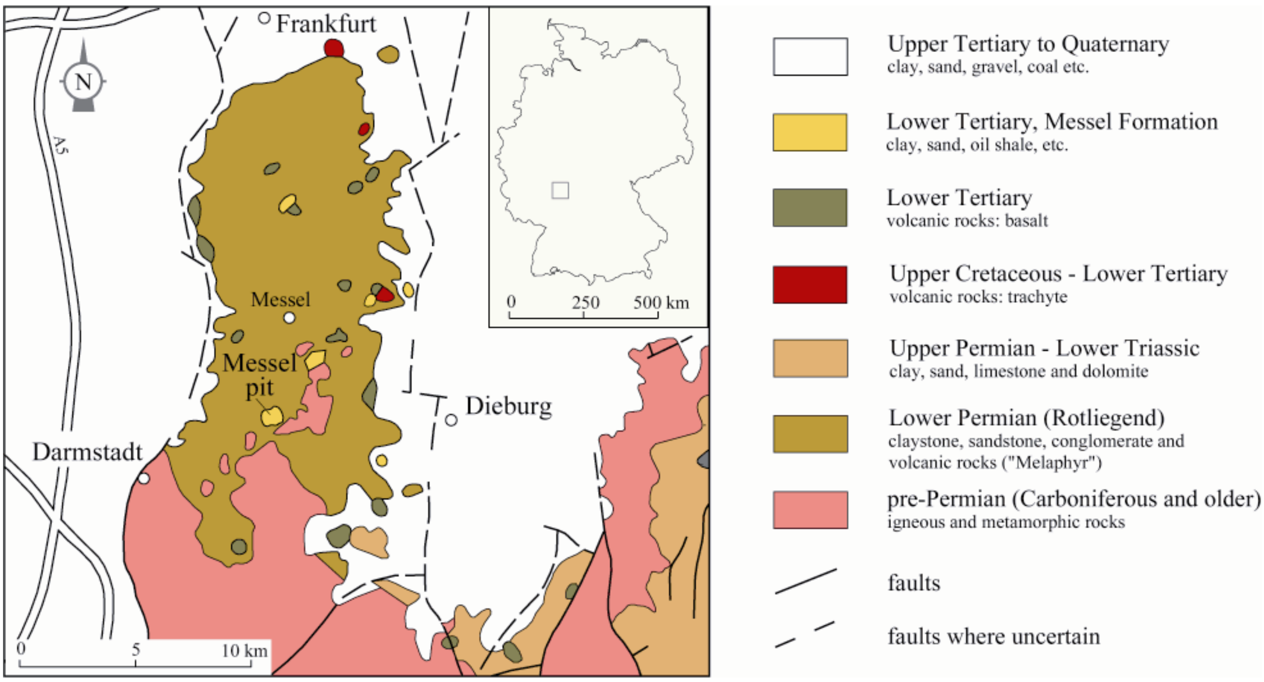

Figure 1. Geological map of the Sprendlinger Horst in the South of Frankfurt (Gemany) and location of the Messel pit (adapted from Harms et al. 1999).

The pit itself was formed during a period of open cast mining of the oil shale which started in the 80s of the 19th century and stopped in 1971. Yet during the period of open cast mining, major deep-seated landslides occurred in most of the engineered slopes (Schaal & Schneider 1995, Nix 2004). Furthermore, shallow failures of the excavation benches affected excavators and technical equipment (Schaal & Schneider 1995). In 1971, the industrial open cast mining was abandoned and in the following years weathering and structural measures flattened the engineered slopes and excavation benches. Nevertheless episodic post failure movements of the reactivated or suspended deep landslides and potential shallow failures may actually endanger visitors or scientists and damage infrastructure. This security situation is unsatisfying for a frequently visited World Heritage Site.

Currently, the pit is intensively geotechnically monitored. Since 1993 the following control- and monitoring systems are in use at least twice a year: 172 geodetic surface monitoring points, 28 inclinometers, 5 deep and 134 shallow wells.

Landslide risk assessment process

Landslide and slope engineering has always involved some form of risk management (AGS 2000) and the use of landslide cartography and the implementation of landslide risk management procedures is internationally widespread (Moon et al. 1992, Fell 1994, Bunce et al. 1997, Ashby 2002, Singh & Vick 2003, Ko Ko et al. 2003). Comprehensive overviews of various aspects of the subject are given by Einstein (1988), Einstein (1997), Einstein (2001), Fell (1994), Fell & Hartford (1997), Ho et al. (2000) and Dai et al. (2002). Despite the numerous approaches there was a lack of a standardized terminology (AGS 2000).

With the objective to establish a uniform terminology, to define a framework for landslide risk management and to provide information on acceptable and tolerable risks for loss of life, a landslide risk management guideline was created by the Australian Geomechanics Society (AGS) in 2000. The guideline itself is based on the Australian risk management standard (AS/NZS 4360:1999) which is regarded as one of the best developed standards to conduct risk management processes (Power & McCarty 2002).

AGS (2000) divide the risk management process into three main components, namely (i) risk analysis, (ii) risk evaluation and (iii) risk treatment. The risk assessment approach presented in this paper follows this division. To avoid confusion in the use of terms, AGS (2000) give a list of definitions of terms which are frequently used in landslide risk assessment. The terminology was developed by the Committee on Risk Assessment of the International Union of Geological Sciences (IUGS 1997). This terminology is also valid for this paper.

Site specific quantitative risk analysis produces numerical values for the level of risk in terms of annual loss of property value or annual probability of loss of life. AGS (2000) provide the following formulas.

$$R_{(Prop)} = P_{(H)} \cdot P_{(S:H)} \cdot V_{(Prop:S)} \cdot E \qquad (1)$$

where

$R_{(Prop)}$: annual risk for loss of property value
$P_{(H)}$: annual probability of the landslide event
$P_{(S:H)}$: probability of the spatial impact ("does the landslide hit the building?")
$V_{(Prop:S)}$: vulnerability of the property (proportion of property value lost)
E: value of the property

$$R_{(DI)} = P_{(H)} \cdot P_{(S:H)} \cdot P_{(T:S)} \cdot V_{(D:T)} \qquad (2)$$

where

$R_{(DI)}$: annual risk for loss of life
$P_{(H)}$: annual probability of the landslide event
$P_{(S:H)}$: probability of the spatial impact with special regard to landslide velocity
$P_{(T:S)}$: temporal probability (i.e. building being occupied at the time of landslide event)
$V_{(D:T)}$: vulnerability of the individual

Please note that one or more hazard events can cause risk to several elements at risk. The sum of the risks determined for every element at risk is called the total risk. The parameters being introduced to equations 1 and 2 are normally not easy to obtain. Very frequently they must be estimated by expert judgement or are subject to intensive discussions. It is one of this paper's objectives to give the reader a systematic approach how these values can be transparently derived.

