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ORIGINAL PAPER

A framework for climate-adaptive geotechnical analysis and design

Alessandra Insana[1] · Marco Uzielli[2] · Tamara Bračko[3] · Amirreza Pourfatollah[1] · Patrizia Vitale[4] · Bojan Žlender[3] · Marco Barla[1] · Vittoria Capobianco[5] · Primož Jelušič[3] · Elham Mahmoudi[6] · Leyla Nik[7] · Julia-Isabelle Ruopp[8] · Fabien Szymkiewicz[9] · Hauke Zachert[8] · Hjördis Löfroth[7]

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Abstract
Climate change impacts are affecting and will more and more alter the already precarious hydrogeological equilibrium, with immeasurable consequences on geo-structures, such as embankments and slopes. Despite the impacts of climate change on geo-structures are clear, what is less straightforward is how to deal with them. Among the possible strategies, adaptation of geo-structures to climate change is essential. The aim of this paper is to provide a modular conceptual and operational framework to support best-practice quantitative geotechnical analysis and design of climate-adaptive geo-structures. To this aim, the paper preliminarily introduces the correlations and causal relationships between climate change signals, climate change effects, and climate change impacts. Such correlations are integrated in the framework which explicitly accounts for climate change into the geotechnical analysis and design process. It can be used by geotechnical engineers to evaluate and assess the climate-adaptivity of both existing and newly planned geo-structures, through a structured insight into their interaction with temporally variable climate change signals. An example application of the framework is provided in relation to a real slope stability problem. This case study is used for validation, then the slope's climate adaptivity is assessed considering different climate scenarios. Results show that by accounting for a remediation measure, the performance of the slope is compliant with design requirements at all temporal scenarios considered, i.e. the geo-structure will be climate-adaptive throughout its service life. This study is part of the research work carried out within the European Large Geotechnical Institutes Platform Working Group on Climate Change Adaptation.

Keywords Geo-structure · Climate change adaptation · Geotechnical analysis · Slope stability

Introduction

The last hundred years have been characterized by a large increase in population (United Nations 2022) and have witnessed the consequences in terms of urban growth of infrastructure and transport. At the same time, natural and agricultural areas have been reduced significantly. As a result, energy needs, environmental pollution, and global warming are becoming increasingly pressing issues with a number of detrimental consequences from climate change to biodiversity loss, degradation of soil health (expressed in terms of its biotic and abiotic components), which could lead to an augmented susceptibility to erosion and excessive seepage, and risks to human health and human-valued assets. Trends related to climate change further exacerbate these risks by acting on physical systems in ways which frequently challenge their stability and functionality. The geotechnical engineering discipline can provide effective approaches and solutions for the mitigation of such risks as it focuses on the attainment and maintenance of adequate levels of performance in physical systems involving geomaterials. However, the geotechnical community has not traditionally accounted for climate change-related effects in the context of analysis and design. For instance, geotechnical site characterization is typically conducted at a single temporal phase, thereby neglecting seasonal fluctuations and longer-term trends in the mechanical and hydromechanical attributes of a system. Consequently, geotechnical design typically relies on a time-invariant geotechnical model. This paper focuses on the explicit inclusion of climate change

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effects in geotechnical efforts and aims to raise awareness of the need to adapt the traditional perspective of analysis and design to take into account not only present scenarios, but also future trends related to climate change.

In its AR6 report, the Intergovernmental Panel on Climate Change (IPCC 2023) noted that each of the last four decades has been successively warmer than any previous decade since 1850. Extreme events, such as heatwaves and droughts, sea level rise, tropical cyclones and extratropical storms, will become more frequent with global warming (IPCC 2023).

Understanding the effects and impacts of climate change is undoubtedly fundamental from the point of view of environmental protection, as is developing models that focus on forecasting future climate scenarios. Unfortunately, climate science is quite uncertain about this. Both Crozier (2010) and Ciervo and Rianna (2017) claim that there remains a high level of uncertainty resulting from scenario-driven global predictions on climate, and a lack of time and spatial resolution of currently available downscaled projections.

Consequences of climate change are multi-dimensional and can impact physical, socio-economic, and institutional assets. Many studies have addressed the physical effects of climate change and related impacts on geo-structures, such as embankments (Vardon 2015; Pk 2017) or slopes (Crozier 2010; Huggel et al. 2010, 2012; Davies 2011; Gariano and Guzzetti 2016; Alvioli et al. 2018), particularly in Alpine regions (Stoffel et al. 2014; Meusburger and Alewell 2008) but not only (Andersson-Sköld et al. 2006; Dixon and Brook 2007; Chiang and Chang 2011; Ciervo and Rianna 2017; Jaedicke et al. 2008; Rianna et al. 2014; Strauch et al. 2015). Often the focus is on soil-atmosphere-interaction (Tang et al. 2018; Cotecchia et al. 2019), partially saturated conditions (Vahedifard et al. 2018), or climate change thermal effects and related geotechnical failures (McCartney et al. 2019). The SafeLand project (Nadim et al. 2014) provided the first analysis of natural landslide risk in relation to climate. Rianna et al. (2016) highlighted, through parametric numerical analyses, the role of soil hydraulic properties in the long-term effects of distinct climate scenarios expected in the Mediterranean basin on the safety conditions of a sloping deposit. The expected changes in weather conditions could lead to completely different effects depending on soil type: (i) a decrease in landslide hazard in low permeability soils; (ii) an increase in landslide frequency in pervious soils.

Insana et al. (2021) examined how geo-structural concerns are addressed in national adaptation plans and found that specific provisions for geo-structural adaptation are generally lacking and are mainly in the form of strategies for specific problems. Two common strategies in this context are monitoring and hazard/risk assessment. These are used primarily in the context of slope stability. However, the risk-based approach to the planning, design, realization, and monitoring of geo-structures, which relies on frameworks such as the one provided in the ISO 31000 "Risk management guidelines" (ISO 2018) is still not harmonized with the conventional engineering approach which is adopted by geotechnical practitioners, and which is conducted in compliance with design codes. Design codes adopt an increasingly risk-based reasoning but yet a widely different glossary.

