A consistent terminology to communicate ground-related uncertainty

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***Preprint statement**: This manuscript is a non-peer reviewed preprint submitted to EarthArXiv.*

Abstract

Engineering geology is highly affected by uncertainty related to geology, geotechnical parameters, models and methods. While the technical aspects of ground-related uncertainty are increasingly well investigated, the terminology to communicate uncertainty - e.g., "It is likely that X will happen." - has not yet been unified and experts use it however they see fit. Due to varying experience, personal biases and societal backgrounds, people may understand uncertainty statements very differently, which is misleading and can even result in legal disputes. This contribution investigates the usage of uncertainty communicating terminology in ground-related disciplines and finds that there is a pronounced prevalence of uncertainty terminology in them. Furthermore, there is a special need to express uncertainty related to quantities (e.g. "most of the project area consists of…"). In response, we propose a framework to consistently communicate ground-related uncertainty encompassing three steps: 1. When you are certain about a statement, do not use uncertainty communicating language. 2. Assess and state the degree of confidence in a statement based on the quantity and quality of the available evidence vs. the agreement of the evidence. 3. If you have high or very high confidence in the statement, communicate the uncertainty in a consistent manner, otherwise elaborate how higher confidence can be achieved. The proposed approach feeds into new uncertainty-aware standards, such as Eurocode 7, and goes beyond them by addressing uncertainty in text and speech. This paper provides the premises for increased awareness of uncertainty communication and encourages further works on the topic.

Keywords uncertainty, uncertainty communication, geological uncertainty, text mining

1. Motivation

In reports and papers, we often find statements like: "*The results suggest that the presence of a lateral thrust …, is very likely …*" (Budetta et al., 2019), "*a multistage failure with significant retrogressive evolution can possibly occur in the future.*" (Luo et al., 2019), "*Influences of environmental factors like sulphate in rainwater or SO2 from the air on salt formation are unlikely.*" (Siedel et al., 2010).

Very likely, *possibly*, *unlikely* are just a few ways how academics and practitioners in ground-related disciplines (i.e. engineering geologists, geotechnical-, mining-, and environmental engineers) try to express uncertainty in technical reports, publications, or other documents. While using verbal descriptions of uncertainty in our everyday language may feel natural, it poses the challenge that expressions like the ones given above may be understood very differently, depending on the context they are presented in and the receivers' experience, technical or also societal background, as expressions of uncertainty may be used very differently in various parts of the world. For example, van Tiel et al. (2022) showed that considerable variances are associated with words that express probabilities, especially when non-absolute phenomena (i.e. probability > 0% and < 100%) are described (e.g. participants in their study associate a probability range of 39-87% with the word "likely"). Replacing verbal descriptions with numerical point estimates or ranges is a viable solution to this problem and may also be preferred in many cases (Dhami and Mandel, 2022). In practical engineering, however, it would sometimes not be meaningful to do so (e.g. due to too low numbers of observations). Furthermore, adding numerical point estimates or ranges all over technical texts furthermore could reduce readability, or it could be undesirable as numbers might give the impression of false certainty. Ultimately, uncertainty descriptions will always be part of the communication of ground-related topics.

Recent literature covers many technical sources of ground-related uncertainty. On a high level, for example, Bar (2024) mentions "known unknowns" such as ground parameters, geological structures or geomechanical behavior as medium-severe ground-related uncertainties and "unknown unknowns" as ground-related, high uncertainties, featuring phenomena like completely unforeseen geological anomalies. Phoon et al. (2022) provide a comprehensive review of uncertainty in geotechnical engineering. Authors like Phoon et al. (2022) or also Karam et al. (2007) differentiate different sources of ground-related uncertainty: geological uncertainty (Brisson et al., 2023; Yan et al., 2023), geotechnical uncertainty also termed "parameter uncertainty" or "spatial variability" (Li et al., 2021; Zhang et al., 2023), transformation uncertainty also called "model uncertainty" (Phoon and Tang, 2019), and method uncertainty (pertaining to the calculation method used in a model, e.g. (Christian, 2004; Tschuchnigg et al., 2015). Besides these sources of ground-related uncertainty, the human uncertainty (e.g. sampling biases, measurement accuracy and precision – sometimes also termed "statistical uncertainty") is acknowledged and, for example, addressed in Elmo and Stead (2021) or Skretting et al. (2023). Uncertainties related to natural hazards and climate impact also receive attention, with Ma et al. (2022) or Kan et al. (2023) being two examples of uncertainty considerations for landslides.

The above-stated works show that technical aspects of ground-related uncertainty are getting attention in literature but the terminology to communicate such uncertainty has not yet been covered. This paper intends to raise awareness about the importance of communicating ground-related uncertainty in a consistent way. To this end, we propose a new, consistent terminology to communicate ground-related uncertainty to avoid misunderstandings between the communicating parties. Clearly communicating ground-related uncertainty becomes increasingly important, especially in light of legal disputes where different interpretations of uncertainty communicating expressions can have severe consequences. Eurocode 7 (EN 1997), constituting the base for geotechnical work, also focuses on explicitly treating uncertainties for ground-related work as part of reliability-based design. This is implemented through probabilistic methods that account for uncertainty through techniques like partial safety factors or Monte Carlo analyses. It is especially important in this context to not only assess uncertainties in a probabilistic way but also to report the results consistently and comprehensibly.

Section 2 gives an overview over uncertainty communication frameworks in other disciplines with a special focus on the framework of the intergovernmental panel on climate change (IPCC) (Mastrandrea et al., 2010) which inspired the herein proposed framework. Main differences between the IPCC communication framework and the framework proposed herein are that proposed classes are fewer and non-overlapping and we also include terminology for describing quantity and correlation strength which is often required in ground-related applications (explanations for these differences given below). To quantitatively underline the perception that uncertainty communication has a higher significance in ground-related fields in comparison to other disciplines, a text mining study (e.g., see Feldman and Sanger (2007) for information on text mining as a subfield of computer science) was conducted to investigate the use of uncertainty expressions throughout different relevant journals (section 3). The proposed framework to communicate ground-related uncertainty is presented in section 4 and a conclusion and outlook is given in section 5. Translations of the uncertainty communication framework from English into German, Italian, Norwegian, Spanish, Chinese and French are given in the appendix to enable widespread usage especially in practice where also technical communication is often non-English. Furthermore, an example of a text from a previous publication of the main author that was revised to exemplify uncertainty communicating language, is also provided in the appendix.

2. Background

The use of specific terminology to describe a quantitative probability associated with uncertainty dates back to the mid-1600s. In the post WWII literature, Prof. Sherman Kent is often credited with popularizing describing probabilities associated with uncertainties for military intelligence and he called the verbal descriptions “words of estimative probability” (Vick, 2002) . This work was continued by Richards Heuer (1999) who introduced Bayesian inverse probability and Tversky and Kahneman’s concepts of cognitive biases in intelligence estimates. Examples of uncertainty and risk communication in other fields of obvious importance such as health and medicine were provided by Fischhoff et al. (2011) and Fallon et al. (2024). An early example for a terminological framework for uncertainty communication in a technical field is given in Table 1, which was developed by Barneich et al. (1996). It was made for the nuclear power industry as a "Subjective Probability Estimate Guide" and reflects the probability of dangerous events as perceived for the nuclear industry.

Table 1: Guidelines for subjective probability estimates for the nuclear energy industry (Barneich et al., 1996).

Verbal description	**Probability**
Event is virtually certain.	1
Event had been observed in the available database.	0.1 (10^{-1})
Event has not been observed earlier or only once in the available database; several potential failure scenarios can be identified.	0.01 (10^{-2})
Event has not been observed earlier in the available database; it is difficult to imagine any plausible failure scenario, perhaps one scenario can be identified.	0.001 (10^{-3})
Event has not been observed earlier, and no plausible scenario can be identified, even after detailed discussions.	0.0001 (10^{-4})

Spiegelhalter (2017) gives a comprehensive review of uncertainty communication including case studies from gambling, climate change (see also section 2.2), toxicology and environmental exposures, security and intelligence, reliability, weather and natural hazard. van der Bles et al. (2019) review and discuss the use of open communication of uncertainty in technical and scientific fields. van der Bles et al. (2020) continue this work and show with experiments that open and explicit uncertainty communication facilitates a greater recognition of uncertainty among people. They concluded that explicitly communicating uncertainty only minimally decreases the trustworthiness of results.

2.1. Uncertainty communication in geotechnical engineering practice

For risk analysis of ground-related civil engineering structures such as dams, slopes, offshore energy installations, and tunnels, Table 2 was developed in 1995 and modified over the years to express uncertainty. It was developed in Norway (in English and Norwegian) to reflect the perception of the words used. The table presents a mean value and a range of values for each expression of uncertainty. The mean values were based on discussions between Norwegian and American risk experts and were first used for the analysis of dam safety. When Table 2 was established, it was found out early that there are both linguistic and societal differences in the perception of the wording used to describe uncertainty. The description terms in Table 2 are discussed as part of each new risk assessment project. The ranges of values in Table 2 were added in the early 2010s and were based on IPCC's (2012) report on managing the risks of extreme events and disasters. The verbal descriptions in Table 2 reflect the perception of the wording in western Europe. They have also been used in other countries such as Peru, Brazil and India. As part of the probability estimation, the following aspects were considered:

- Statistics from observations, model tests, laboratory and in-situ tests, analysis of data etc.
- Calculation of physical mechanisms, e.g. stability, seepage and deformation analyses.
- Earlier experience with similar constructions or processes, like internal erosion for dams, skirt penetration for offshore foundations etc.
- Discussion and consensus reached after discussions during the analyses (often in a workshop format).
- Engineering judgment and expert opinion.

The assigned probabilities need to be justified: they shall be based on a demonstrable chain of reasoning and not on speculation (Vick, 2002). Vick (2002) also expressed that elicitation processes from the collective judgment of experts, structured within a process of debate, can yield as good an assessment of probabilities as mathematical analyses. It is also not uncommon to set a range of total probabilities in the results of the analyses to reflect an uncertainty in the estimate and then use the verbal descriptors in Table 2.

Table 2: Verbal description of uncertainty and probability (mean values used in Norway and range of probabilities (after IPCC, 2012)).