LANDSLIDE RISK ASSESSMENT FOR THE MESSEL PIT

It is of vital interest to a geotope's operator to have a clear understanding of the risks to which a visitor of a geotope is exposed. This is especially important with respect to the magnitude of monetary investments which are needed to maintain an acceptable level of safety but also a decisive factor for the determination of insurance premiums.In the following sections, the applied methodology is discussed in detail. Please, note that the presented risk assessment framework was carried out separately for both identified slope failure mechanisms (i) episodic post failure movements of reactivated or suspended deep landslides and (ii) potential shallow failures of weathered and flattened slopes.

Risk assessment for deep seated slides

Most of the extensive deep landslides occurred in the beginning of the 20th century. Episodic reactivations of the displaced masses are triggered by intense rainfalls causing a temporary rise in pore water pressures. Figure 2 shows a representative subsurface model with the basic geological features. The displaced material moves on a shear surface along the bedding planes of the Messel oil shale (MMF). As displacements of the stiff oil shale masses are large, the shear strength along existing failure planes may be characterized by the residual frictional component of strength, φ_R. The residual cohesion c_R is assumed to be zero (Skempton & Petley 1967, Abramson et al. 2001). Some parts of the pit can be regarded as areas of "first time slides" (movement zone no. 5, Figure. 3, Table 1) the shear strength of the stiff fissured oil shale may be characterized by φ'. The weakness introduced by the fissures reduces the cohesion c' to zero.

Two different groundwater conditions have to be considered: (1) an unconfined shallow aquifer in the oil shale of the Middle Messel Formation and (2) a deep artesian aquifer in the breccias of the Lower Messel Formation (Figure. 2).

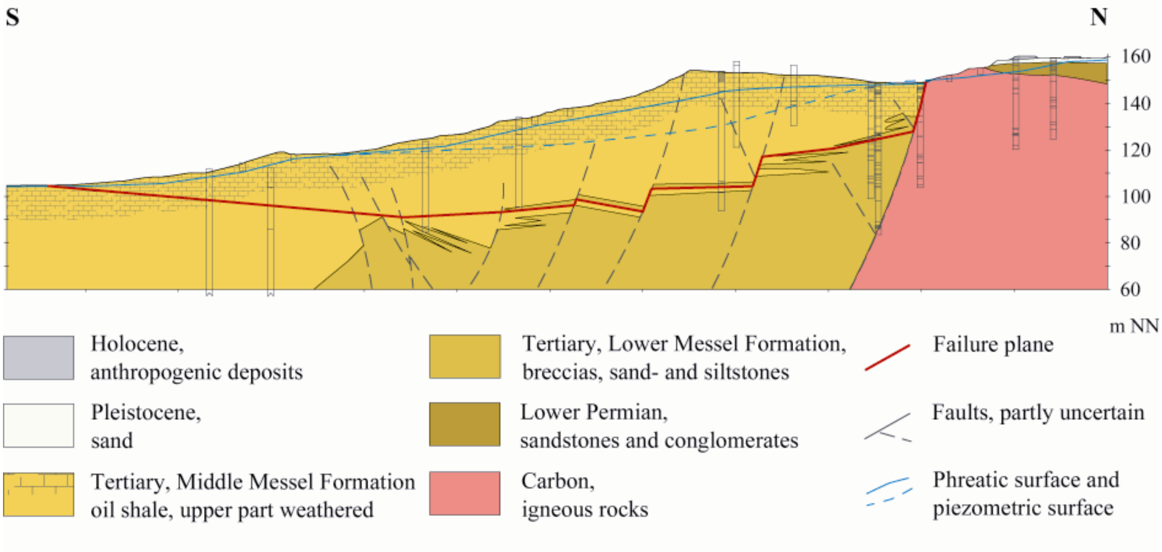

Figure 2: Schematically illustrated representative subsurface model with the basic geological, hydrogeological and geotechnical features.

For scenario (1), a phreatic surface is defined and pore water pressures are calculated for steady-state seepage conditions. The concept is based on the assumption that all equipotential lines are straight and perpendicular to the phreatic surface segment passing through a slice element in the slope (Abramson et al. 2001). For scenario (2) a piezometric surface is specified. The pore water pressure is calculated from the vertical distance (pressure head) between the piezometric surface and the failure plane (Abramson et al. 2001).