Recently, Rianna et al. (2023) provided a simplified procedure aimed to assess the climate-expected kinematic evolution of a slow landslide active in Southern Italy. Vitale and Liu (2024) and Vitale et al. (2025) reflected on the need to address (and to embed in design codes) uncertainties in geotechnical design in relation to climate change's impact on geo-structures that will play a key role in answering the question of how safe a geo-structure is. Comegna et al. (2025) highlighted the non-negligible potential role of cracking, induced by long drought periods, on the activity of landslides involving highly plastic clays. The use of machine learning to develop landslide susceptibility maps under future climate scenarios is also spreading (Pourfatollah et al. 2025).

In this paper a modular conceptual and operational framework is provided to support best-practice quantitative geotechnical analysis and design of climate-adaptive geo-structures. Climate adaptivity of a geo-structure is here defined as its capability to ensure compliance with a pre-set "target" level of performance throughout a temporal interval characterized by climate change. It is a concept strictly related to the sustainability of a system, as defined by Basu et al. (2015), i.e., its ability to survive and retain its functionality over time. Time is inherently included within the sustainability and the climate-adaptivity concepts, which must be addressed by considering supplies and demands that can change over time. Through this framework, which explicitly integrates climate change into the geotechnical analysis and design process, geotechnical engineers can assess the climate-adaptivity of geo-structures through a structured insight into their interaction with temporally variable climate signals. The framework can be used in a forward mode in the planning of new analyses and designs, or it can be employed to evaluate and assess the climate adaptivity of existing geo-structures. To foster the harmonization between risk and design paradigms, a structured discussion of the similarities and differences between the modules of the proposed framework and the ISO 31000:2018 guidelines for risk management (ISO 2018) is provided.

The illustration of the framework is preceded by two fundamental sections addressing the correlations and causal relationships between climate change signals, climate change effects, and climate change impacts as defined in Insana et al. (2021). An application of the framework to a real slope stability problem is provided to the readers to exemplify its practical adoption. This case study is used for validation, then the slope's climate adaptivity is assessed considering different climate scenarios.

The presented topic is part of research work that is being accomplished within the ELGIP (European Large Geotechnical Institute Platform) working group Climate Change Adaptation (WG CCA, https://elgip.org/working-groups/climate-change-adaptation/).

Correlations among climate change signals, effects, and impacts for geo-structures

Climate change needs to be described in a way that is useful for conducting geotechnical analyses. For this reason, the ELGIP WG CCA has identified appropriate climate change signals as well as climate change effects and impacts on geo-structures (Insana et al. 2021) that will be briefly recalled in Sect. 2.1. Correlations among signals, effects and impacts are presented in Sect. 2.2.

Climate change signals, effects, and impacts

Table 1 lists the most relevant climate change signals for geo-structures (S1 to S8). Climate change signals need to be converted into a geomechanical form to be able to carry out geotechnical analyses. Therefore, the different effects that each signal can have on soil, bedrock, groundwater, surface water and vegetation, have been mapped, such as degradation of material strength due to increased saturation and physical weathering, increased surface runoff, increased shrink-swell behaviour of clay soils, etc. After the list of the signals, Table 1 shows the most typical climate change effects from a geo-expert perspective (E1 to E17). Some of the effects of climate change can be caused by different climate change signals. The definition of climate change effect E1 has been intentionally extended here with respect to Insana et al. (2021), with the aim to highlight the relevance of topsoil health in preventing phenomena such as erosion and excessive seepage as highlighted in the EU Soil Strategy for 2030 (European Commission 2021) and of hydro-mechanical/atmosphere processes. The relationship between signals and effects is independent of the type of geo-structure, but it may be soil-dependent. For example, increased precipitation can cause increased surface runoff or increased infiltration, depending on the ratio between rainfall intensity and soil hydraulic conductivity.

These climate change effects cause one or more climate change impacts that relate to a specific type of geo-structure. Finally, Table 1 shows possible climate change impacts (I1 to I17) related to the climate change effects.

Causal chain and relevance of climate change signals, effects and impacts on geo-structures

The taxonomy of the causal relationships between climate change signals, effects, and impacts is needed to fully and reliably classify and describe the consequences of climate scenarios on geo-structures. This paper aims to contribute to the progressive compilation of such a taxonomy.

In addition to listing climate change signals, effects and impacts, the causal chain in Fig. 1 shows schematically their cause-effect relationships. It can be used to qualitatively map the path from one or more signals, which depend on the climate projection of a specific geographic region, to the corresponding impact(s), as explained in the framework presented in Sect. 3. All climate change signals can lead to instabilities, e.g. of slopes, embankments, and other engineering structures. The number of effects arising from a certain signal can also be immediately visualized. This mapping is useful to support geotechnical analysis and design accounting for climate change, as it will be explained in Sect. 3.

Development of a methodological framework for climate change-related geotechnical analysis and design

A best-practice conceptual sequence which reflects well-established geotechnical principles, and which allows the optimal integration of climate change modeling, can be identified, though of course geotechnical systems are unique in terms of the combination of site conditions and scope of design. This section illustrates a general framework for the planning, design, and assessment of climate-adaptivity of geo-structures. Building on the contents of the previous sections, the framework incorporates the critical identification of climate signals, climate change effects and impacts and provides operational guidance to allow best-practice inclusion of climate change into geotechnical analysis and design.