Verbal description	Probability
Virtually impossible, *known physical conditions or process that can be described and specified with almost complete confidence*	0.001 (»0.0 – 0.005)
Very unlikely, *although the possibility cannot be ruled out on the basis of physical or other reasons*	0.01 (0.005 – 0.02)
Unlikely, *but it could happen*	0.10 (0.02 – 0.33)
As likely as not, *with no reason to believe that one possibility is more or less likely than the other*	0.50 (0.33 – 0.66)
Likely, *but it may not happen*	0.90 (0.66 – 0.98)
Very likely, *but not completely certain*	0.99 (0.98 – 0.995)
Virtually certain, *known physical conditions or process that can be described and specified with almost complete confidence*	0.999 (0.995 – »1.0)

The dam safety community in several countries has adopted "words of estimative probability" (i.e. uncertainty expressions) as a way of initiating its expert elicitation process for assigning probabilities to event trees associated with potential failure mode analysis. There has been occasional criticism of this practice. Nonetheless, the practice remains, and recommended tables such as Table 2 are contained in "Best Practice" guidances (e.g. U.S. Army Corps of Engineers (USACE) (2019)). Other tables describing uncertainty and probabilities were developed in different countries with different numerical values. An exemplary uncertainty communication framework from China is given in Table 3 (Li et al., 2006; Zhang et al., 2016) and it can be seen that the probability values that are assigned to the classes are remarkably different than in Table 2.

Table 3: Subjective probability estimates for risk assessment of dams in China (Li et al., 2006; Zhang et al., 2016).

Verbal description	Probability	Probability
Event is virtually unlikely	0.000001 – 0.0001	$10^{-6} - 10^{-4}$
Event is very unlikely	0.0001 – 0.01	$10^{-4} - 10^{-2}$
Event is likely	0.01 – 0.1	$10^{-2} - 10^{-1}$
Event is very likely	0.1 – 0.5	$10^{-1} - 5 * 10^{-1}$
Event is virtually certain	0.5 – 1.0	$5 * 10^{-1} - 1$

2.2. Intergovernmental Panel on Climate Change

Driven by the need to communicate complex and uncertain topics to the public and decision-makers, the IPCC published a guidance note on the "consistent treatment of uncertainties" in 2010 for their 5th assessment report (Mastrandrea et al., 2010). The proposed system has proven itself since then and is now also included in the sixth assessment report (IPCC, 2021).

The IPCC approach for characterizing and understanding uncertainty in assessment findings is a multistep procedure (Figure 1) with two central steps. First the confidence in a finding is assessed which is a function of i) the amount of evidence (i.e. observations, experiments, theory, statistics and models) and ii) the agreement between independent lines of evidence. The highest confidence is given when there is robust evidence and a high agreement within that evidence. The lowest confidence is achieved vice versa. In a second step of the IPCC approach, a probability assessment is made based on statistical or modelling analyses, other quantitative analyses or expert judgment. Probabilities are expressed through defined likelihood statements (note: IPPC uses "likelihood" synonymously with "probability") with overlapping probability classes.

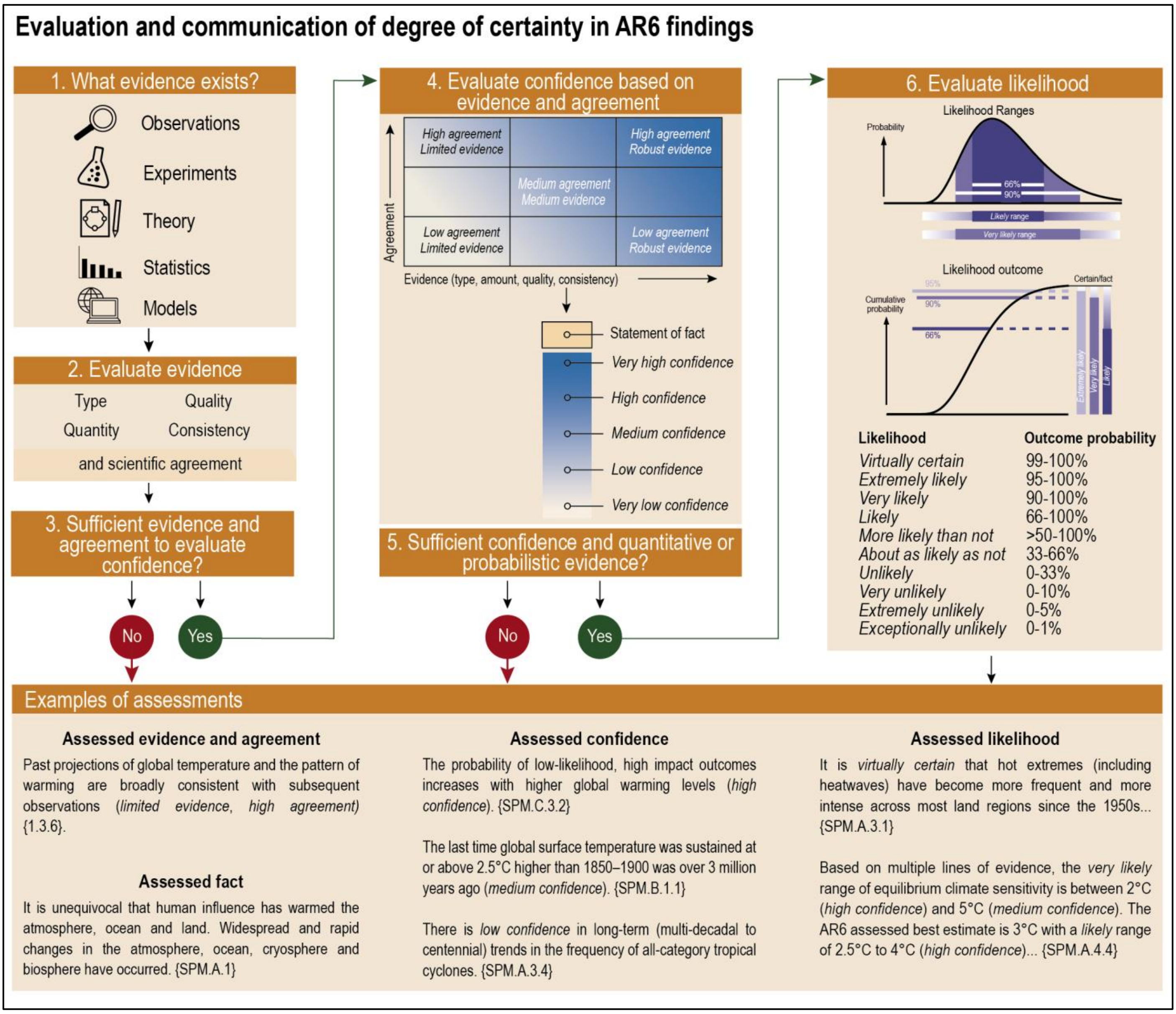

Figure 1: The IPCC's uncertainty communication framework. Box 1.1, Figure 1 in IPCC, 2021: Chapter 1. In IPCC (2021).

The IPCC itself states in the last assessment report (IPCC, 2021) that while their framework fulfils its purpose, it also faces criticism and that there is room for improvement. This especially concerns how well low-to-medium probabilities (0-66%) can be communicated. Juanchich et al. (2020) show that communicating low-medium probabilities with negations draws excessive attention on the likelihood that something will not occur instead of that it might occur (e.g. target range 0-33%, IPCC: *it is unlikely that* vs. *there is a small likelihood that*). The phenomenon that uncertainty expressions implicitly draw attention towards one end of the spectrum is known as "directionality of verbal uncertainty expressions" and is also consistent with other sources (e.g. Honda and Yamagishi (2006); Teigen and Brun (1999)).

3. Use of uncertainty expressions today

Methods of text mining were applied to i) find quantitative evidence for the suspicion that there is an increased need for uncertainty terminology in ground-related topics and ii) to identify commonly used expressions of uncertainty communication beyond those related to likelihood and probability as presented in the previous section. To this end, the expression frequency (f_e) of different uncertainty expressions was assessed for a total of 65690 abstracts from selected journals. f_e was defined as the total number of occurrences of a specific expression within the abstracts of one journal $n_{occurences}$ divided by the total number of investigated abstracts of that journal in a defined timeframe $n_{documents}$.

$$f_e = \frac{n_{occurences}}{n_{documents}} \quad (1)$$

Only exact matches of the uncertainty expressions were counted to avoid double counting. The following expressions were selected for investigation, based on the authors' experience on how uncertainty is communicated today: *certainly, definitely, dominantly, exclusive, largely, likely, locally, maybe, majority, mostly, partly, perhaps, possibly, predominantly, presumably, probably, singularly, sporadically, supposedly, unlikely*. Other terms could have been included and it also needs to be mentioned that whether these expressions are communicating uncertainty can be context dependent. Note that the chosen expressions also included words for low uncertainty (e.g. "certainly"), as well as different categories of uncertainty including probabilities (e.g. *likely, unlikely*), quantity descriptions (e.g. *most, sporadically*) or general expressions of vagueness (e.g. *maybe*). For each expression, their form as adjective and adverb – if existing – as well as their capitalized version were considered. In further analyses, the occurrences of all variations of one expression were aggregated.

The abstracts were retrieved from 23 Elsevier journals and selected so that they cover a range of subjects from engineering to geology. The abstracts were automatically accessed via the Elsevier API (Elsevier, 2024a) on Scopus (Elsevier, 2024b). Abstracts were analyzed for articles ranging from (including) 2010 to 22nd January 2024 as this time frame is considered as representative for the modern use of language in ground-related disciplines. Table 4 shows the included journals, numbers of analyzed abstracts and time frames (some journals started publishing after 2010). Note that the numbers of analyzed abstracts do not necessarily correspond to the total number of published papers of the respective journal in that time frame as i) only abstracts that were automatically retrievable via the API are included, ii) some publications do not have abstracts (e.g. discussion papers). Scopus subject areas for each journal were compiled for further assessment of expression frequencies across subject areas.

Table 4: Journals that were included in the investigation for mapping the expression frequencies for uncertainty expressions.