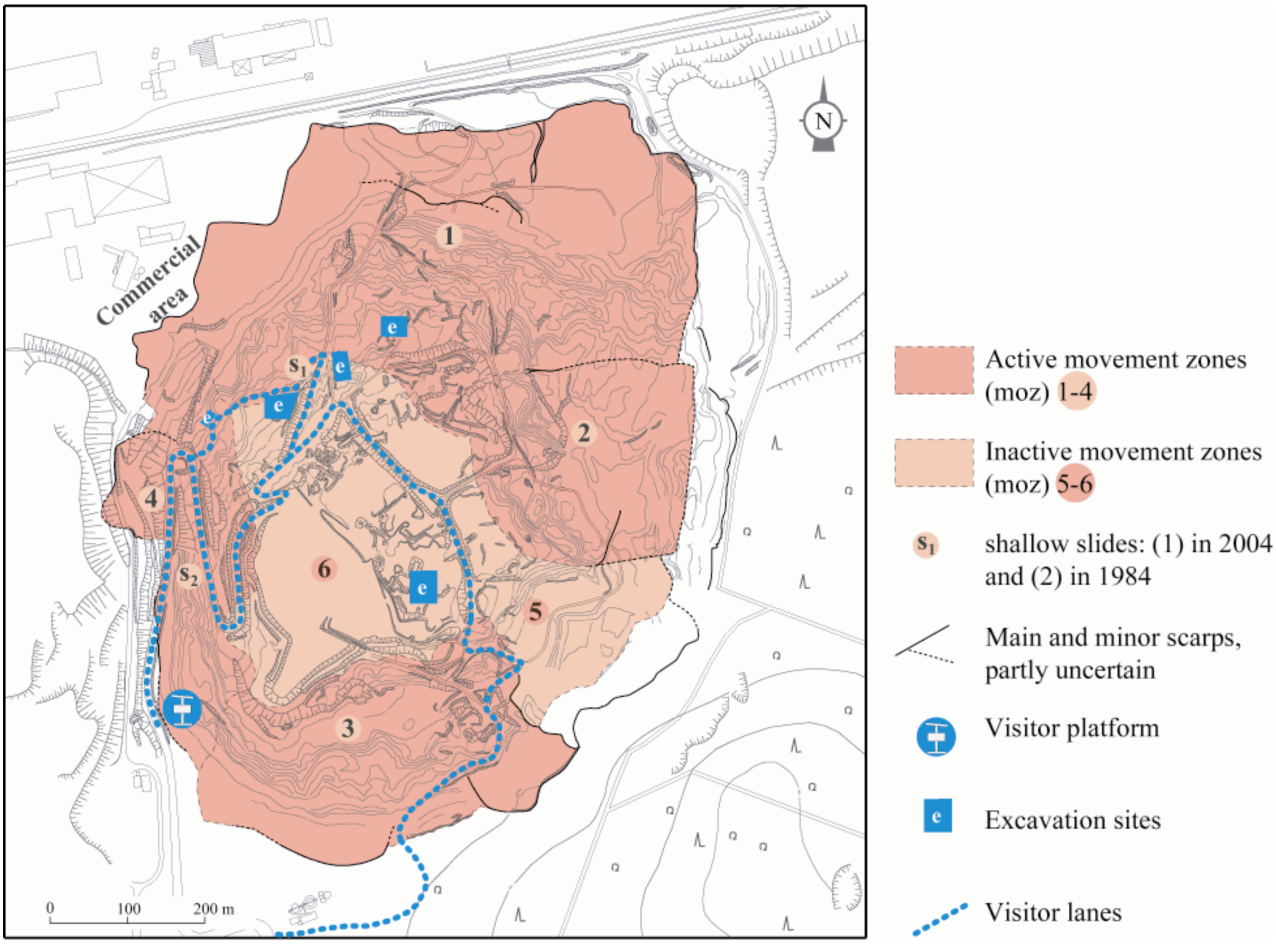

Figure 3. Messel pit landslide map; illustrated are the main features of deep and shallow landslides as well as structural elements.

Due to the intense geotechnical measurements, six zones of movement (moz) can be distinguished (Figure. 3) and were used for the risk analysis of the deep landslides. The zones of movement no. 1-4 cover reactivated or suspended deep slides; zone of movement no. 5 covers the only stable part of the slopes; movement zone 6 covers the lowest part of the pit and is therefore no zone of original slide movement. However, it is affected such that the sliding masses of the higher zones move into this area (Figure. 3).

The following Table 1 lists selected parameters of the deep landslide inventory, obtained by geophysical investigations (seismic etc.) and an intensive geotechnical monitoring program, including GPS surveying, monitoring wells and inclinometers.

Table 1. Deep landslide inventory.

A	B	C	D	E	F	G
	Zone of movement no. 1	**Zone of movement no. 2**	**Zone of movement no. 3**	**Zone of movement no. 4**	**Zone of movement no. 5**	**Zone of movement no. 6**
Surface area (m^2)	194059	67085	92965	64227	32113	110726
Sliding area (m^2)	194059	67085	92965	64227	-	-
Length of displaced mass L_d (m)	299	207	182	101	-	-
Width of displaced mass W_d (m)	657	264	486	598	-	-
Depth of displaced mass D_d (m)	50	42	17	15	-	-
Volume of displaced material (m^3)	5135382	1203510	788040	472968	-	-
Type of movement	noncircular rotational slide	noncircular rotational slide	noncircular rotational slide	noncircular rotational slide	-	-
Direction of movement (°)	175°-185°	265°-275°	340°-350°	80°-100°	-	-
95% quantile of annual displacements from 1993-2003 (mm)	129	170	62	75	-	-

Risk calculation for loss of property

The properties (elements at risk) considered are: Visitor lanes, visitor platform, a supply road and a part of an enterprise property (Figure. 3). The factors needed for the calculation are (see equation 1): probability of the landslide occurring, probability of spatial impact, vulnerability and the values for the element at risk. Please note that although the risk calculation is carried out numerically there is a significant judgemental aspect to estimating several of the input parameters for the calculation model e.g. vulnerability of property. The following Table 2 gives the assigned values and the resulting annual risk for loss of property and risk for loss of property value.

One of the most critical and difficult steps of landslide risk analysis – though there are a variety of methods available – is the estimation of the annual probability of landsliding (Table 2, column C). This contribution uses a formal probabilistic analysis approach which accounts for the uncertainty and variability of parameters like material strength, pore pressure etc. to estimate the likelihood of post failure movements of existing deep landslides. Component input parameters are modelled as random variables, defined by their probability density function (PDF). As a result of the probabilistic analysis the PDF of the Factor of Safety (FOS) was estimated by Monte Carlo simulation and the probability of failure was calculated directly. This approach is comprehensively outlined by Mostyn & Fell (1997), Li (1991, 1992) and Abramson et al. (2001).

For the presented analysis, the steps performed were: (i) development of an appropriate geological slope model (Nix 2004), (ii) formulation of the performance function of the slopes using Morgenstern and Price´s rigorous limit equilibrium method, (iii) specification of model input parameters based on laboratory tests [γ •of LMF (kN/m^3), γ •of MMF (kN/m^3), φ_R of LMF (°),φ_R of MMF (°)] and field investigations (phreatic surface location, pressure head differential) (Nix 2005), (iv) derivation of the probability density function (PDF) of the FOS by Monte Carlo simulation of the input parameters. The PDF of the FOS was then used to determine the probability of failure.