Overview of the framework

Conceptually, the framework follows the methodological best-practice sequence commonly observed by geotechnical engineers when analyzing existing geo-structures or designing new ones. This sequence (Table 2; Fig. 2) entails a preliminary phase (Phase I) comprising the scoping of the activity (including the service life, the level of performance,

Table 1 List of climate change signals (S), effects (E) and impacts (I) on geo-structures

Signals	S1	Increased precipitation
	S2	Decreased precipitation/increased drought periods
	S3	Increased air temperature and periods of warm weather in winter
	S4	Increased number of intense rain/drought cycles
	S5	Increased number of frost/thaw cycles
	S6	Increased frequency and intensity of extratropical cyclones and storms
	S7	Sea level rise
	S8	Increased wind speed
Effects	E1	Degradation of material strength due to increased saturation, degradation of soil health, hydro-mechanical/atmosphere processes, increased seepage capacity, physical weathering
	E2	Increased mineral dissolution due to increased chemical weathering
	E3	Increased water erosion
	E4	Increased surface runoff
	E5	Increased surface and groundwater level/flow
	E6	Degradation of material strength due to shrinkage/desiccation and increased physical weathering
	E7	Decreased surface and groundwater level/flow
	E8	Increased wind erosion
	E9	Changed geotechnical properties of perennially frozen soil
	E10	Degradation of material strength due to increased saturation/desiccation and increased weathering
	E11	Increased shrink-swell behaviour
	E12	Increased water and wind erosion
	E13	Degradation of material strength due to increased frost heave/thaw settlement and physical weathering
	E14	Frequent and higher sea water rise from storm surges
	E15	Increased loading due to strong wind and wave action
	E16	Landward encroachment of the sea
	E17	Increased dynamic load
Impacts	I1	Instability of slopes
	I2	Instability of embankments
	I3	Instability of other engineered structures
	I4	Structure collapse/damage on karstic topography
	I5	Damage/failure of structures from flooding
	I6	Overtopping/breaching of dams/dikes
	I7	Cracking/instability of slopes
	I8	Cracking/instability of embankments
	I9	Cracking/instability of other engineered structures
	I10	Structure settlement/subsidence
	I11	Damage/failure of structures from strong wave action
	I12	Damage/failure of tall structures foundation from strong wind action
	I13	Instability of coastal slopes
	I14	Instability of coastal embankments
	I15	Instability of other engineered coastal structures
	I16	Damage/failure of engineered coastal structures from flooding
	I17	Overtopping/breaching of dikes/levees

and the regulatory framework that must be observed), the examination of available documentation regarding the site which will host the geo-structure (Phase II), and the reasoning process (Phase III) which leads to the comprehension of the overall geotechnical functioning of the system (i.e., in terms of the interaction between the geo-structure and the mechanical and hydrogeological attributes of the site). Phases I-III lead to the planning and execution of site investigation activities (Phase IV) aimed at collecting quantitative data required for geotechnical site characterization and, subsequently, for analysis and/or design (Phase V), as described in greater detail in a subsequent paragraph.

The framework proposed herein does not alter this fundamental sequence; rather, it superimposes an additional dimension involving the explicit (initially) conceptual and (subsequently) quantitative inclusion of climate-related

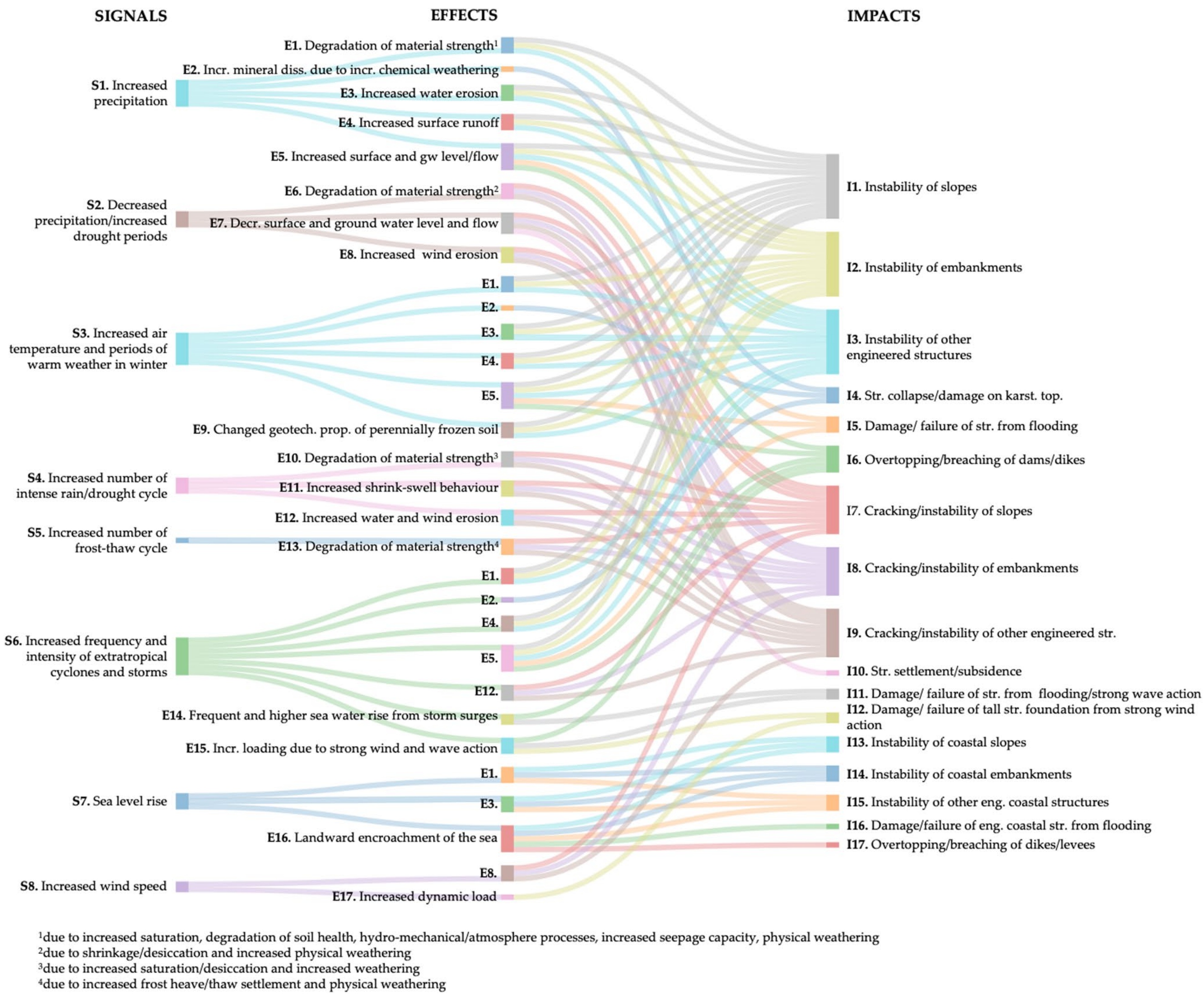

Fig. 1 Causal chain between climate change signals, effects and impacts on geo-structures

