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Managing uncertainties in the geotechnical design of climate change resilient infrastructures

Gérer les incertitudes dans la conception géotechnique d'ouvrages résilientes au changement climatique

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ABSTRACT: The design of geotechnical infrastructures is the outcome of a qualitative interpolation of a series of factors, from the feasibility study to the final design phase. It is good practice to start the geotechnical assessment from the geo-morphological data available at the studied area. This is combined afterwards with available information from surrounding projects, additional geotechnical investigations and professional experience. The overall outline of the design is provided by technical standards, other than by the needs of customers and society. One of the challenges that the geotechnical engineer encounters during the design is to find the correct balance between those decision factors, especially in areas where the risk for geohazards may be relevant both for the project itself and for the socio-economic development of the area. Furthermore, it is more and more acknowledged that uncertainties in geotechnical design also need to be addressed in relation to the impact of climate change on structures. This paper presents an overview of the current climate change adaptation strategies for geo-structures in Europe, highlighting the need for scientific research for the implementation of methodologies centred on geotechnical engineering practice and design. Hence, it invites to discuss at a more practical level about the future needs for conceiving geotechnical infrastructures resilient to the effects of climate change.

RÉSUMÉ: La conception des infrastructures géotechniques est le résultat d'une interpolation qualitative d'une série de facteurs, depuis l'étude de faisabilité jusqu'à la phase de conception finale. Il est de bonne pratique de démarrer l'évaluation géotechnique à partir des données géomorphologiques disponibles dans la zone étudiée. Ceci est ensuite combiné avec les informations disponibles sur les projets environnants, des enquêtes géotechniques supplémentaires et l'expérience professionnelle. Le cadre de la conception est défini par des normes techniques, autres que par les besoins des clients et de la société. L'un des défis de l'ingénieur géotechnique est de trouver le bon équilibre entre ces facteurs de décision, en particulier dans les zones où les géorisques peuvent être pertinents à la fois pour le projet lui-même et pour le développement socio-économique de la zone. Ensuite, il est de plus en plus évident que les incertitudes dans la conception géotechnique doivent également être prises en compte en ce qui concerne l'impact du changement climatique sur les structures. Cet article présente un aperçu sur les actuelles stratégies d'adaptation au changement climatique pour les géostructures en Europe, en soulignant le besoin de faire de la recherche pour la mise en œuvre de méthodologies centrées sur la pratique et la conception géotechnique. Ainsi, il invite à discuter des besoins futurs pour concevoir des infrastructures géotechniques résilientes aux effets du changement climatique.

Keywords: Climate change adaptation; reliability; sustainability; uncertainties; geotechnical design.

1 INTRODUCTION

Climate change is the greatest global health threat facing humanity in the 21st century, as stated by the World Health Organization in Health and Climate Change (2018). The European Commission has committed to be climate-neutral by 2050, by establishing a set of measures through the European Green Deal (2019) and in line with the long-term strategies in the Paris Agreement (2015). The European Commission adopted its new strategy to become climate resilient by 2050 in the EU Climate Adaptation Strategy (2021).

Despite the international commitment to cut net global emissions to zero by 2050, average global temperature will increase because of a raising concentration of greenhouse gas emissions in the atmosphere and governments are challenged to limiting the global temperature rise to 1.5°C (International Energy Agency, 2021). In this context, the outlined decarbonization roadmap needs to be addressed faster and with more efficient solutions.

Climate change signals (i.e., a general increase in temperature and a changing precipitation pattern) have been observed in Europe, with a different degree of impact on geo-structures throughout the region (Insana et al., 2021; IPCC, 2023). To deal with the changing frequencies and intensities of environmental hazards induced by climate change, geotechnical engineers need to rationally consider climate change when designing a new structure. However, it remains a challenge to assess and quantify the impact of climate change on geo-structures. In this view, reliability and risk-based approaches that account for uncertainties in climatic loads and soil strengths are useful tools for engineering recommendations and final decisions.