Table 2. Annual risk for loss of property (deep landslides) and corresponding input values

A	B	C	D	E	F	G	H
Objects	**Zone of movement**	**Prob. landslide (annual) [%]**	**Prob. spatial impact**	**Vulnerability of property**	**Annual risk for loss of property**	**Value for element at risk (€, €/m, €/m²)**	**Annual risk for loss of property value**
		$P_{(H)}$	$P_{(S:H)}$	$V_{(Prop:S)}$	$R_{(Prop)}$	E	
Visitor platform	4	0.2564	1.00	0.013	3.333E-03	200000.00	666.64
Visitor lane	1	0.1463	1.00	0.01	1.463E-03	100.00	0.146
Visitor lane	2	0.9316	1.00	0.01	9.316E-03	100.00	0.933
Visitor lane	3	0.3728	1.00	0.01	3.728E-03	100.00	0.373
Visitor lane	4	0.2564	1.00	0.05	1.282E-02	1000.00	12.820
Visitor lane	5	0.054	1.00	0.01	5.400E-06	100.00	0.0005
Visitor lane	6	0.9316	0.0015	0.01	1.377E-05	100.00	0.0138
Commercial area	1	0.1463	1.00	0.01	1.463E-03	100.00	0.146

The probabilistic calculations yielded the results shown in Table 2, column C. Descriptively, based on Corps of Engineers (1997), the performance of movement zones no. 1-4 (reactivated or suspended deep slides) would be classified as "unsatisfactory" to "hazardous". The performance of movement zone no. 5 would be classified as "good". The likelihood of sliding masses moving into movement zone 6 (annual probability of landsliding) was assumed to be equal to the greatest annual probability of landsliding of an adjacent slide (in this case 0.9316 for moz 2).

Since each of the properties considered lies on top of a moving earth slide and is therefore completely affected by its movement, the probability of the spatial impact was set to 1 (=100 %). Only the visitor lanes in movement zone 6 (moz 6) must be treated separately since they are not located on top of a sliding mass itself but in front of an earth slide's toe (sliding masses move into this area, cp. Figure. 3). For the specification of the probability of the spatial impact the following approach was used: Due to the geotechnical measurements an annual sliding distance of at most 170 mm was derived (Table 1), which is equal to the 95 % quantile of the rate of the annual displacement. The length of visitor lanes being affected by slope movements (moz 6) was estimated with a GIS and a buffer operation around the zones of movement. A total length of 1.2 m was determined. The total length of visitor lanes in movement zone 6 is 805.17 m so that the probability that a deep slide will hit a part of this visitor lanes is 0.0015 (=0.15 % = 1.2 m / 805.17 m).

Vulnerability values were determined by expert judgement via the serviceability of the properties considered. The values may range between 1.0 (completely destroyed) and 0 (the serviceability is not affected by the event). The vulnerability of the visitor's platform is of major concern since the majority of the visitors ascend the platform to have a look into the Messel pit. To enable a good view into the pit, it was necessary to found the platform in a slow moving slide which causes the platform to incline. Between 1998 and 2002 a yearly increase of inclination by 0.04° was determined. For the purpose of this study, we assume that the platform's serviceability is put into question if its inclination reaches 3° which may subjectively be regarded as skewed so that people will not enter the platform. Based on these data, it can be assumed that the visitor's access to the platform must be restricted after a period of about 75 years. So 1/75 (=0.013) gives the yearly loss of serviceability, hence a vulnerability of about 0.013 was assumed.

Visitor lanes are small dirt roads which can quickly and cheaply be repaired. Moreover, it can be assumed that only parts of these lanes and not the lanes in their total lengths are affected by the movement and that their repair will not be necessary year by year. Due to these reasons the vulnerability was set to a low value of 0.01. The vulnerability of the supply road (moz 4) is of major concern since it is the only paved road into the pit and is therefore vital to the fossil excavations and all kinds of supply. Due to the slow slope movement it cannot be expected that the road is out of operation after one year. The vulnerability was set to a fairly low value of 0.05. A similar value was provided by Leone et al. (1996) for road degradation.

The part of the commercial area which is affected by the sliding masses is an area serving for the storage of building-material. Only parts of this area are affected by landsliding and repair will not be necessary year by year. For this reason the vulnerability was again set to a low value of 0.05.

The monetary values for the elements at risk were derived from local price levels which are considered necessary to reasonably reconstruct parts of the properties. Please note that the values are given in [ ], [/m] and [/m^2] respectively.

Risk calculation for loss of life

Visitors (on platform and lanes), scientists (at excavation sites) and workers (at commercial area) were identified as "elements" at risk. Table 3 gives the computed annual risk for loss of life and the corresponding input values for each zone of movement.

Table 3. Annual risk for loss of life (deep landslides) and corresponding input values.

A	B	C	D	E	F	G
Persons	Zone of movement	Probability of landsliding (annual)	Probability of. spatial impact	Temporal probability	Vulnerability of the individual	Annual risk of loss of life
		$P_{(H)}$	$P_{(S:H)}$	$P_{(T:S)}$	$V_{(D:T)}$	$R_{(DI)}$
Visitors on platform	4	0.2564	1.00	5.000E-01	7.77E-06	9.959E-07
Visitors on lanes	1	0.1463	1.00	4.285E-04	3.36E-05	2.103E-09
Visitors on lanes	3	0.3728	1.00	1.332E-03	3.36E-05	1.666E-08
Visitors on lanes	4	0.2564	1.00	2.242E-03	3.36E-05	1.929E-08
Visitors on lanes	5	0.054	1.00	9.230E-05	3.36E-05	1.672E-12
Visitors on lanes	6	0.3728	0.011	2.602E-03	3.36E-05	1.202E-10
Scienticts at excavation sites	1	0.1463	1.00	0.105	3.39E-04	5.205E-06
Scienticts at excavation sites	4	0.2564	1.00	0.105	3.39E-04	9.123E-06
Employees at commercial area	1	0.1463	1.00	0.026	4.35E-05	1.670E-07

The values for the annual probability of a landslide occurring $P_{(H)}$ and the probability of spatial impact $P_{(S:H)}$ have been taken over from Table 2. Due to the fact that there are no visitor lanes and excavation sites within movement zone 2, this zone has been left out. Please note that in contrast to Table 2, a temporal probability $P_{(T:S)}$ and a specific vulnerability $V_{(D:T)}$ have been introduced to Table 3.