Table 2 Overview of the main steps of the framework for climate-adaptive geotechnical analysis and design

Phase	Description
I	Design scoping
II	Context definition
III	Conceptualization
IV	Data acquisition
V	Analysis/design
VI	Evaluation
VII	Treatment

signals on the geotechnical system and the assessment of their effects and impacts on the geo-structure. Since "climate change" implies the belief that climate-related signals, effects, and impacts vary over time, the framework explicitly requires predicting and assessing the performance of the geo-structure for multiple temporal scenarios which refer to site-specific timeframes that depend on local climate projections and the geo-structure's service life. If the performance of the geo-structure is compliant with design requirements at all temporal stages considered, the geo-structure is termed "climate-adaptive" (Phase VI) and construction (for a new geo-structure) or upgrading (for an existing one) operations can take place. If this is not the case, the design needs to be reviewed or modified (Phase VII). In case an existing geo-structure turns out to be climate-adaptive without considering any new technical intervention, then no action is needed.

The framework can be applied to all scales typically pertaining to geotechnical projects, ranging from territorial scale to manufactural scale, since it does not alter the fundamental principles and analysis approaches of geotechnical engineering but adds climate-related aspects which entail the explicit assessment of the temporal variability of the geo-structure and the actions which affect it.

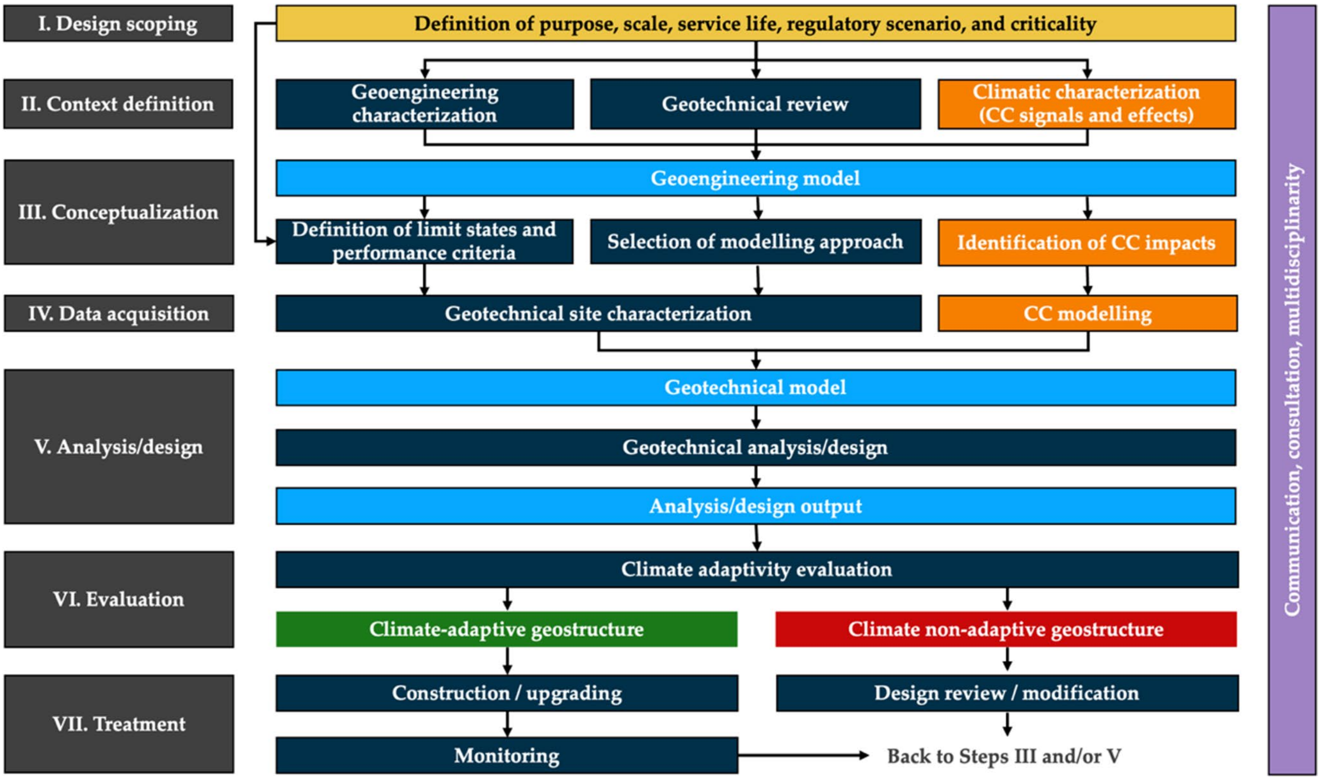

Fig. 2 Framework for climate-adaptive geotechnical analysis and design (CC stands for climate change)

Operation of the framework

Operationally, the framework is defined according to a sequential seven-module scheme (grey boxes in Fig. 2). Such scheme intentionally replicates, where possible and pertinent, the phases outlined in the general risk management process defined in the ISO 31000:2018 Guidelines for Risk Management (ISO 2018).

It is paramount to remark that the framework does not need to be followed from beginning to end. Rather, the availability of a comprehensive modular sequence allows the application of the framework to existing and realized designs as well as to new projects in all its steps. It will have to be tailored for each specific geotechnical problem. In case not all steps are directly addressed in a specific instance, the phases which are not explicitly included in the analysis can still serve as a best-practice conceptual checklist to be consulted to assess the overall climate-related aspects of the project. Much information will be already available for existing structures, therefore some phases could be just verified or bypassed.

In the operational flowchart shown in Fig. 2, boxes in dark blue represent geotechnical engineering activities, elements in light blue denote the outputs, and orange elements refer to activities which are related most directly to climate change modeling. Climate change is thus included in the analyses and evaluations following Phase IV.