Journal (ISSN)	Abbreviation	SCOPUS Subject Area	Abstracts	From
Applied Computing and Geosciences (2590-1974)	ACAGS	Computer Science, Earth and Planetary Sciences	99	2019

Journal (ISSN)	Abbreviation	SCOPUS Subject Area	Abstracts	From
Cement and Concrete Research (0008-8846)	CEMCON	Engineering, Materials Science	2933	2010
Coastal Engineering (0378-3839)	CENG	Engineering, Environmental Science	1709	2010
Computers and Geosciences (0098-3004)	CAGEO	Computer Science, Earth and Planetary Sciences	2675	2010
Computers and Geotechnics (0266-352X)	COMGE	Computer Science, Earth and Planetary Sciences	4109	2010
Earth and Planetary Science Letters (0012-821X)	EPSL	Earth and Planetary Sciences	7427	2010
Earth-Science Reviews (0012-8252)	EARTH	Earth and Planetary Sciences	2497	2010
Engineering Geology (0013-7952)	ENGEO	Earth and Planetary Sciences	3719	2010
Geoscience Frontiers (1674-9871)	GSF	Earth and Planetary Sciences	1485	2010
Gondwana Research (1342-937X)	GWR	Earth and Planetary Sciences	2646	2010
International Journal of Disaster Risk Reduction (2212-4209)	IJDRR	Earth and Planetary Sciences, Social Sciences	3875	2012
International Journal of Rock Mechanics and Mining Sciences (1365-1609)	IJRMMS	Earth and Planetary Sciences	2536	2010
Journal of Rock Mechanics and Geotechnical Engineering (1674-7755)	JRMGE	Earth and Planetary Sciences	1300	2013
Journal of Structural Geology (0191-8141)	SG	Earth and Planetary Sciences	2162	2010
Journal of Wind Engineering and Industrial Aerodynamics (0167-6105)	INDAER	Energy, Engineering	2885	2010
Marine and Petroleum Geology (0264-8172)	JMPG	Earth and Planetary Sciences	4925	2010
Quaternary Geochronology (1871-1014)	QUAGEO	Earth and Planetary Sciences	1038	2010
Quaternary Science Advances (2666-0334)	QSA	Earth and Planetary Sciences	128	2020
Sedimentary Geology (0037-0738)	SEDGEO	Earth and Planetary Sciences	1911	2010
Soils and Foundations (0038-0806)	SANDF	Earth and Planetary Sciences, Engineering	1425	2010
Structures (2352-0124)	STRUCTURES	Engineering	5767	2015
Tectonophysics (0040-1951)	TECTO	Earth and Planetary Sciences	4570	2010
Tunnelling and Underground Space Technology (0886-7798)	TUST	Earth and Planetary Sciences, Engineering	3869	2010

Figure 2 shows the top 10 highest expression frequencies among the selected uncertainty expressions for the journal Engineering Geology (ENGEO). All journals analyzed with the Scopus subject areas “Earth and Planetary Sciences” and “Earth and Planetary Sciences, Engineering”, have the expression *most*, and *mostly* as the most frequently used uncertainty expression. *locally* follows on place 2 for the majority of these journals and *possibly* on place 3 for less than half of them. While it is likely that the use of the word *most* to build superlatives contributes to its prominent position, we still see that this reflects a strong need to verbally describe quantities in geoscientific subjects.

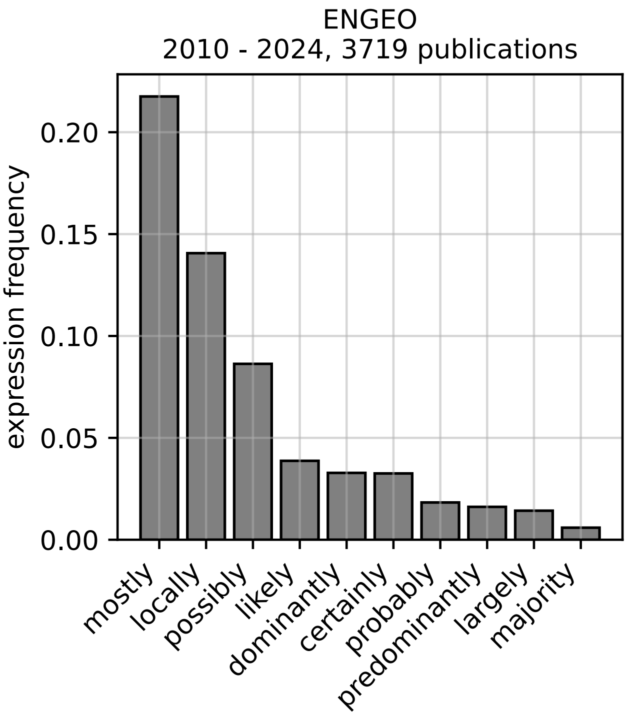

Figure 2: Top 10 uncertainty expression frequencies of the journal Engineering Geology (ENGEO) from 2010 to January 2024.

The text mining study also enables to investigate expression frequencies over time for individual words. Figure 3, for example, shows that the journals almost exclusively show no pronounced increasing or decreasing expression frequency over time for the word likely, which was also observed for other expressions.

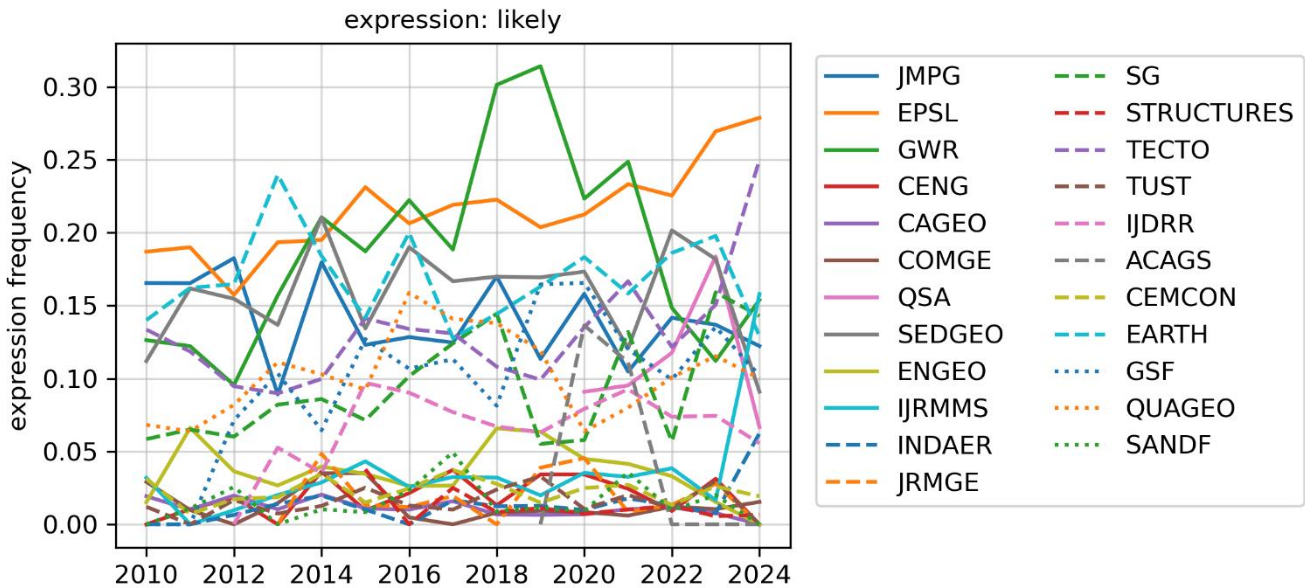

Figure 3: Expression frequencies of "likely" and its variants for different journals since 2010. See Table 4 for journal abbreviations. See Figure 4 for total averages per journal.

Finally, the total average expression frequencies (i.e. a journal's average expression frequency since 2010 or later if it started to publish after 2010) between journals were computed as the average values of the data shown in Figure 3 and shown in the bar chart of Figure 4. The bars in Figure 4 are colored according to the Scopus subject areas as an indication for the journals' main scopes. It can be observed that there is a clear increase in the usage of the above selected uncertainty expressions the more ground-related a journal's scope is. Journals with a focus on geology like "Earth and Planetary Science Letters" or "Gondwana Research" are leading in the use of uncertainty expressions, while journals with a focus on engineering topics like "Computers and Geotechnics" or "Structures" are on the lower end of their usage. It also can be observed that the three lowest ranking pure "Earth and Planetary Sciences" classified journals "Engineering Geology", "International Journal of Rock Mechanics and Mining Sciences" and "Journal of Rock Mechanics and Geotechnical Engineering" show a comparatively low expression frequency of "likely" and are ranked among other more engineering-related journals which fits to the more pronounced engineering scope of these journals.

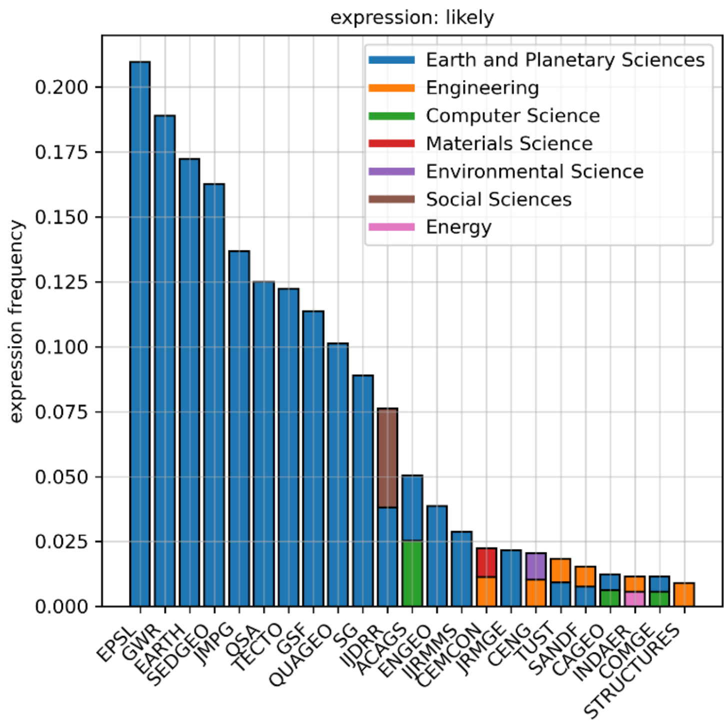

Figure 4: Total expression frequency of "likely" since 2010 for all investigated journals. Bars are colored according to the journal's "Scopus subject area". See Table 4 for journal abbreviations. See Figure 3 for yearly expression frequencies per journal.

Analyses for all journals as presented in Figure 2 to Figure 4 can be found in the Github repository in Appendix 8.

4. Proposed communication framework for ground-related uncertainty

Based on the use of uncertainty communication in other fields, the authors' experience, and the assessment of occurrences of uncertainty expressions in literature, we propose the following terminological framework. Uncertainty about ground-related findings, interpretations and observations should be communicated in a stepwise process.