As to the calculation of the temporal probability it must be taken into account that there are several 'types' of individuals who have a different exposure to the hazard. These are: (i) visitors of the pit, (ii) scientists at the fossil excavation sites and (iii) enterprise employees. However, the group of visitors can further be divided into (i) visitors who enter the pit and walk along the visitor lanes and (ii) visitors who do not enter the pit but just climb the platform to have a look into the pit. For each of the mentioned groups, the temporal probability was computed as follows.

Visitors on platform: Up to the year 2003 the mean number of visitors on the platform is 49,923.75, say 50,000. The temporal probability $P_{(T:S)}$ may be defined as the proportion of the year where the platform is occupied by people. Though the visitor access to the platform is temporarily not limited, we assume that the platform will only be occupied during day time (=12 hours). This results in a value of 0.5 for $P_{(T:S)}$.

Visitors on lanes: Since 1992 the Messel pit is visited by 5096 visitors per year. Usually these visitors enter the Messel pit in groups of approximately 30 persons. As visitors/visitor groups are mobile they may be regarded as moving 'objects' along the visitor lanes. It is assumed that while visiting the pit, the visitors remain on these lanes. Generally, deep seated landslides homogenously affect the entire part of a visitor lane located on the slide and have to be regarded as 'linear' events The temporal probability for a visitor on visitor lanes may then be described by the proportion of the year where parts of visitor lanes are occupied by visitors. An equation proposed by Hoek (2000) has been modified to

$$P_{(T:S)} = \frac{V}{24 \cdot 365} \cdot \frac{L}{v_V \cdot 1000} \cdot \frac{1}{G_S} \qquad (3)$$

where

- V is the number of visitors per year,
- L is the length of a lane [m] which is affected by slope movement,
- v_V is a visitor's velocity in [km/h] and
- G_S is the average size of visitor groups.

Please remind that the overall risk analysis framework presented, accounts for an individuals risk for loss of life. Thus, the approach presented assumes that the time period of a visitor occupying a part of the visitor lanes equals the time period of a visitor group occupying this part of the visitor lanes.

Scientists at fossil excavation sites: The temporal probability $P_{(T:S)}$ for scientists at excavation sites measures the percentage of time that scientists will be present at excavation sites. For the calculation of $P_{(T:S)}$ we assume 115 working days (excavation period: April-September) with 8 h working time per day. This results in a total number of 920 working hours per scientist per year and a temporal probability of $P_{(T:S)}$ = 920 h / (365 * 24 h) = 0.105.

Enterprise employees: The temporal probability $P_{(T:S)}$ for enterprise employees measures the percentage of time that workers will be present at the affected commercial area. For the calculation 230 working days per year with 8 h working time per day are assumed which gives a total number of 1840 working hours per worker. Moreover it is assumed that the area under consideration is not permanently but just frequented 1h/day. This results in a temporal probability of $P_{(T:S)}$ = (230 d * 8 h * 0.125) / (365 d*24 h) = 0.026.

Vulnerability in the present context may be defined as the probability of loss of life of an individual. Typically, the level of vulnerability is expressed on a scale of 0 (0 % probability of being killed by a land slide = 100 % chance of survival) to 1 (100 % probability that a life will be lost given the land slide occurs). As mentioned before, visitors (on platform and lanes), scientists (excavation sites) and workers (commercial area) were identified as elements at risk. For each of these groups of persons appropriate vulnerability levels had to be established.

The applied approach relies on the statistics of historic records, the results of the geotechnical monitoring program and the counted or supposed number of visitors, scientists and workers. Essential element of the concept evolved is the number of persons entering the Messel pit during a period of landslide movement. We assume that the percentage of persons entering the pit during a period of landslide movement with or without getting physically affected by the landslide is an appropriate measure for the level of vulnerability (probability of getting affected by a landslide).

Based on the concept explained above, the vulnerability $V_{(D:T)}$ of visitors (cp. column F, Table 3) is calculated by dividing the total number of persons affected by landslides by the total number of visitors during periods of landslide movement. The periods of landslide movement for each zone are well known since the whole pit is intensively geotechnically monitored. The resulting values are for (i) visitors on lanes $V_{(D:T)}$ = 3.36E-5, (ii) visitors on platform $V_{(D:T)}$ = 7.77E-6. Please, note that up to the year 2003 none of the persons entering the Messel pit during a period of landslide movement was killed or even harmed by a landslide. Consequently, the numerator should not be 1 but 0. However, setting the numerator to 0 causes the vulnerability to become 0 which in turn causes equation 2 to result in 0 (no risk). To avoid this problem, a preliminary, upper boundary value of 1 for the number of persons being affected by landslides was assigned. Since only a 10-year record of people visiting the Messel pit is available, the vulnerability values should be updated within a regular period.

The same concept is applied to the calculation of the vulnerability of scientists at excavation sites and the vulnerability of employees at the commercial area. An essential element of the approach adopted is the number of scientists and workers entering the Messel pit during a period of landslide movement. For the scientists we assume 115 working days during the excavation period and on 14 people being permanently present at the excavation site. For the employees at the commercial area we assume 230 working days per year. The area under consideration is not permanently occupied by workers. We therefore assume that two workers enter the affected area 10 times per day. The resulting value for vulnerability $V_{(D:T)}$ of scientists at excavation sites is $V_{(D:T)}$= 3.39E-4 whereas the vulnerability of employees is $V_{(D:T)}$= 4.35E-5. Please, note that the numerator of 1 again represents a worse case scenario implying that at least one person has been harmed by a landslide.

Risk assessment for shallow seated slides

Since 1971 a shallow slide failure was registered only twice, in 1987 and in 2004 (Figure. 3). The moving mass is confined by discontinuities or tension cracks and slides in a translational movement on shear surfaces along the bedding planes of the Messel oil shale (MMF). Generally, the failure planes daylight into the slope face i.e. the dip of the failure planes is smaller than the dip of the slope face (Figure. 4). Both of the failures in 1987 and 2004 were triggered by intense rainfall, presumably causing a temporary raise of water pressure in the tension crack and on the failure plane. Most of the observed shallow landslides are relatively small, the volume of displaced material ranges between 50 m^3 and 250 m^3 and travel distance varies between 7 m up to 15 m. Based on descriptions and personal observations, the landslide velocity may be classified as moderate to rapid with an estimated velocity of several meters per day.