While the following paragraphs provide an articulate conceptual explanation of all phases of the framework, Sect. 4 provides an example of how the framework can be concretely applied to engineering practice. The original conceptualization of the framework presented here was adapted by Bracko et al. (2024).

Phase I: design scoping

Phase I is aimed at the correct scoping of the analysis for the planned or existing geo-structure. This phase could include information regarding: (a) the declaration of the purpose of the analysis/design; (b) the definition of the problem scale; (c) the definition of the service life of the geo-structure; (d) the definition of the regulatory/normative scenario defined by local design codes; and (e) the definition of the level of criticality.

The scoping phase provides the fundamental pillars of the analysis as it identifies regulatory constraints and/or obligations and sets binding albeit possibly qualitative criteria for the subsequent quantitative definition of target performance levels. It is perhaps useful to highlight that "performance" is used as a predictive attribute rather than an observational component. This use of the term is consistent with the glossary adopted by evolutionary probabilistic and semi-probabilistic approaches adopted in geotechnical design codes (which define reliability as the probability of achieving a target level of performance, with general applicability to both ultimate and serviceability limit states) and performance-based design approaches, in which the quantitative definition of performance defines the design acceptability criterion.

Phase II: context definition

Phase II is aimed at the preliminary characterization of the geoengineering and climatic context for the geo-structure. This is a markedly multidisciplinary activity which involves competences from different though complementary fields: geotechnical engineering, geology, seismology, hydrogeology, environmental engineering, engineering geology, climatology among others. The context definition phase could include: (a) the geological, geomorphological, seismological, and hydrogeological characterization of the site; (b) a desk review of existing qualitative and, where available, quantitative geotechnical information regarding the site; and (c) the preliminary climatic characterization of the area, involving the collection and critical review and assessment of relevant local climate signals and subsequent effects among those discussed in Sect. 2.1 and listed in Fig. 1.

Typically, existing geotechnical projects may not be accompanied by climate-related information. In this regard the framework may serve, for instance, as a reference for the collection of climate-related data. Phase II yields the preliminary geoengineering model of the site, which pertains conceptually to Phase III but results from the synthesis of points (a) and (b), as well as a set of relevant climate change signals resulting from point (c). Phase II is conceptually equivalent and homonymous to the “context definition” module in ISO 31000:2018.

Phase III: conceptualization

Phase III is aimed at: (a) the definition of the conceptual geoengineering model of the site; and, consequently, at (b) the identification of the controlling performance criteria and/or limit states guiding the geotechnical analysis of the geo-structure; and (c) the selection of the modelling approach to be implemented in Phase V. Phase III is also a qualitative phase and involves the integration of the climate change effects and the climate-independent information from Phase II. This integration results in the definition of the geoengineering model, which provides the preliminary qualitative description of the physical interactions which are most relevant with reference to the case-specific geo-structure.

The geoengineering model also defines qualitatively the set of relevant climate change impacts, i.e., the possible phenomena occurring within the geo-structure, among those addressed in Sect. 2.1 and listed in Fig. 1. The conceptual geoengineering model consequently allows, in the context of design approaches, to identify the performance criteria and/or the limit states which are most relevant for the geo-structure. This identification process is also directly connected with the regulatory context addressed in Phase I because different design codes may require addressing specific limit states and/or performance criteria. In turn, the identification of controlling limit states and performance criteria contributes to the selection of the modelling approach.

The selection of the modelling approach also stems from the geoengineering model. In principle, geotechnical analyses can be performed using analytical, empirical, and numerical approaches. Depending on the stratigraphy and geomechanical properties of a geo-structure, on the type and number of relevant climate change impacts, and on the scope of the analysis, one approach may be preferrable with respect to another, or multiple approaches may be used in synergy. Regulatory prescriptions defined in Phase I may also condition the selection of the approach, for instance by requiring specific types of analyses and the definition of specific parameters (e.g., characteristic values and partial factors if using Eurocode 7). Moreover, the choice of the analysis approach should also consider the capability to adequately model climate change effects. The choice of the geotechnical approach contributes to the planning of the data acquisition strategy to be conducted in Phase IV. Conceptually, Phase III can be associated with the “risk identification” module in ISO 31000:2018, because it involves the definition of the “hazards” acting on the geo-structure and the “vulnerabilities” of the geo-structure itself.

Phase IV: data acquisition

The acquisition of geotechnical and climate-related data conducted in Phase IV allows the transition from the qualitative geoengineering model to the quantitative geotechnical model. Geotechnical testing campaigns should always refer to (at least) the scope of design, the target level of performance of a system, the geographic extension of the site, and the conceptual geoengineering model of the geo-structure. When addressing climate change, the optimal planning, conduction, and interpretation of geotechnical testing campaigns must also account for the case-specific climate effects identified in Phase II, e.g., by varying the effective stress level of a laboratory specimen to simulate temporally varying groundwater levels.

The periodic conduction of geotechnical testing and monitoring campaigns (e.g., measurement of pore water pressure, measurement of volumetric water content, readings from inclinometers, etc.) to capture seasonal trends may also be planned to account more explicitly for the temporal variability of the geotechnical system. Testing conditions for future states of the geo-structure must be harmonized with quantitative climate change scenarios. These are defined with reference to the scope of the analysis and to the definition of the service life of the geo-structure itself.

The climate modeling chain typically involves a sequential process moving progressively from global to local scales through the definition of emission macro-scenarios (e.g., reference concentration pathways), global circulation models (GCM), regional climate models (RCM) and subsequent statistical calibration (e.g., through bias correction). A detailed insight into climate modeling lies beyond the scope of this paper. The outcome of this process is a set of quantitative climate projections for each of the climate signals which are deemed relevant in the conceptual geotechnical model.

In ISO 31000:2018, data acquisition is functional to the estimation of hazard, vulnerability, and exposure in the "risk analysis" module. Here, data acquisition is awarded a self-standing module to highlight the centrality of geotechnical site characterization and climate change modeling. Data-centrism may well provide the new paradigm for geotechnical engineering and evolutionary geotechnical design codes (Hadjigeorgiou and Harrison 2011; Bozorgzadeh et al. 2019; Phoon 2020; Uzielli 2023).