- Step 1) if one wants to communicate something that is certain, then uncertainty communicating terminology should not be used as this only hinders clear communication.

- Step 2) one should assess and state the level of confidence in a statement as a function of the robustness of the available evidence vs. the agreement of that evidence. If there is insufficient confidence (i.e. medium to very low), this should be reported, and one should elaborate how a higher confidence can be obtained.
- Step 3) if the confidence in the statement is high enough, consistent terms to express uncertainty should be used.

The full flow chart of the three-step framework is given in Figure 5. To improve communication of ground-related uncertainty also beyond the English language, translations of Figure 5 are given in the appendix for these languages: German, Norwegian, Spanish, Italian, Chinese and French. The translations were made with the intention to translate the English terminology as accurately as possible. Nevertheless, it will take experience and perhaps recalibration over time to ensure that the framework works in the same way for all languages. The exact perception of the expressions also varies from country to country.

The following definitions apply:

- *Confidence*: a qualitative measure of one's trust in the validity of a finding, based on the robustness of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement between different sources of evidence (based on IPCC (2021)).
- *Probability*: how likely an individual event or broader outcome is to happen. Often used synonymously with likelihood (even though this is incorrect in terms of statistical definitions). Probabilistic information can, for example, be derived from statistical analyses of investigations and observations, parametric and probabilistic modelling such as Monte Carlo analyses, earlier experience with similar constructions or processes and expert judgment.
- *Quantity description*: A description of a proportionate share of an occurrence within a volume, area, length or piece count. The quantitative information can come from field investigations (e.g. scanning, drill core logging, geophysics), laboratory investigations (e.g. mineralogical analyses, grain size analyses) or be the result of higher-level interpretations.
- *Correlation strength*: The quality of the linear or non-linear correlation between one set of data and another.
- *Factual data:* The definition from buildingSMART (2020) applies: “The results of site investigation campaigns and documentation conducted specifically for the project and pre-existing data (other sources), including measurements and observations. Examples are borehole data, test results and field mapping, geological tunnel documentation and other surveys.” Ground-related disciplines usually have a special understanding of “facts” where, for example, a borehole log or an outcrop mapping is treated as a fact, even though these are themselves interpretations.

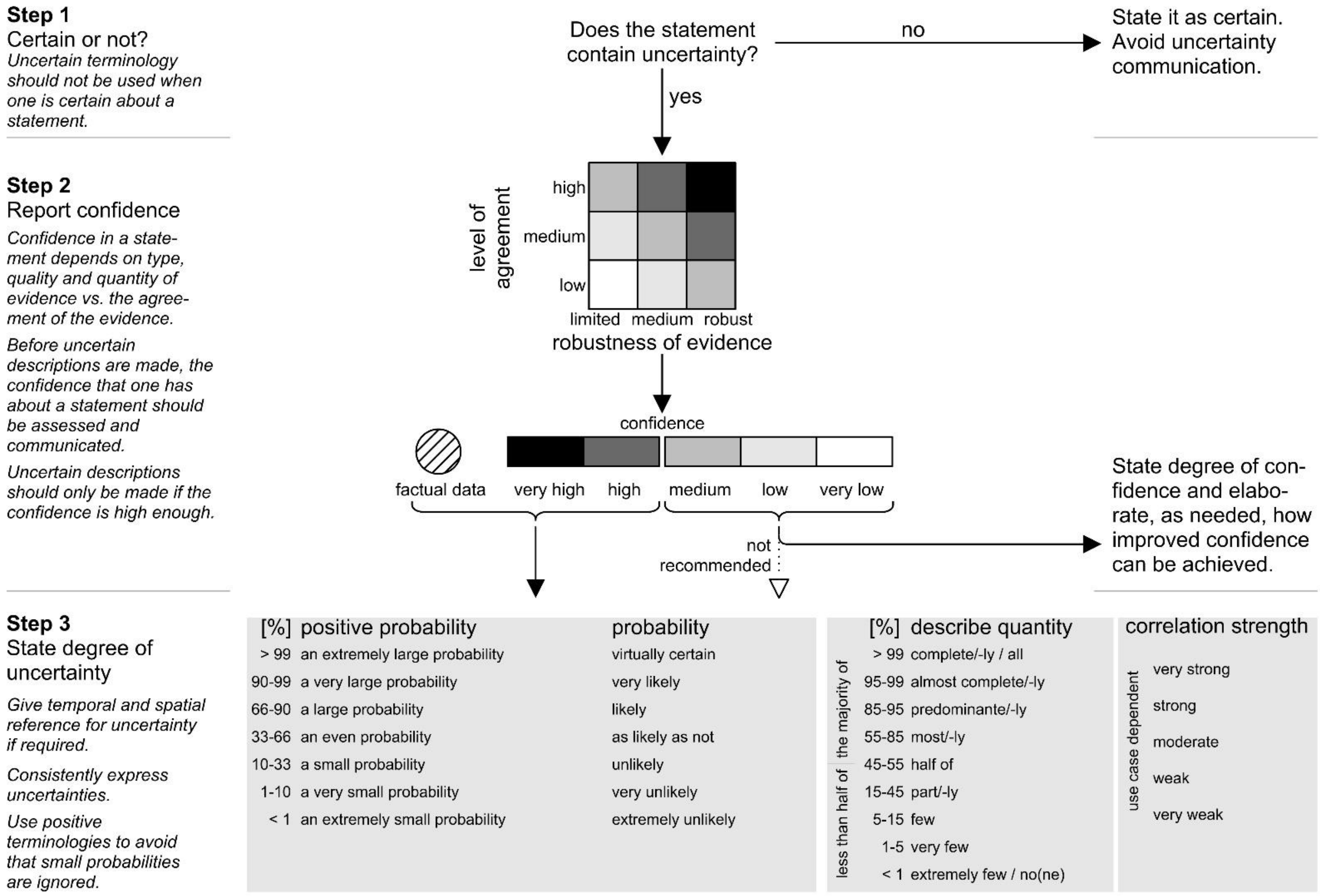

Figure 5: The proposed framework to communicate ground-related uncertainty.

It is important to highlight that the proposed uncertainty communication framework is not meant to be used to elicit quantities or probabilities from experts' statements. The proposed communication framework should be the consistent frontend to the quantities and probabilities that experts derived in various ways. Expert elicitation denotes the quantification of expert opinion in the form of judgmental probabilities (Baecher, 1999) that should be done in a systematic manner (Garthwaite et al., 2005). Besides this clarification, it needs to be highlighted that the communication framework was designed in a way to improve the clarity of communication from domain-expert to domain-expert (e.g. geologist to geologist) and to help the domain-expert communicate to non-domain-experts (e.g. geotechnicians to geologist, geologist to community mayor).

To showcase the use of the whole communication framework, an example is given in Appendix 7 where the whole section "3.3. Geotechnical Characterization" from Erharter et al. (2019) is revised in an uncertainty aware manner.

4.1. Report confidence

The *confidence* one has in a statement should be based on the robustness of the available evidence vs. how well evidence agrees with each other (see examples below). Robustness of evidence refers to the type, quality and quantity of evidence and must be estimated on a project specific basis. The confidence associated with statements about factual data (see definition above) is usually high, as they are either directly measured or in case of observations, often the product of multiple sensory perceptions (see, feel, smell, taste → high agreement) from experts that were calibrated through study, practical experience and engineering judgement (robust evidence). It is nevertheless recommended to consider and report the confidence for uncertain aspects of factual data.

The robustness of evidence should be described as *limited*, *medium* or *robust*. In cases of simple and homogeneous ground conditions, few investigation measures may yield sufficiently robust evidence, whereas complex and heterogeneous ground conditions demand a larger number and broader spectrum of investigation measures. The level of agreement refers to how well different sources of evidence point towards the same conclusion and should be specified as *low*, *medium* or *high*. This leads to the challenge that one will struggle to estimate the required amount of investigations to achieve robust evidence in case of previously unknown ground conditions as they may or may not turn out to be complex during the investigation itself. The solution is multi-phase ground investigations campaigns with an increasing level of investigation detail that allow sequential acquisition of knowledge about the ground (see also section 2.4 and especially figure 2-11 in Baynes and Parry (2022) in this context). This allows repeated checking if the results from subsequent investigations corroborate each other or not and whether further investigations are required. Therefore, both the robustness- and the level of agreement of evidence must be estimated in a project specific manner. Some projects may turn out to require one initial and coarse investigation campaign that shows that the ground conditions are in fact simple and then few additional underpinning investigations are sufficient to achieve robust evidence (the same goes for projects where there is pre-existing knowledge about the ground). The initial, coarse investigations of other projects may, however, show that the ground conditions are complex and eventually conflicting with pre-existing knowledge and therefore more sources of evidence will be required to achieve robust and mutually agreeing evidence and by that high or very high confidence.

The following examples are given to illustrate confidence assessments:

- One would have very low confidence in a ground investigation if only a few exploratory drillings are available for a comparatively large area (limited evidence) and the results of the few drillings that exist conflict with each other and / or conflict with the existing knowledge about the geology of that area (low agreement).
- In the same case, one would have medium confidence in a ground investigation if these few available exploratory drillings (limited evidence) show results that are consistent among each other and are in agreement with existing knowledge of the area (high agreement).
- The same medium confidence but on the opposite side of the chart would, for example, occur when clay related swelling pressure is to be investigated: even if one conducts all possible laboratory swelling pressure tests that are available today (robust evidence) having more than medium confidence on the design value for the swelling pressure is difficult as swelling pressure tests in the laboratory may show problematically high pressures whereas in-situ pressure observations often indicate comparatively low values (low agreement) (Kirschke, 2010; Steiner, 1993).
- The assessment of the lower boundary of an aquifer could, for example, be made with very high confidence if multiple sources (robust evidence) such as past project experience, exploratory drillings and a geoelectric survey are all in agreement with each other and show the same boundary (high agreement).

Having *low* confidence in a finding, assessment or interpretation does not mean that there is *high* confidence in its opposite and conversely. For example, if one assesses rock mass strength but only has a *limited* amount of evidence that is deemed to be in *medium* agreement with each other, then a resulting statement could be: "The rock mass strength is expected to be high (low confidence) but more investigations are required to obtain a higher confidence." The *low confidence* into that statement does not mean that one has a *high confidence* into the opposite - a low strength rock mass.