Figure 4 shows the schematic subsurface model with the basic geological features. Planar sliding failure may occur on pre-existing shear surfaces along the bedding planes of the Messel oil shale (MMF). The main scarp at the upper edge of the planar sliding wedge may be tied to a tension crack etc. in the slope face. The shear strength of stiff fissured oil shale for “first time slides” may be characterized by φ´. Due to the weakness introduced by the fissures the cohesion c´ is assumed to be zero (Skempton & Petley 1967). For failure surface and tension crack the water pressure model is illustrated in Figure 4 (b). Maximum water pressure occurs at the base of the tension crack and drainage at the toe of the slope is possible.

The performance function of the slope is formulated according to Hoek & Bray (1981). Based on available morphological data, field investigations and laboratory tests, the following input parameters were used as random variables: slope angle (°), slope height (m), γ of MMF (kN/m^3), φ´ of MMF (°), failure plane angle (°), filling of tension crack (%).

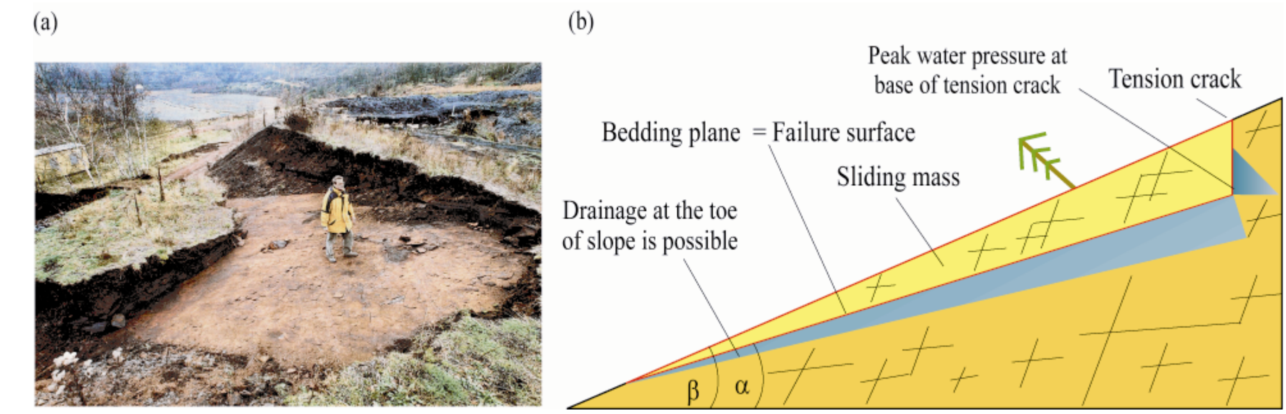

Figure 4: Schematically illustrated representative subsurface model with the assumed geological, hydrogeological and geotechnical features (photo courtesy of Darmstädter Echo).

A probabilistic stability analysis based on Monte Carlo Sampling (250000 iterations) resulted in a probability of shallow failure $P_f = 0.0054$ (see also Table 4). Descriptively, the performance of the slopes particularly with regard to shallow failures may be classified as “above average” (Corps of Engineers 1997).

Risk calculation for loss of property

Compared to the deep seated slides, the sliding volumes of the shallow slides are small and do not affect larger areas. The visitor platform and the enterprise property are outside the area of known shallow landslides and remain unaffected by this type of slope failure. Table 4 therefore only shows the risk for loss of property for the visitor lanes.

Table 4. Annual risk for loss of property (shallow landslides) and corresponding input values

A	B	C	D	E	F	G
Objects	Prob. Landslide (annual)	Prob. spatial impact	Vulnerability of property [%]	Annual risk for loss of property	Value for element at risk (property) (€/m)	Annual risk for loss of property value
	$P_{(H)}$	$P_{(S:H)}$	$V_{(Prop:S)}$	$R_{(Prop)}$	E	
Visitor lanes	5.380E-03	0.063	0.01	3.377E-6	100.00	0.00034

For the determination of the probability of the spatial impact on visitor lanes $P_{(S:H)}$, the following assumptions have been applied: (i) based on historic records of observed shallow slides, a maximum sliding distance of 15m is assumed, (ii) inside the pit, the shallow slides could potentially occur everywhere along a lane and (iii) the total length of the visitor lanes is 2072m.

With the assumed sliding distance of 15m the approximate potential area affected by landslides imposing a threat to the visitor lanes is 2072 m * 15 m = 31080 m^2. Taking into account a failure on the lanes themselves (with a lane width of 2 m) we have a potential hazard area of 35224 m^2 (= 2072 m * 2 m + 31080 m^2). With a total area of the Messel pit of 561174 m^2 the probability that a lane will be hit by a shallow landslide is 0.063 (= 6.3 % = 35224 m^2 / 561174 m^2).

The vulnerability values $V_{(Prop:S)}$ for the visitor lanes were taken from Table 2 and set to 0.01 and 100 /m respectively.

Risk calculation for loss of life

Visitors (lanes) and scientists (excavation sites) were identified as “elements” at risk. Table 5 gives their annual risk for loss of life and the corresponding input values.

The values for the annual probability of a landslide occurring $P_{(H)}$ and the probability of spatial impact $P_{(S:H)}$ along the visitor lanes have been taken from Table 4. For the calculation of the probability of spatial impact $P_{(S:H)}$ for scientists at the currently five excavation sites, the total area and perimeter of the sites were determined (total area =

4600 m^2 and a total perimeter of 600 m). It is assumed that sliding into an excavation site is principally possible from three sides. The probability of the spatial impact is calculated with ¾ * 600 m * 15 m + 4600 m^2 = 11303 m^2 where 15 m is the maximum travel distance of a shallow slide. Thus, with a total pit area of 561174 m^2, the probability for the spatial impact is $P_{(S:H)}$ = 11303 m^2 / 561174 m^2 = 0.02 = 2 %.