Phase V: analysis/design

Phase V receives the outputs of the geotechnical site characterization and climate modeling processes conducted in Phase IV to define and implement a quantitative operational geotechnical model (e.g., numerical, analytical, machine learning-based, etc.). The latter must fully comply with the conceptual model, and it must rely on the modelling approach defined in Phase III. The conduction of Phase V must account for climate change signals and effects. Typically, this is achieved by conducting a parametric study which applies varying geotechnical and/or hydrogeological parameters to the deterministic model to reflect (qualitatively) climate change effects and (quantitatively) climate projections. The parametric approach can allow, for instance, the assessment of the effects of time-variant rainfall patterns on groundwater levels, soil strength (internal friction angle, cohesion), deformability, and permeability among other things.

Outputs of Phase V reflect the current and future performance levels of a geotechnical system in terms of the limit states identified in Phase III. Performance levels are expressed consistently with the analysis approach. For instance, in designing a shallow foundation, performance can be expressed as the ratio of a capacity to a demand parameter (when using load and resistance factor design codes such as Eurocode 7 EN 1997 2004) or in terms of stress-strain distributions (when using numerical approaches). This phase is conceptually equivalent to the "risk estimation" phase as defined in ISO 31000:2018, which is a sub-module of the "risk analysis" module.

Geotechnical models and climate projections are pervaded by significant uncertainties. In the light of the increasing acknowledgment of the relevance of geotechnical uncertainties and owing to unprecedented computational power, the geotechnical discipline is experiencing a momentous shift in paradigm from the original deterministic approach to non-deterministic approaches (e.g., Uzielli 2023). Design codes are embracing this shift in paradigm, with notable examples being Eurocode 7 (EN 1997 2004), which involves the non-deterministic assignment of characteristic values and the subsequent application of partial factors which are themselves calibrated from statistical processes. Fully probabilistic and performance-based approaches to geotechnical designs have been developed and it is expected that future design codes will rely increasingly on probabilistic concepts.

Phase VI: evaluation

In Phase VI, the evaluation of climate adaptivity of both new or existing geo-structures is conducted through the comparison of the calculated system performance with the target performance defined preliminarily in Phase I and calibrated in Phase III through the definition of limit states. Depending on the type and scope of the analysis, performance criteria can be given by regulatory requirements (e.g., capacity-demand ratio), quantitative engineering criteria (e.g., maximum differential settlement, maximum strain in a slope), or (much less conveniently) subjective assignment by the geotechnical engineer. This phase is equivalent to the "risk evaluation" phase in ISO 31000:2018, in which calculated risk is compared with tolerable/acceptable risk and determines whether current and future scenarios of the geo-structure are compliant with target performance, i.e., whether a geo-structure is climate-adaptive.

A fundamental aspect of compliance evaluation in the light of climate change lies in its temporal variability. The temporal variability of performance induced by climate change effects may yield favorable evaluation outcomes for current scenarios but unfavorable evaluations for future scenarios. Climate change may result in the transition from a design being currently compliant to being non-compliant in the future, thus hindering the attainment of climate adaptivity as defined herein. The assessment of climate adaptivity, which inherently refers to time-dependent variations of the geotechnical model due to the presence of climate effects, differs from standard geotechnical design evaluations, in which the temporal evolution of a system investigated in the design process typically depends on phenomena such as consolidation or creep which are not related to temporally variable climate signals and effects, and which can be predicted using geotechnical engineering methods. Given the possible temporal variability of compliance evaluation, it is necessary to refer to the design service life of the geo-structure, defined in Phase I, since a design must remain suitable throughout such timespan.

When dealing with a new geo-structure, the design is carried out for the whole lifetime and therefore possible consolidation interventions should be included in the design in the first place. Instead, when assessing an existing geo-structure, possible threshold values of the signals (e.g., rainfall, temperature, wind, etc.) and effects could be identified, for instance by back-analysis, that may lead to one or more future negative impacts (concerning the Serviceability Limit State and/or the Ultimate Limit State). The calculated threshold values should be taken into account in the assessment of the expected climate scenarios of the study area, in order to chronologically estimate when the requested consolidation intervention should be implemented.

Phase VII: treatment

Depending on the outcome of the climate adaptivity evaluation performed in Phase VI, the subsequent "treatment" conducted in Phase VII can involve multiple scenarios. If the current and future state of a geo-structure are compliant with performance criteria, construction can proceed in case of new designs, or no intervention is necessary in case of existing geo-structures. If non-compliance is assessed, it is necessary to modify the geo-structure. In case of new designs, this may entail a critical review and revision of design. In case of existing geo-structures, compliance may be achieved by altering the geo-structure through upgrading, e.g. by technical interventions. An example of the latter scenario is given in Sect. 4 through the geotechnical stabilization of a non-climate-adaptive slope. Appropriate actions and measures depend on the type of the geo-structure and associated climate change signals, effects, and impacts. Many examples of possible structural mitigation measures can be found in the literature (Hutchinson 1977; Sujatha et al. 2023) among which a useful list is presented in LaRiMit (Uzielli et al. 2017; Capobianco et al. 2022). For both planned and existing geo-structures, the attainment of climate-adaptivity may require the reconsideration of the geoengineering model (Phase III) and/or the operational geotechnical model (Phase V). The first case occurs when the information derived from Phase II is not interpreted correctly and the conceptual modeling of the geo-structure is sub-optimal (i.e., incomplete or erroneous definition of geotechnical limit states, unsuitable climate change modeling, etc.). The revision of the conceptual model results in the cascading revision of the operational model as well since full coherency between the two is paramount. The second case results from the incorrect transition from the conceptual geotechnical model to the operational geotechnical model. This can occur because of insufficient geotechnical site characterization, incorrect interpretation of testing data, non-optimal selection of the operation geotechnical modeling approach and/or inaccurate/imprecise climate change modeling among other causes.