Furthermore, *very low* or *low* confidence should communicate that the best possible conclusion could not be reached with a higher confidence level at the current moment (IPCC, 2021). If a *very low* to *medium* confidence is assessed, suggestions should be made how a higher confidence can be achieved, which in most cases will refer to a higher quantity and / or more targeted ground investigations or further development of the used theory and models. In cases where even state-of-the-art investigations and analyses are insufficient to achieve a *high* or *very high* confidence (e.g. third example above), this should be explicitly reported.

4.2. State uncertainty

We only recommend making uncertainty communicating statements when one has a *high* or *very high* confidence in the statement based on the confidence assessment as elaborated in the previous section. If a *medium* or lower confidence is given, the decision basis for the uncertainty statement is likely too low. In that case, the recommended course of action is to assess and discuss how a higher confidence can be achieved (e.g. acquiring more observations) and actively communicate that instead of making an uncertainty communicating statement that has no sufficient evidence basis. If, however, an uncertainty communicating statement must be made, then it is imperative to communicate the very low to medium confidence in that statement along with it as to avoid that the receiver of the statement is under the impression that it was made with a high confidence.

The terminology of Table 5 is proposed to describe *quantities*, of Table 6 to describe *probabilities* and section 4.2.3 addresses the communication of correlation strength. Whenever possible, a more comprehensive presentation than the scales given below should be provided, for example, by providing complete probability distributions or percentile ranges. The proposed expressions were chosen so that they are as neutral as possible and do not contain additional meanings. For example, low quantities are sometimes described as "there are singular occurrences of…" in which case "singular" communicates a low quantity but may also be understood as "spatially heterogeneous", or "patchy". If, however, expressions other than the ones in Table 5 and Table 6 need to be used, then their quantitative or relative meaning should be defined.

In both cases of descriptions of *quantities* and *probabilities*, a temporal or spatial reference must be provided as the uncertainty communicating statement is relative in nature and meaningless otherwise. For example, the extent of a project area or the length of a tunnel must be defined if one describes whatever applies to "*most of*" it; if one states "It is very likely that the slope will fail" it must also be defined in which timeframe. Providing these references can be done either in combination with the specific statement or in a general manner at a suitable place in the text if there are multiple references to it.

4.2.1. Quantity descriptions

The expressions in Table 5 describe quantities in a consistent way. All classes are non-overlapping except for the classes “>50 % - *The majority of*” and “< 50% - *Less than half of*” which can be used as an option in very uncertain cases. The differences between the two boundary classes (i.e. > 99 %, resp. < 1 %) and the next classes is the smallest from all class differences, but it is seen as necessary to have two specific classes to describe either a complete quantity or the complete absence of something.

When one describes quantities, care must be taken to exactly specify what the quantity relates to. In cases with more than two variables, Table 5 needs to be mathematically adjusted. For example, if a drill core consists of 40% rock type A, 30% rock type B and 30% rock type C, then it would be correct to specify “The drill core consists in part of rock type A, in part of rock type B and in part of rock type C.” in relation to the total core length. With respect to the rock types themselves, however, it would be correct to state that “rock type A constitutes the majority of rock types in the drill core” because the amount of rock type A is > 33% in this three-variable example.

Table 5: Terminology to communicate volumetric, areal, or countable quantities of occurrences.

Quantity [%]	**Description**	**Example**
> 99	Complete/-ly / All	The construction pit is completely located in silty clay.
95-99	Almost complete/-ly	The outcrop was almost completely made of weathered granite.
85-95	Predominant/-ly	Gabbro consists predominantly of plagioclase.
55-85	Most/-ly	Most of the project area is covered in glacial deposits.
> 50	The majority of	The majority of the slip surface is at a depth of 50 meters below ground.
45-55	Half of	Half of the drillings encountered sedimentary rocks.
< 50	Less than half of	The water’s conductivity exceeds 3000 µS/cm in less than half of the wells.
15-45	Part/-ly	The soil type A1 partly contains silt.
5-15	Few	Pyrite was observed in few locations of the thin section.
1-5	Very few	Very few anhydrite was observed in the tunnel face.
< 1	Extremely few / No(ne)	Flowing ground was encountered in extremely few tunnel sections.

4.2.2. Probability

As opposed to the IPCC framework but in agreement with Table 2, the proposed ranges of *probability* (Table 6) are non-overlapping to set clear boundaries for each probability term and the number of classes is reduced. In cases where a finer discrimination of probability classes can be applied (e.g. due to extensive data) the use of more and / or more use-case specific classes is however encouraged. In cases where probabilities span over multiple orders of magnitude, the whole classification needs to be adjusted towards a logarithmic scale and Table 1 and Table 3 could serve as examples.

Furthermore, the authors want to promote the use of positive uncertainty language for ground-related uncertainty since low-probability occurrences or events may have the highest consequences, thus attention should be drawn onto them and not directed away from them. For example, consider how these two statements might be perceived differently even though they describe the same probability of 1-10%: "*It is very unlikely that another rock fall greater than 100 m³ will occur within the next week*" vs. "*There is a very small probability that another rock fall greater than 100 m³ will occur within the next week*". While in the former case, the attention is drawn towards the impossibility of the rock fall event, in the latter case, the attention is drawn towards the possibility that it might occur, thus accentuating the need to avoid potential damage to property and life. Accounting for that, positive probability terminology based on Juanchich et al. (2020) is proposed.

Table 6: Terminology to communicate probabilities of events or broader outcomes and positive expression alternatives.

[%]	Probability	Positive probability	Example
>99	Virtually certain	An extremely large probability	It is virtually certain that the samples will be disturbed with the chosen sampling technique.
90-99	Very likely	A very large probability	It is very likely that the slope will fail within the next 6 months.
66-90	Likely	A large probability	It is likely that the deformations will exceed 2 mm / week in the first 3 days after the excavation.
33-66	As likely as not	An even probability	There is an even probability that methane gas will be encountered within the next 2 km of excavation.
10-33	Unlikely	A small probability	There is a small probability that the ground water level will exceed the defined high ground water level in spring.
1-10	Very unlikely	A very small probability	There is a very small probability that another rock fall with ≥ 100 m³ will occur within the next two days.
<1	Extremely unlikely	An extremely small probability	There is an extremely small probability that another earthquake of magnitude 7 or greater will occur in the next ten years.

4.2.3. Strength of correlation

Fixed ranges for verbal descriptions of correlation strengths have been proposed by some authors (Evans, 1996) but this is not seen as meaningful in the ground-related context. The quality of a correlation depends on the underlying nature of the correlation (i.e. linear vs. non-linear), on the use case and the origin of the data. Synthetic data from simulations typically contains less noise than real-world measured data and therefore, it results in comparatively high correlation coefficients (see e.g. Erharter (2024) for correlations of synthetic rock mass properties). Cone penetration test interpretation relies heavily on correlations between in-situ- and mechanically derived values but whether the correlation can be seen as strong or weak depends on many factors such as the investigated material (Robertson and Cabal, 2022). Tunnel boring machine operational data is increasingly used to derive the advance conditions from it (Erharter et al., 2023; Heikal et al., 2021) which also often entails correlation analyses but as the data is a mixed signal from many sources (rock mass, machine, operation), it is very noisy and comparatively low correlation coefficients could be counted as strong.

We therefore recommend that correlation strength is consistently communicated using the following terms: i) very weak, ii) weak, iii) moderate, iv) strong, v) very strong. As given above, the underlying quantitative thresholds are to be defined on a use case specific basis, but in general it is recommended to set higher thresholds for less noisy data.

For example, assume that a correlation is analyzed with a metric where 0 implies no correlation and 1 full correlation. In case the data does not contain a lot of noise (e.g. as it often is the case for synthetic data), then the thresholds may for example be set to: very weak … 0.5, weak … 0.65, moderate … 0.75, strong … 0.85, very strong … 0.95. In case of a very noisy dataset (e.g. as it often is the case for observations from on-site geological mapping), it could be more appropriate to set the same thresholds to 0.2, 0.35, 0.5, 0.65, 0.85, respectively. In any case, the decision basis and rational behind setting the thresholds should be justified and transparently communicated and the reasons for different correlation strengths should be explained.

5. Conclusion and outlook

The past years have shown a remarkable increase in interest in ground-related uncertainty and technical aspects of the topic are being approached from many sides. Possibly related to the technical focus of ground-related disciplines, the verbal expressions of ground-related uncertainty have not found attention yet and words such as *likely*, *mostly* etc. are used as authors see fit even though they are usually connected to real quantities or probabilities.

This paper proposes a consistent three-step terminology to express ground-related uncertainty in scientific and technical documents. A three-step procedure is introduced where i) certain statements are made as such, ii) the confidence in a statement is qualitatively assessed and reported and iii) probabilities are stated or quantities or correlation strengths are qualitatively described. The proposed system should on the one hand serve as a guideline for practitioners and academics alike, but on the other hand also generally draw more attention to the verbalization of uncertainty in our field. The objective of this paper is to bring attention to the topic and encourage further discussion of it. Explicitly and clearly communicating uncertainty with well-defined terms increases transparency and understanding of complex ground-related topics and does not diminish trust into results (van der Bles et al., 2020). After coming to an agreement about the definitions and the magnitude order of the "linguistic variables" the next step could include applying fuzzy logic or Bayesian methods in connection with the terminology. Thus, the consequences of the coaction of different parameters could be evaluated.

The International Association of Engineering Geology (IAEG) recommends differentiation of the engineering geological model reporting into a) factual information and observations, b) interpretations including conceptualizations and c) opinions (Baynes and Parry, 2022). The proposed uncertainty language can be used to increase the transparency and trustworthiness of all of these reports and we see it as especially relevant and directly applicable for a) and b) as in engineering geology both factual information and interpretation may be affected by ground-related uncertainty (see explicit elaboration on this topics in section 4). In case of c) opinions, it might be more challenging to rigorously apply the herein proposed communication framework, but we nevertheless encourage to also communicate opinions in a consistent and transparent way and for example differentiate between different strengths of opinions or explicitly assert a credence to an opinion.

The text mining study that is presented in section 3 quantitatively underpins the need for improved uncertainty communication in ground-related fields. The executed text mining study, however, has a limited scope and served the purpose of underlining the relevance of uncertainty communication in this paper. Follow up text mining studies are encouraged that could encompass i) a broader selection of journals, ii) more uncertainty terms and / or whole phrases, iii) full texts of publications instead of abstracts, iv) using modern natural language processing techniques such as large language models for text analyses to consider contexts.