Table 5. Annual risk for loss of life (shallow landslides) and corresponding input values

A	B	C	D	E	F
Persons	Prob. landslide (annual)	Prob. spatial impact	Temporal probability	Vulnerability of the individual	Annual risk of loss of life
	$P_{(H)}$	$P_{(S:H)}$	$P_{(T:S)}$	$V_{(D:T)}$	$R_{(DI)}$
Visitors on lanes	0.00538	0.063	4.84E-05	0.1	1.637E-09
Scientists at excavation sites	0.00538	0.0201	1.050E-01	0.1	1.138E-06

Please, note that in contrast to Table 4, a temporal probability $P_{(T:S)}$ and a specific vulnerability $V_{(D:T)}$ have been introduced to Table 5. The temporal probability $P_{(S:H)}$ for visitors on lanes depends on the number of visitors, their velocity and the space required by a visitor. Based on the statistical data of the last 12 years, 5096 (=5100) visitors yearly visit the pit and walk along the lanes respectively. Usually, these visitors do not remain unguided but enter the Messel pit in groups of approximately 30 persons. It is assumed that while visiting the pit, the visitors remain on the lanes. In contrast to the deep seated landslides which affect larger areas of the pit, the shallow slides are regarded as a more 'punctual' phenomenon. The temporal probability for visitors on visitor lanes may then be described by the likelihood that a part of the visitor lanes is occupied by visitors. An equation which is adapted from Australian Geomechanics Soceity (AGS 2000) was applied.

$$P_{(T:S)} = \frac{V}{24 \cdot 365} \cdot \frac{Sp_V}{v_V \cdot 1000} \qquad (4)$$

where

V is the total number of visitors per year

Sp_V is the space [m] a visitor 'occupies' – like the length of a lane for instance

v_V is a visitor's velocity [km/h].

Based on the assumptions described above, it is calculated that the Messel pit has 0.58 visitors/hour (= 5100 visitors/(24 hours * 365 days)). Furthermore, we assume that, while walking on the lanes, each visitor occupies approximately 1 m of the length of a lane. The speed of a visitor is assumed to be around 6 km/h which is normal walking speed. Hence, the temporal probability for a visitor is P(T:S) = 0.58 * (1 m / (6 km/h * 1000)) = 9.6E-5. However, visitors enter the pit in groups and do not walk in a queue but normally close together, side by side for instance. A group of 30 people (group size G_S = 30) does therefore not cover a length of 30 m but just 15 m. For this reason we introduce a group factor G into equation 3 which gives equation 4.

The group factor cannot be specified in a general form since it depends on the specialities of a publicly accessible geotope and should therefore be locally adapted. E.g. while visitors of a cave may be forced to walk in a queue, visitors of a quarry may be 'concentrated' on one spot. Here we assume that two visitors will walk side by side which gives a group factor of G = 0.5. Thus, for a group of visitors, the temporal probability is calculated as $P_{(T:S)}$ = 0.58 * (1 m *0.5)/(6 km/h * 1000))= 4.8E-5.

$$P_{(T:S)} = \frac{V}{24 \cdot 365} \cdot \frac{G_S \cdot Sp_V \cdot G}{v_V \cdot 1000} \cdot \frac{1}{G_S} = \frac{V}{24 \cdot 365} \cdot \frac{Sp_V \cdot G}{v_V \cdot 1000} \qquad (5)$$

The temporal probability $P_{(T:S)}$ for scientists at excavation sites measures the percentage of time that scientists will be present at excavation sites. The appropriate value can be taken from Table 3.

As mentioned before, visitors on lanes and scientists at excavation sites were identified as "elements" at risk. For these groups of persons appropriate vulnerability levels had to be established. Actually no historic records are available for Messel, relating adverse effects on persons and shallow slides. On this account the vulnerability of individuals was adopted from published data (Finlay et al. 1999, AGS 2000). Based on the quoted descriptions an adequate vulnerability of 0.1 was introduced to Table 5. This value is assigned to persons in open space, not being buried by debris, having a high chance of survival.

EVALUATION OF THE TOTAL RISK FOR LOSS OF PROPERTY AND LOSS OF LIFE

The total risk is the sum of the risk for each hazard and for each element. The calculations for the total risk for loss of property and the total risk for annual loss of property value yielded the results presented in Table 6. A value of 3.21E-02 for the total risk for loss of property is a fairly high value. However, the determined annual risks for loss of property values (1.333E+03 ; 1.43E+01 /m and 1.463E-01 /m^2 respectively) are fairly low so that the total risk for loss of property may be considered as a low risk (AGS 2000).

Table 6. Total risk for loss of property.

A	B	C	D	E	F	G
Objects (moz)	Annual risk for loss of property (deep slides, table 2)	Annual risk for loss of property (shallow slides, table 4)	Total annual risk for loss of property	Annual risk for loss of property value (deep slides, table 2)	Annual risk for loss of property value (shallow slides, table 4)	Total annual risk for loss of property value
Visitor platform (4)	3.333E-03		3.333E-03	1.333E+03		1.333E+03
Visitor lanes (1)	1.463E-03			1.463E-01		
Visitor lanes (2)	9.316E-03			9.316E-01		
Visitor lanes (3)	3.728E-03	3.377E-06		3.728E-01	3.4E-04	
Visitor lanes (4)	1.282E-02			1.282E+01		
Visitor lanes (5)	5.400E-06			5.400E-04		
Visitor lanes (6)	1.377E-04		2.735E-02	1.045E-02		1.43E+01
Commercial area (1)	1.463E-03		1.463E-03	1.463E-01		1.463E-01
		Σ	3.210E-02			

The calculations for the total risk for loss of life gave the results presented in Table 7. To better assess the evaluated risks for the various elements at risk, the determined risk values of the presented study were compared to risk values from other studies (Fell 1994, AGS 2000) and plotted on the graph shown in Figure 5.