This paper provides a panoramic of the alternative strategies and methodologies to tackle climate change effects on geo-structures. Relying on a "factor of safety" design approach and conservative assumptions (especially when in lack of geotechnical and environmental data) is not considered a viable way in the actual environmental situation. Thus, this short review aims at enhancing the discussion on the future needs of the industry to design climate change resilient geotechnical infrastructures.

2 CLIMATE CHANGE ADAPTATION OF GEO-STRUCTURES

2.1 Causal chain mapping of climate change impacts on geotechnical infrastructures

Concern for environmental issues in Europe arose in the second half of the 19th century, when people became more and more aware of environmental pollution and damages to nature following the Industrial Revolution. This is also the background of the first United Nations Conference on the Human Environment, held in Stockholm in 1972 (UN Chronicle, 2007). Protecting ecological integrity became the core of the discussion and, hence, economic and social development happened to be constrained by environmental limits. This led to the concept of sustainable development and, hence, to environmental sustainability (Our Common Future, 1987, From One Earth to One World §I-3 and Part I §2-I). The latter was, then, defined as the ability to maintain an ecological balance in our planet's natural environment and conserve natural resources to support the wellbeing of current and future generations (Our Common Future, 1987; Paris Agreement, 2015).

Insana et al. (2021) presented an overview of research and literature review studies conducted in the last three decades on climate change impact on geo-structures. Their research shows that, in Europe and in most parts of the world, the concern is mostly focused on natural and engineered slopes, and far outnumbers those dealing with geo-structures. However, the concern over the impact of climate change on onshore geotechnical infrastructures has been rising in the last decade, especially in Europe. This is shown in the analysis carried out by Gariano et al. (2016) and updated by Insana et al. (2021). Geoscientists and engineers are analysing and mapping the causal chain of climate change impacts on geo-structures.

An in-depth study was conducted by Insana et. al. (2021) with regards to European regions. The research shows how climate change signals can have multiple effects on geotechnical and geological properties. Hence, the instability of slopes is just the visible output of a series of processes in the ground, groundwater, and vegetation, which leads to soil properties degradation. The survey conducted in this research shows that the most relevant impacts of climate change for geo-structures in Europe are the following: instability of natural and engineered slopes, damage/failure of engineered structures from flooding, and overtopping/breaching of dikes and levees.

There are many climate change features that have been identified in the context of climate change scenarios. Vardon (2015) and Vahedifard et al. (2016) provide an overview of climate change impacts on geotechnical infrastructures.

2.2 Climate change adaptation strategies related to geo-structures

Strategic documents on climate change adaptation (CCA), such as national adaptation plans (NAPs) and related action plans, have been initiated and drafted by most of the countries all over the world, as recommended in COP 16 (Conference of the Parties to the United Nations Framework Convention on Climate Change at its 16th Session, 2021). NAPs and related actions drafted by European countries are aligned one to another, and they refer to CCA of geo-structures with regards to damages of infrastructures (roads and rails) as a cause of instability of slopes, soil erosion, soil subsidence, and flooding. However, as highlighted by Insana et. al. (2021), specific strategies for geotechnical CCA are lacking. Put differently, strategies developed for adaptation of geo-structures are not centred on geotechnical engineering practice and design, but more on the consequences of climate change on natural hazards.

In the actual context of climate change, risk assessment and monitoring have become the most common adaptation strategies. In this regard, early warning systems, hazard and vulnerability mapping, and improved drainage are common management tools for climate change associated risks (Insana et al., 2021; IPCC, 2023). The implementation of these strategies is mainly in relation to slope stability (Insana et al., 2021).

In the future, it is crucial to give attention also to other geo-structures, while enhancing slope stability. In this context, other measures such as reliability theory and probabilistic approach, adaptation of technical standards for the design of geotechnical infrastructures, the observational method and pre-mortem analyses, need to be assessed and implemented further in daily engineering practice.

3 THE EFFECT OF UNCERTAINTIES ON THE PERCEIVED FACTOR OF SAFETY

3.1 Uncertainties in design from climate change

The question that the geotechnical engineer needs to address during the design is how safe the structure is under the applied loads and given the assessed geotechnical conditions. Furthermore, the geotechnical assessment needs to include the impact of climate change on all loads and geotechnical factors.