Regardless of the outcome of the climate adaptivity evaluation, a correct geotechnical engineering approach cannot prescind from observation and monitoring. The observational method is conceptually built into the geotechnical profession since its dawning era (Terzaghi 1961) and is being increasingly implemented into quantitative analysis through statistical and probabilistic Bayesian approaches (Baecher 2021). Even if climate adaptivity is assessed positively (i.e., compliance with target performance criteria is predicted throughout the service life of the geo-structure), monitoring during service life of the geo-structure remains essential to ensure that the inevitable aleatory and epistemic uncertainties, which pervade geo-structures and climate change projections and which are accounted for implicitly in deterministic geotechnical methods or (preferably) explicitly through non-deterministic methods, do not result in unforeseen lack of performance.

Analogous to the recommendation in ISO 31000:2018, communication, consultation, and multidisciplinarity should accompany every step of the framework whenever possible and pertinent (purple box in Fig. 2). Communication enables optimal conduction and transmission of technical activities to stakeholders. Just as importantly, it contributes to the diffusion of the conceptual and operational standpoints of the framework and, ultimately, to a societal-level increase in the awareness of the relevance of climate adaptivity. Consultation entails the interaction with relevant technical or non-technical actors, whether identified by regulatory prescriptions or deliberate choice, and is aimed at the periodic check for compliance, convergence, and unity of intents. Multidisciplinarity is related to the importance of merging competences and experiences from different fields pertaining to technical (e.g., geoengineering-related disciplines) and non-technical (e.g., political, economic, and socio-cultural) disciplines.

Application of the operational framework to a slope stability problem

With the aim to provide a simple exercise of preliminary application of the framework presented in Sect. 3 to a specific geo-structure and illustrate its use, the case of a slope stability problem is considered in this section. The example described is based on a landslide that occurred in Slake, Slovenia, after intense and prolonged rainfall at the end of November 2021 (Fig. 3). As the landslide affected a local road, the resources allocated to restore it were limited and proportional to the road's limited strategic importance. Hence, the focus of this section is on the application of the framework, rather than on the level of the geomechanical analysis or on the landslide remediation measures undertaken.

Phase I: design scoping

The analysis aims to identify the possible causes of slope instability and to plan and verify the effectiveness of remedial measures, ensuring the climate-adaptivity of the slope and the safety of the nearby residential buildings. The slope failure event involved a plan area of approximately 2500 m^2, damaging a local road and threatening a residential house in the immediate surroundings.

The reference regulatory scenario is provided by the Eurocode standard, specifically Eurocode 7 (EC7), according to which the service life to be considered for ordinary performance levels is 50 years (EN 1990 2004), along with local technical specifications and the Manual for the Implementation of Geotechnical Investigations (IZS 2018). When planning the scope and type of necessary geotechnical investigations, the specified standard differentiates between facilities according to geotechnical categories. In this case, geotechnical category 3 was assumed, corresponding to facilities and structures in areas where the probability of soil instability or constant movements exists.

Climate change is considered in the analysis, according to climate signal scenarios (see Fig. 1), as explained in Sect. 4.2.

Phase II: context definition

Consultation of the landslide probability map confirmed that the site is located in an area with a high landslide hazard. Preliminary observations of the area were conducted to determine the landslide depth, width, and length, and to visually assess its causes. The investigated slope is characterized by an average inclination of about 22°. The landslide was about 6 m deep (medium-depth landslide, according to Varnes 1978), 50 m wide and at least 50 m long, with the break-off edge extending over a length of around 30 m along the road.

A preliminary characterization of the geoengineering context for the slope under analysis was carried out. An assessment of the geological conditions of the area under consideration was inferred from the geological map, as shown in Fig. 4. The ground cover consists of layers of sandy clay, with plastic consistency, extending to a depth of 3 m. Deeper is sandy clay with semi-solid consistency up to a depth of 6 m. Below that depth, the hill base of the marl can be found. It is known that the saturation of the soil depends on the season and the amount of precipitation. However, no information is available about the groundwater level.

Figure 5a shows daily temperature and precipitation data recorded at the Podčetrtek meteorological station (the

(a) (b)

Fig. 3 Landslide occurred in Slake (Slovenia) in 2021: front crown (**a**) and right crown edge (**b**)

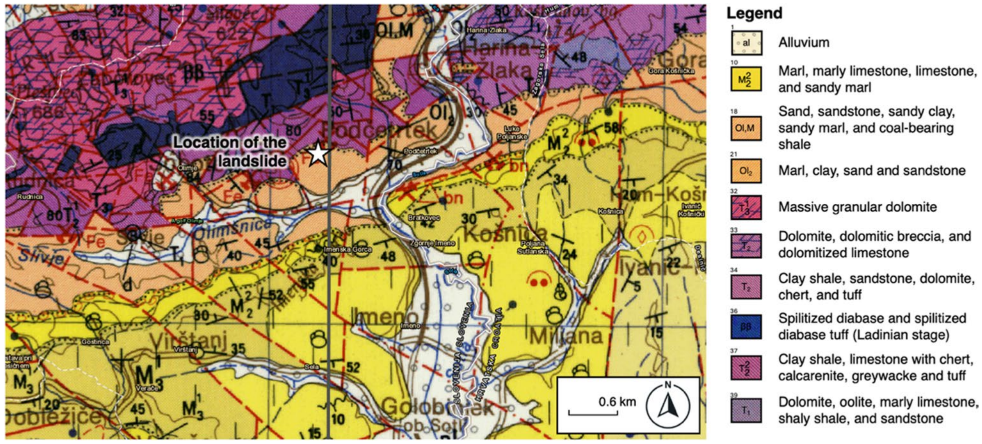

Fig. 4 Geological map in the area surrounding the landslide. (modified from Geological Survey of Slovenia).