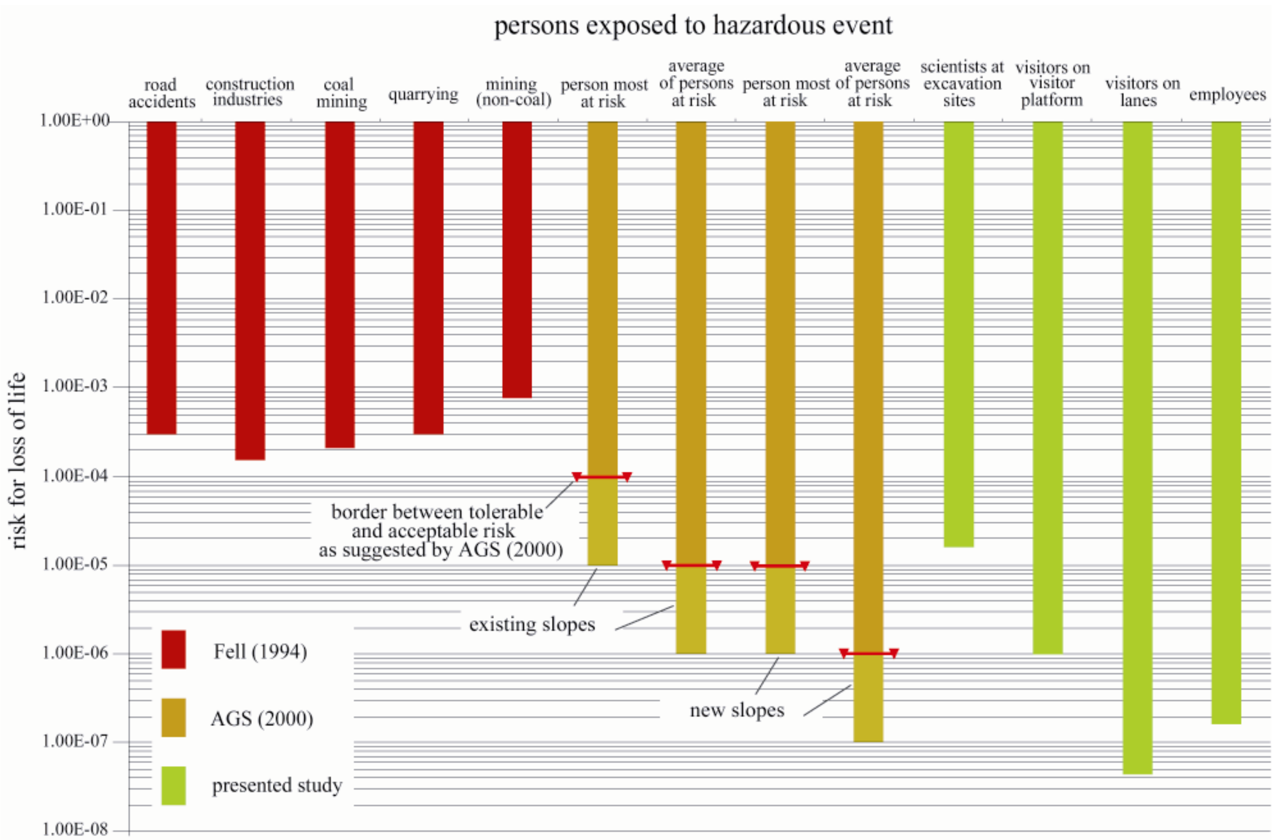

Figure 5: Comparison of different risk levels (explanations see text).

Fell (1994) did not explicitly give any risk values for geosites; however, he presented a variety of values for some every-day situations but also for geologically related activities which is considered a useful basis to assess the risk in the Messel pit. Figure 5 also shows risk values for loss of life for landslide events as suggested by AGS (2000).

The graph shows that the determined risk levels for the visitors of the Messel pit are well below all tolerable risk levels and mostly below the levels which are considered acceptable. Only the scientists at the excavation sites are exposed to a higher risk which is due to their activity in specially prepared excavation sites. However even this risk level is below the levels for other geologically related activities like quarrying or coal mining for instance.

Table 7. Total risk for loss of life.

A	B	C	D
people (zone of movement no.)	annual risk for loss of life (deep seated slides, table 3)	annual risk for loss of life (shallow slides, table 5)	Σ = total risk
visitors on visitor platform (4)	9.959E-07		9.959E-07
visitors on lanes (1)	2.103E-09		
visitors on lanes (3)	1.666E-08		
visitors on lanes and supply road (4)	1.929E-08	3.274E-09	
visitors on lanes (5)	1.672E-12		
visitors on lanes (6)	1.202E-10		4.144E-08
scientists at excavation sites (1)	5.205E-06	1.138E-06	
scientists at excavation sites (4)	9.123E-06		1.547E-05
Employees at commercial area (1)	1.670-07		1.670E-07

DISCUSSION AND CONCLUSIONS

A systematic approach was presented which allows a transparent risk assessment for the visitors of the Messel pit. The determined results show that the visitors of the pit as well as the employees of the adjacent enterprise are exposed to a risk level which is well below some every day situations. To reduce the risk for loss of life for scientists the width and the depth of the excavation trenches were reduced. Moreover, it is not allowed that a group of scientists entirely enters an excavation trench. The risk for the properties is regarded acceptable since the financial consequences are fairly low.

However, the study did not show that there was no risk for loss of life or no risk for loss of property. To cover even low risks for loss of life, risk transfer in terms of insurance may be an option. The given calculations may be a useful means to calculate reasonable insurance premiums. Additionally, the results presented in Table 6 give a feeling for the order of magnitude of money which is needed to maintain the infrastructure of the pit.

In the presented study, fully probabilistically derived factors of safety for the slopes were combined with crisp vulnerability values derived by expert judgement. However, the authors are aware that the vulnerability values as well as the other input parameters should not be represented by just one value but will certainly have a range of possible values. It should be tried out to configure a fully probabilistic risk assessment workflow which allows introducing value ranges in terms of model distributions to every parameter.

The high amount of available data is due to the high degree of geotechnical surveillance. A comparable degree can certainly not be expected for every geosite. However, this does not mean that the presented approach cannot be used for other geosites. The lack of geotechnical information may then be balanced by expert judgement.

Risk management processes are dynamic processes of an iterative nature. The presented calculations must therefore be re-evaluated with newly collected or updated data in a monitor and review stage. The time-intervals of these re-evaluations may depend on the results of the geotechnical measurements which will be continued on a regular basis.

Acknowledgements: The authors would like to thank the Senckenberg Naturforschende Gesellschaft for their kind support and the permission to evaluate the presented data.

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