It is important to remember that communication depends on local culture and the perception of the words used for the verbal description of uncertainty. Therefore, a system should always be put in context of those using and applying the scale of uncertainty descriptors. While the proposed system has yet to prove its practical applicability through future projects, it is a first step to improve the clarity of communicating ground-related uncertainty.

Acknowledgements

Mr. Andreas Hofbauer's efforts for critically reviewing the manuscript from a linguistic point of view are acknowledged. Feedback to the preprint of this paper was considered and eventually included. Thanks for the preprint review go to Gregory Baecher, Nezam Bozorgzadeh, Pete Quinn, Timo Schweckendiek, Andreas Botnen Smebye, Marco Uzielli and Herbert Einstein. Gratitude for translating the terminological flowchart of Figure 5 go to Andreas Botnen Smebye (Norwegian), Ana Page (Spanish), Luca Piciullo (Italian) - all from NGI - and Dr. Yuanqin Tao from Singapore University of Technology and Design (Mandarin Chinese).

CRediT Author statement

Georg H. Erharter: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project Administration, Software, Visualization, Writing – original draft; **Suzanne Lacasse**: Conceptualization, Methodology, Writing – original draft; **Franz Tschuchnigg**: Conceptualization, Methodology, Writing – original draft; **Ewald Tentschert**: Conceptualization , Writing – review & editing; **Dennis Becker**: Conceptualization, Writing – review & editing; **Kok-Kwang Phoon**: Conceptualization, Writing – review & editing;

Declaration of competing interest

The authors declare no conflicts of interest.

Funding statement

No funding was received for conducting this study.

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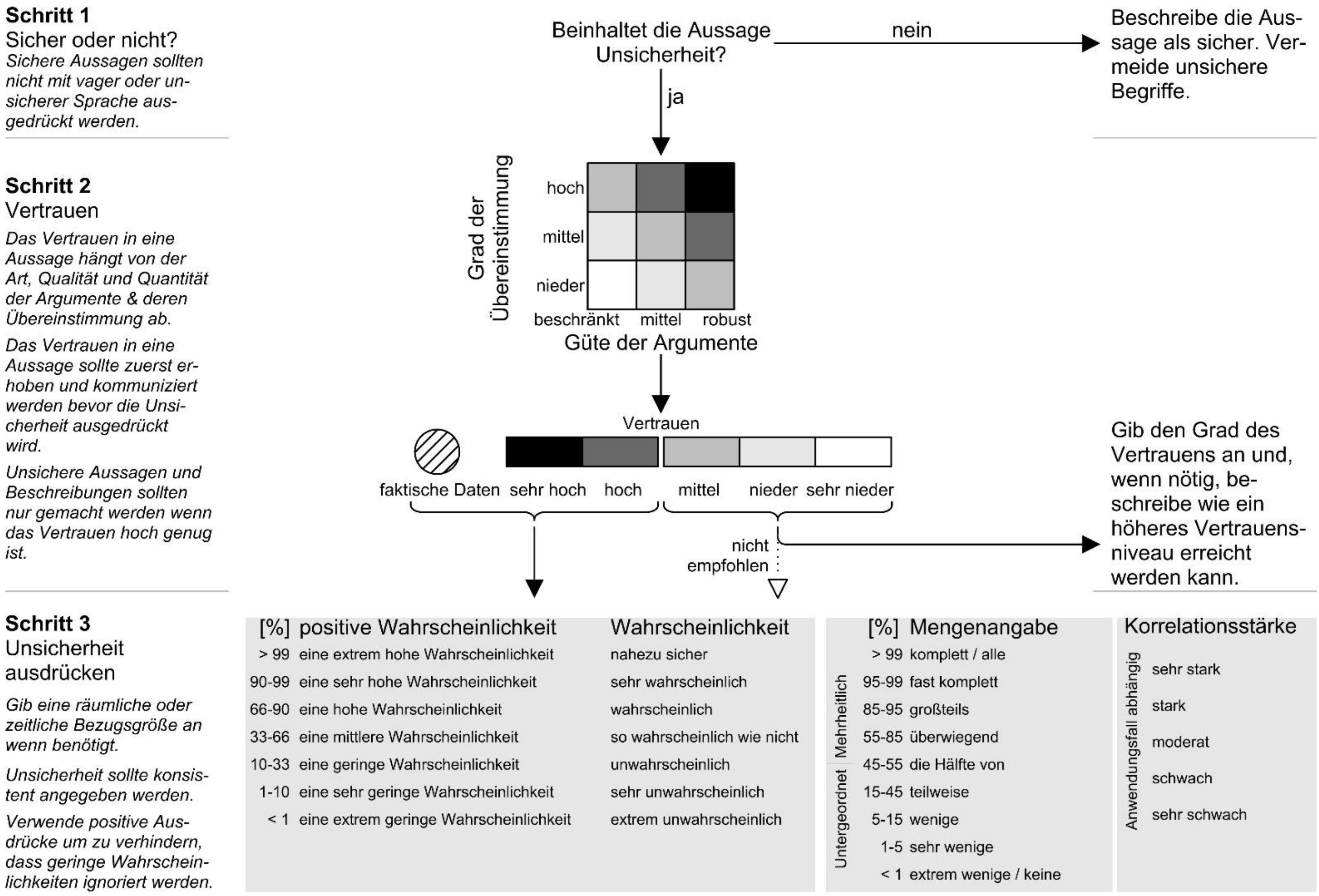
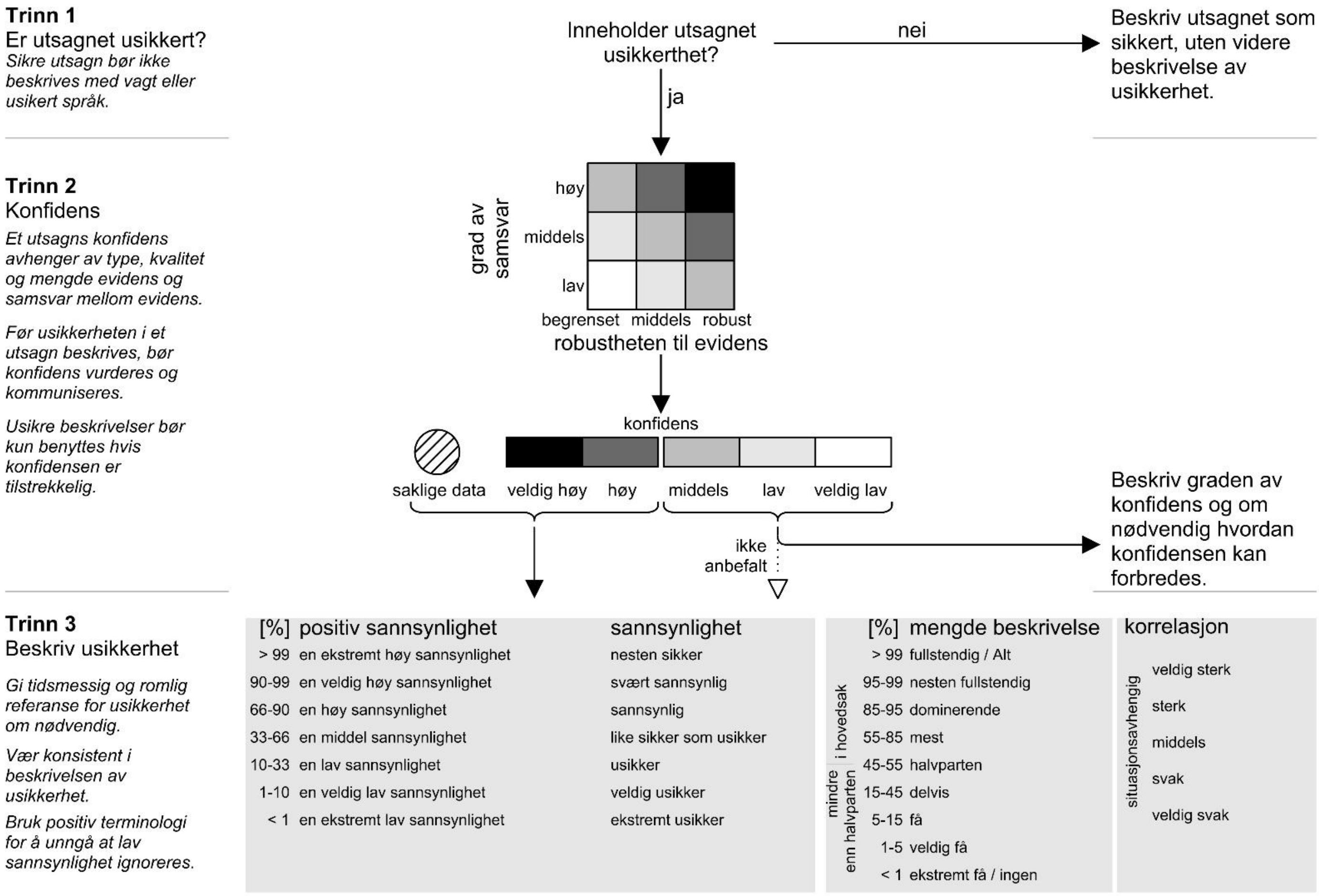
Appendix