As a response to a changing climate, it is necessary to adapt the geotechnical design to the mutation of uncertainties associated with a geotechnical problem. The uncertainties identified in the prediction of the response of geo-structures (i.e., spatial variation, limited site exploration and observation, soil parameters, various testing methods, loads, calculation model) need to be re-assessed in terms of altered environmental load and remodeled soil parameters due to climate change (i.e., soil drying, soil suction, soil dessication, soil erosion and flooding, soil saturation).

The upcoming second generation of Eurocodes may respond to some extension to such imminent demand.

3.2 Safety factor and reliability-based design

The factor of safety is a deterministic approach to a safety assessment, and it embodies a quantification of the margin of safety (*M*). As elaborated by Lacasse et al. (2019), the uncertainty in the safety margin can be addressed as a spectrum of failure probabilities (P_f). The risk analysed in a safety assessment will never be zero, because there will always be a certain level of uncertainty (i.e., a finite probability that a failure may occur). Silva et al. (2008) summarised in a diagram the correlation between safety factor and failure probability, based on experience, engineering judgement and historical statistics. One of the take-aways of the diagram is that for a certain factor of safety there is a wide range of perceived failure probability, depending on the uncertainties in the analysis. Lacasse et al. (2019) shows well this concept for slope stability issues in *Figure 1*.

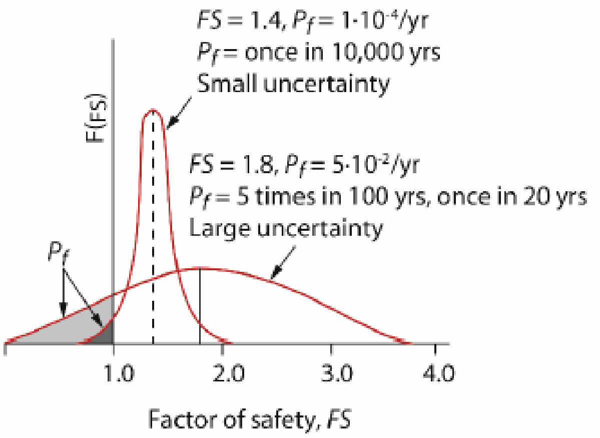

Figure 1. Variation of the safety factor of a slope with regards to failure probability (Lacasse et al., 2019).

A reliability-based approach accounts for the uncertainties in the analysis and their correlation, hence leading to a more rational assessment of safety of geotechnical structures. Such approach should, therefore, be used as a complement to the deterministic analysis, to provide a more robust design (Lacasse et al., 1998, 2019).

A simplification of the full reliability-based design is given through the LRFD (load and resistance factor design) approach. The partial safety factors in the LRFD approach reflect the uncertainty encountered in the design. The partial safety factors can also be calibrated such that a targeted safety level is ensured for determined levels of uncertainty in the geotechnical problem. However, uncertainties may be different from those assumed in the calibration phase, especially in the current environmental context. So, it is fundamental to couple such approach with a full reliability analysis using a target reliability index, to improve resilience to climate change effects in geotechnical design. Several examples of application of the reliability approach to actual case studies on- and off- shore are described by Farrokh (2017).

4 CONCLUSIONS

This short review shows that there is an increasing need for adapting the geotechnical design of geo-structures to the effects of climate change.

Our planet is undergoing an environmental adaptation to climate change. This process is happening fast, and it is affecting geotechnical infrastructures. It is difficult for geotechnical engineers to quantify such uncertainties and to take them into account in the design phase.

The interest for implementing efficient strategies to tackle climate change effects on geo-structures is increasing in Europe.

There are many different strategies which are assessed and developed in the European region (i.e., adaptation of technical standards, implementation of monitoring systems and of the observational method, implementation of reliability-based methodologies). The main challenge that geotechnical engineers face nowadays is how to combine those strategies and tools into practical solutions for a sustainable and climate change resilient design. Furthermore, such difficult task needs to be contextualized in interdisciplinary projects and with a holistic approach to design. In the future, there is the need to increase the connection between research and practice in geotechnical engineering for a climate change resilient design.

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