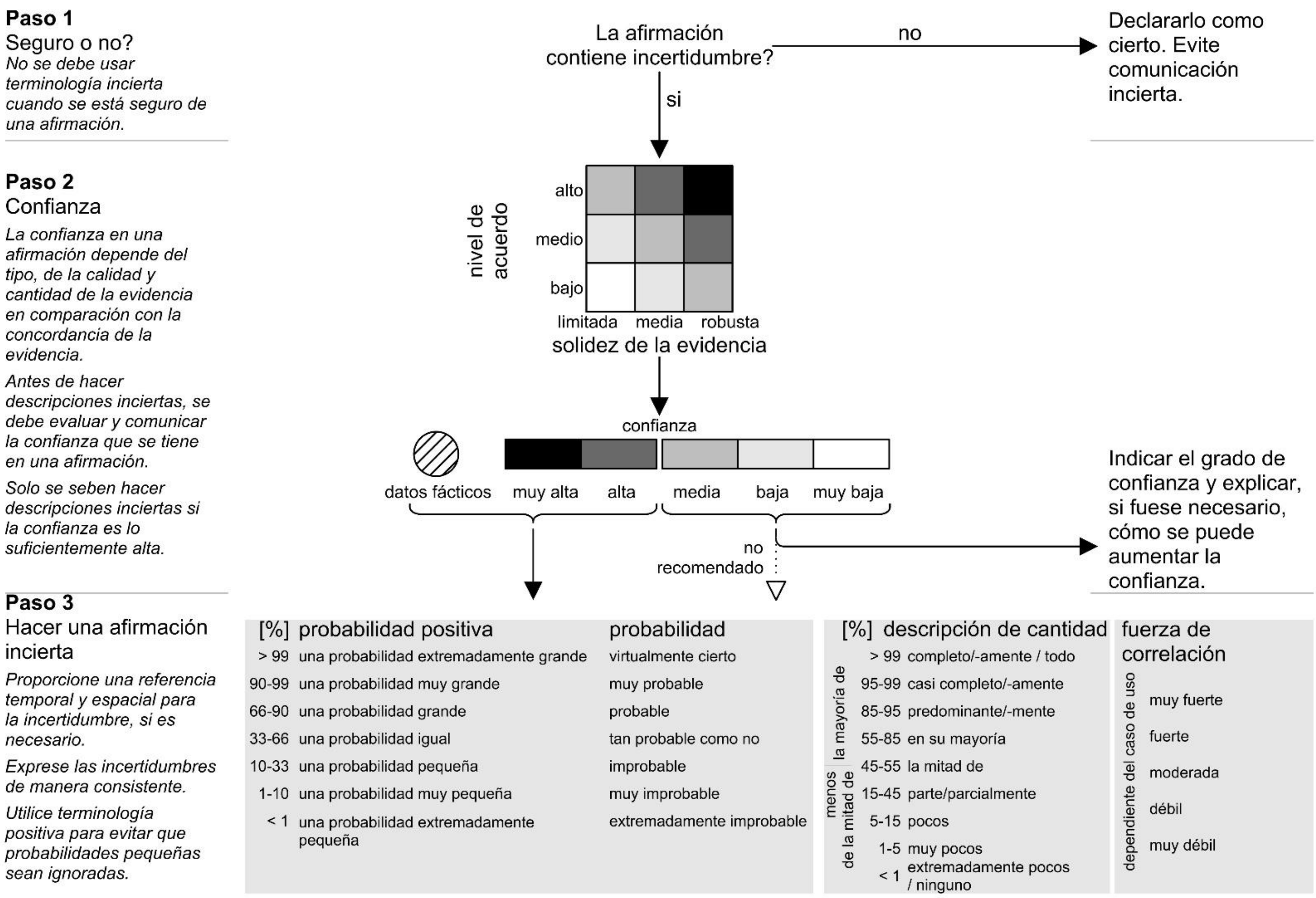
Appendix 1: German translation of Figure 5.



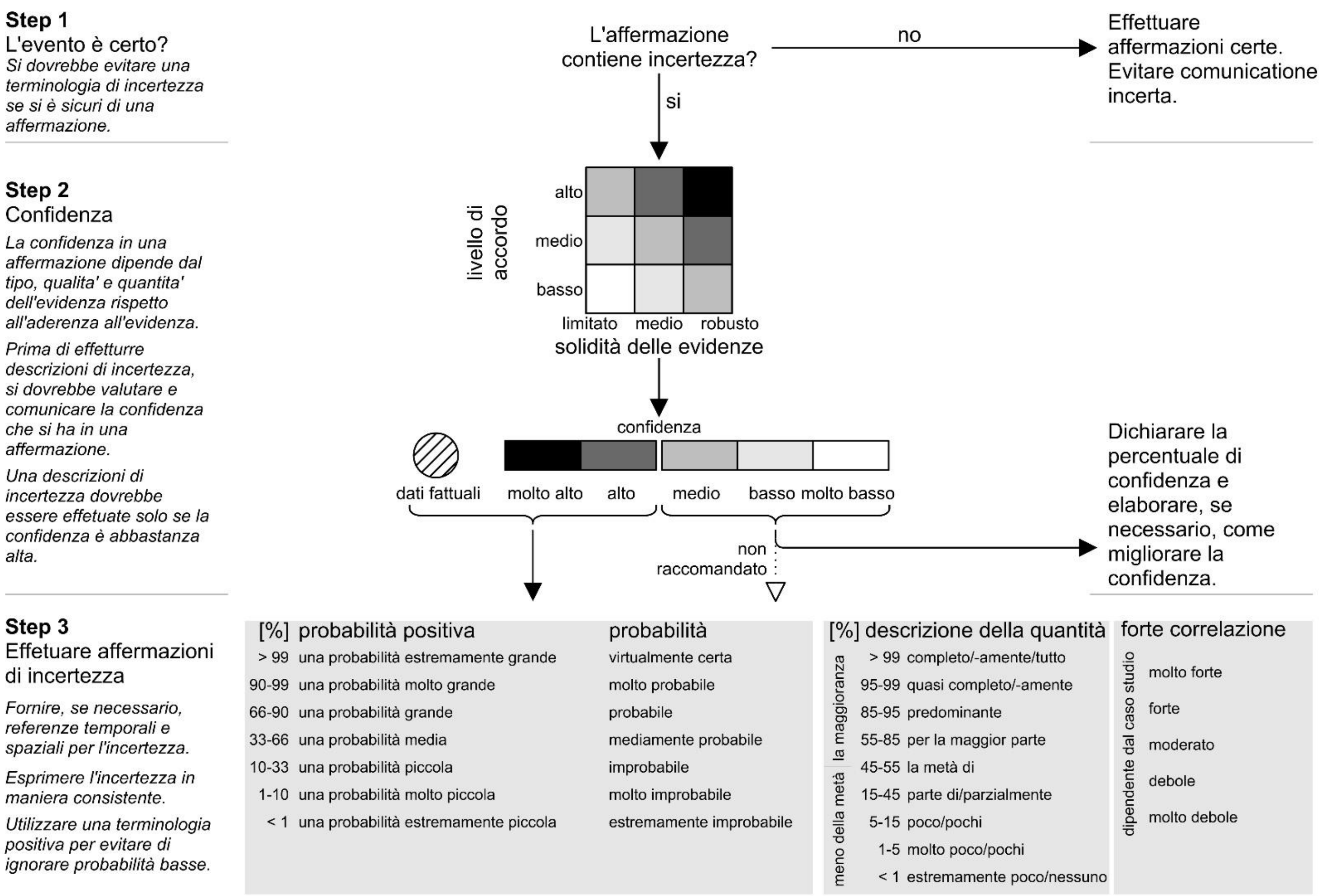
Appendix 2: Norwegian translation of Figure 5.



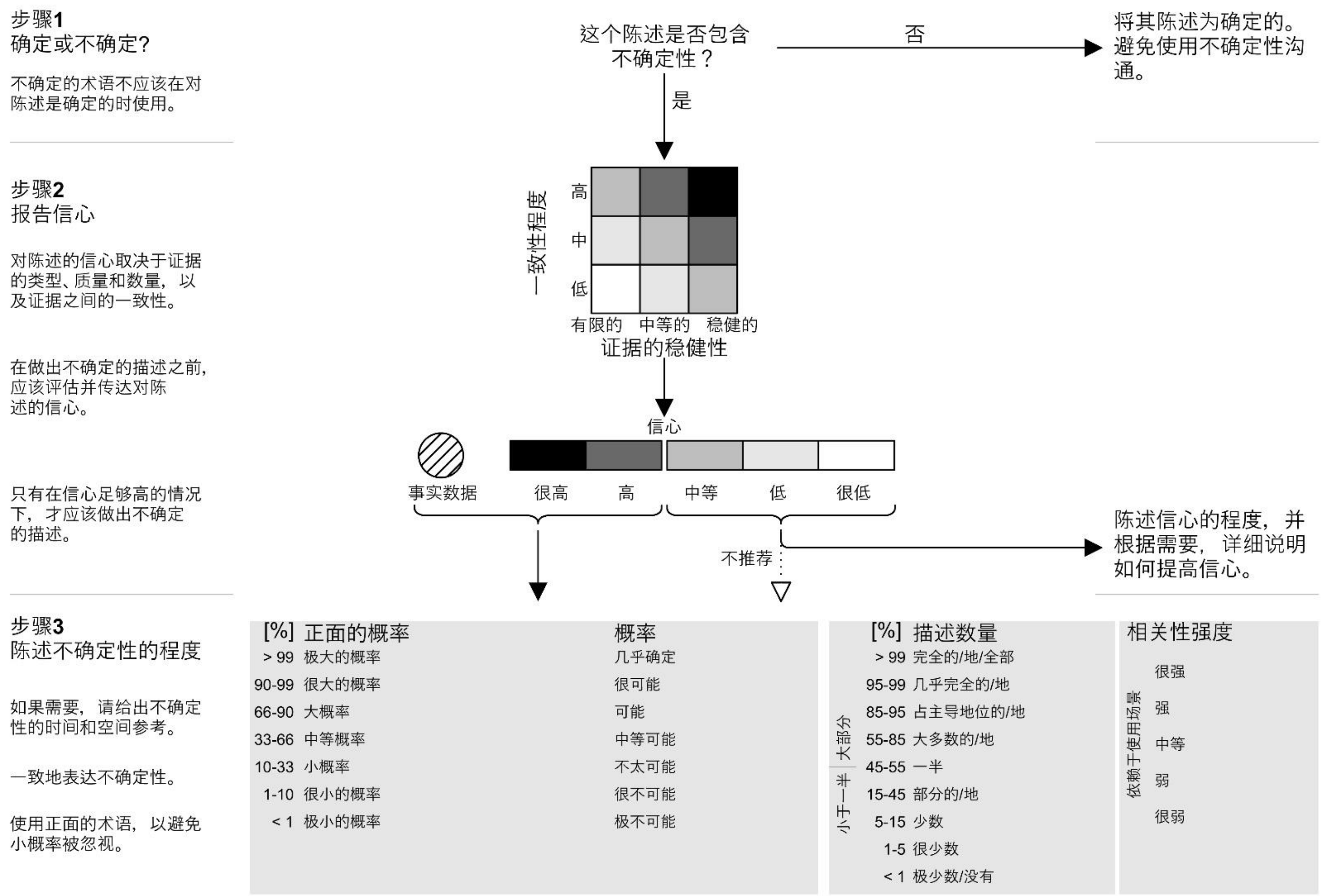
Appendix 3: Spanish translation of Figure 5.



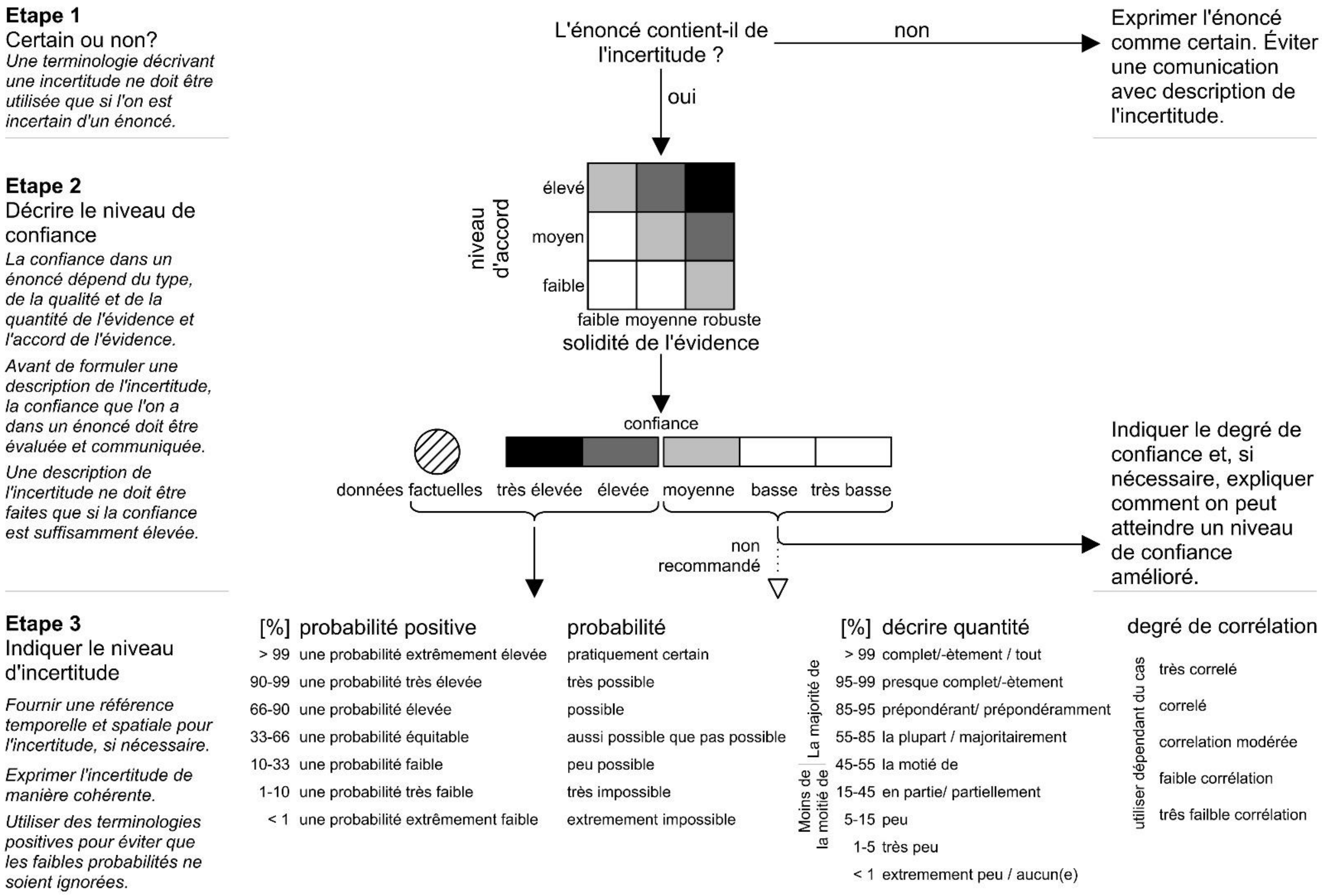
Appendix 4: Italian translation of Figure 5.



Appendix 5: Mandarin Chinese translation of Figure 5.



Appendix 6: French translation of Figure 5.



Appendix 7: Example for an application of the proposed uncertainty communication framework.

This example is provided to showcase how a text with ground-related content can be written in an uncertainty communicating manner. The text originates from Erharter et al. (2019) and contains a geotechnical characterization of a rock mass in the transition zone between rock and soil. First the original text of the section under consideration is provided, then a version that conforms with the proposed uncertainty communication framework and lastly a commentary to the uncertainty language. The original text is unmodified except for the citation style which was merged with the present publication so that citations can be found in the overall reference list of this paper. For references to tables and figures, the reader is referred to the original version of Erharter et al. (2019). This example was chosen as it is a published case study of a real engineering geological investigation from a practical project. At the time of publication and project work, no mature communication framework for ground-related uncertainty was available. While only the original publication is to be seen as valid in terms of technical content, the herein shown revision of the text is based on the technical knowledge of the first author who is the same for both the present paper and Erharter et al. (2019).

<u>Original text:</u>

In Table 1, results of the geotechnical laboratory tests are presented. Uniaxial compressive strengths (UCS) are based on uniaxial and triaxial compression tests, values for cohesion (c) and friction (ϕ) on triaxial compression tests and the Cerchar Abrasiveness Index (CAI) was determined after (Cerchar, 1986). To achieve more statistically significant values, the laboratory results of the last investigation campaign 2006 were also incorporated into the analysis. Due to the above-mentioned difficulties in sample acquisition and test execution, the results must be interpreted with caution.

The UCS, cohesion, friction angle, tensile strength and CAI generally increase the more sandstone a sample contains. The observations are also in good accordance with field rock strength determinations according to ÖNORM EN ISO 14689-1 (Österreichisches Normungsinstitut, 2019). Based on them, thick sandstone layers have a "medium high" rock strength (25 to 50 MPa) and marls range from "medium weak" (12.5 to 25 MPa) down to "extraordinarily low" (0.6 to 1 MPa). This broad range of UCS values below 25 MPa also characterizes the UAFm as a typical "hard soil – soft rock" material (i.e. material in the transition between rock and soil) (Österreichisches Normungsinstitut, 2019).

Nevertheless, the limited number of tests and the observed high variability of the results still leave uncertainties regarding the distribution of possible rock strengths. Accounting for this, 80 point load tests (PLT) were conducted and analysed. Although different sources recommend against the use of PLTs for soft rocks (Hoek et al., 2005; Thuro, 2010), they are seen as an additional source of information to investigate the scattering of rock strengths. No difference between marl, marl-sandstone or sandstone was observed with the PLTs. As this application of PLTs was not done under standard test settings, no UCS values were calculated from the PLTs. The results show a right skewed distribution with a median point load index (IS) of 1.12 and a maximum of 5.43 (Figure 4). This means that the majority of results is situated in the low-strength area with some outliers of higher strength which confirms the general observation of a weak but heterogeneous rock mass.

Uncertainty communicating revision – comments are indicated with superscripts:

In Table 1, results of the geotechnical laboratory tests are presented. Uniaxial compressive strengths (UCS) are based on uniaxial and triaxial compression tests, values for cohesion (c) and friction (ϕ) on triaxial compression tests and the Cerchar Abrasiveness Index (CAI) was determined after (Cerchar, 1986). To achieve more statistically significant values, the laboratory results of the last investigation campaign 2006 were also incorporated into the analysis. Due to the above-mentioned difficulties in sample acquisition and test execution, the results must be interpreted with caution.

The UCS, cohesion, friction angle, tensile strength and CAI generally increase the more sandstone a sample contains (very high confidence)[1]. The observations are also in good accordance with field rock strength determinations according to ÖNORM EN ISO 14689-1 (Österreichisches Normungsinstitut, 2019). Based on them, thick sandstone layers have a "medium high" rock strength (25 to 50 MPa) and marls range from "medium weak" (12.5 to 25 MPa) down to "extraordinarily low" (0.6 to 1 MPa)[2]. This broad range of UCS values below 25 MPa also characterizes the UAFm as a typical "hard soil – soft rock" material with a very high confidence[3] (i.e. material in the transition between rock and soil) (Österreichisches Normungsinstitut, 2019).

Nevertheless, the limited number of tests and the observed high variability of the results still leave uncertainties regarding the distribution of possible rock strengths. Accounting for this, 80 point load tests (PLT) were conducted and analysed[4]. Although different sources recommend against the use of PLTs for soft rocks (Hoek et al., 2005; Thuro, 2010), they are seen as an additional source of information to investigate the scattering of rock strengths. No difference between marl, marl-sandstone or sandstone was observed with the PLTs[2]. As this application of PLTs was not done under standard test settings, no UCS values were calculated from the PLTs. The results show a right skewed distribution with a median point load index (IS) of 1.12 and a maximum of 5.43 (Figure 4). This means that the majority of results[5] is situated in the low-strength area with some outliers of higher strength which underpins that the UAFm in the project area is very likely to be a weak but heterogeneous rock mass (high confidence)[6].

Commentary to uncertainty communicating revision:

[1] A very high confidence is assigned to this statement as it is based on multiple different geotechnical laboratory tests and field observations (i.e. robust evidence) that all indicate increasing values (i.e. high agreement).

[2] A confidence statement could be assigned to observations like these but this is not strictly necessary for clearly factual data as described in section 4.1 and it also would not help the readability of the text to do so. For the sake of consistency, the proper way to address this is to include a statement at an appropriate place (e.g. the beginning of the chapter or paper) that clarifies the confidence level for factual observations like field-based strength assessments.

[3] This statement was made as the product of multiple laboratory investigations and field observations (robust evidence) that are in accordance with each other and the literature (high agreement).

[4] This statement can serve as an example for step 1 of the proposed uncertainty communication framework, which states that uncertainty communicating language should not be used for certain things. In this case it would be confusing

to state, for example, "*Accounting for this, many more point load tests were conducted and analysed*." as the number of tests is certain.

[5] Note the uncertainty language related to quantities (see Table 5).

[6] The final characterization of the rock mass is a prognosis towards the expected nature of the rock mass during project execution. As it is a prognosis, a probability statement (here: "it is very likely that…") is in place to sufficiently communicate the certainty that the experts have about the prognosis. The base for this probability statement in this case is expert judgement. The "high confidence" that is assigned to the whole uncertainty statements results from the available evidence / data at the time of this specific engineering geological investigation, before any construction has started, where multiple sources of evidence (robust evidence) all pointed in the direction (high agreement) that the rock mass will be as it is described in the text.

Appendix 8: Supplementary information from the text mining study.

Extended analyses and figures of the text mining study are available in the following Github repository:

https://github.com/geograz/Ground-Related-Uncertainty-Communication