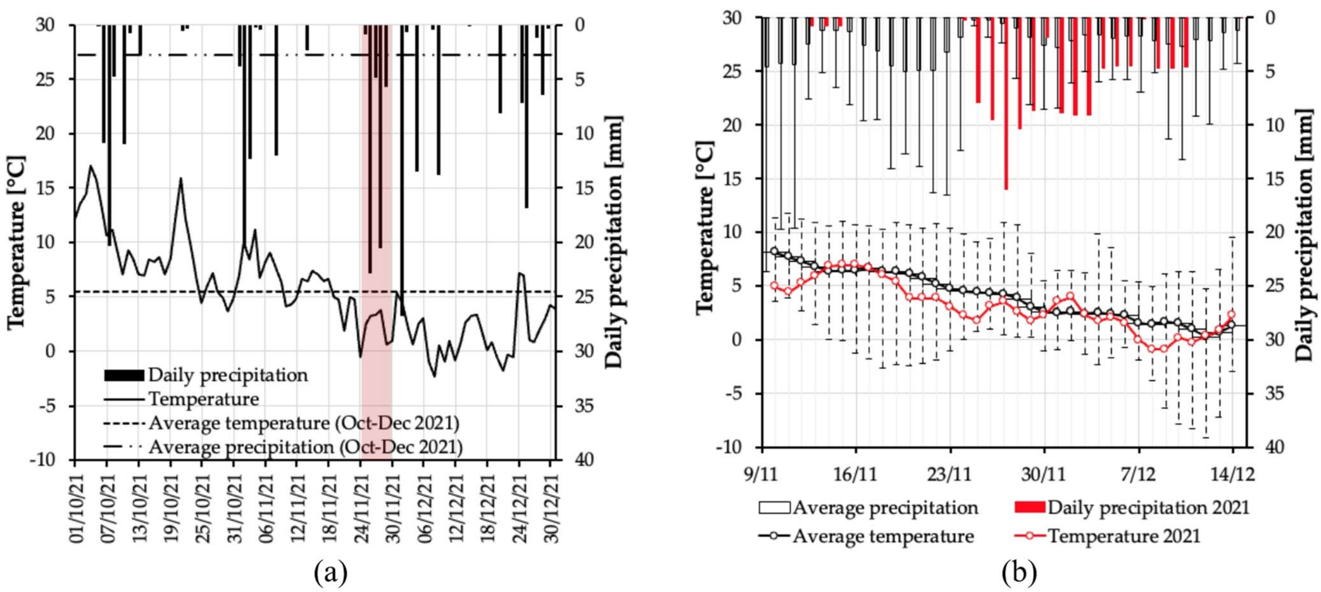

Fig. 5 Climate records in terms of temperature and precipitation near the landslide location (**a**) in Oct-Dec 2021 (in red is the approximate time of the landslide) and (**b**) for different years over five weeks around the date of the landslide event (3-days moving average), obtained from the agrometeorological portal of Slovenia (data for 2009, 2010, 2017, 2018 and 2020 were unavailable in the database)

available station closest to the landslide location) from October to December 2021. Furthermore, Fig. 5b shows the ranges (minimum-maximum) of the 3-days moving average of the historical temperature and precipitation values between 2008 and 2023 (2021 excluded) over five weeks around the date of the landslide in the same station, compared with the 3-days moving average in 2021. In some years (specifically 2013 and 2016) similar or even higher values of average precipitation compared to 2021 occurred, but no information about possible landslide events occurred at the site were available for those years. Except for these cases, the precipitation event that occurred in 2021 was significantly higher than in other years during the same period. This excessive rainfall likely contributed to the instability of the slope. On the other hand, temperature was not higher than in other years, thus leading to exclude climate change signal S3 in Fig. 1. Based on such preliminary climatic characterization of the landslide area, located in a temperate climate zone according to the Köppen climate classification (Beck et al. 2018), the climate change signal involved is mainly increased precipitation (signal S1 in Fig. 1).

Thanks to the correlations shown in Sect. 2, the corresponding climate change effects can be easily identified as: the increase in net water infiltration, degradation of material strength due to increased saturation, degradation of soil health, hydro-mechanical/atmosphere process, increased seepage capacity and physical weathering (E1) and increased surface and groundwater level and flow (E5), including porewater pressure.

Phase III: conceptualization

Based on the information collected in Phase II, the conceptual geoengineering model can be formulated by combining geological-geotechnical information and climate change signals/effects. Figure 6 schematically depicts the slope with the geomaterials and stratigraphy investigated in Phase II, as well as the main triggering climate signal, namely precipitation. On one side a share of precipitation, the one that exceeds the soil's infiltration capacity, flows on the ground surface in the form of runoff, whereas the remaining share infiltrates into the ground, thus recharging the groundwater. However, evaporation (water that can evaporate from the soil surface) and transpiration (water loss through plants or roots) also play an important role and contribute to reducing the amount of water in the soil. All these factors have an effect on the water balance, which is reflected in the stability of the slope.

According to the regulatory framework defined in Phase I, the assessment of the slope stability should be performed in terms of ultimate limit states (ULS). In this case, the verification will be performed against the global stability limit state. Typically, the ULS global stability verification is carried out by means of either (i) methods based on a hypothesized failure surface (so-called "strips methods" for soils or "rigid wedge methods" for rock masses), (ii) limit analysis methods, that provide approximate lower or upper limit solutions, or (iii) numerical methods, such as finite elements. Since for ii) closed-form solutions are available only in case of simple geometries, based on the analysis of the stratigraphy, the identified impact of climate change (namely instability of slopes I1), and the objective of the analysis it is decided to opt for i), i.e. the Limit Equilibrium Method (LEM) was selected as analysis approach. This method provides the ratio between the available shear strength (with its characteristic value) and the shear stress acting along the sliding surface, that is the global factor of safety FS. Due to different regulations in the different European countries, a global safety factor of 1.3 was selected as performance criterion guiding the geotechnical analysis of the geo-structure. The adequateness of the safety margin is based on the amount of knowledge of the problem, on the available data reliability and on the calculation model adopted in relation to the geological and geotechnical complexity, as well as on the basis of the consequences of a possible landslide.

The numerical study of the slope-vegetation-atmosphere interaction, influencing the seepage through the slope and, therefore, the slope stability, has been performed by combining hydraulic and LEM simulations. The interaction has been simulated in transient conditions through two-dimensional (2D) uncoupled hydraulic simulations, carried out using the FEM code Seep/W (GEOSLOPE International

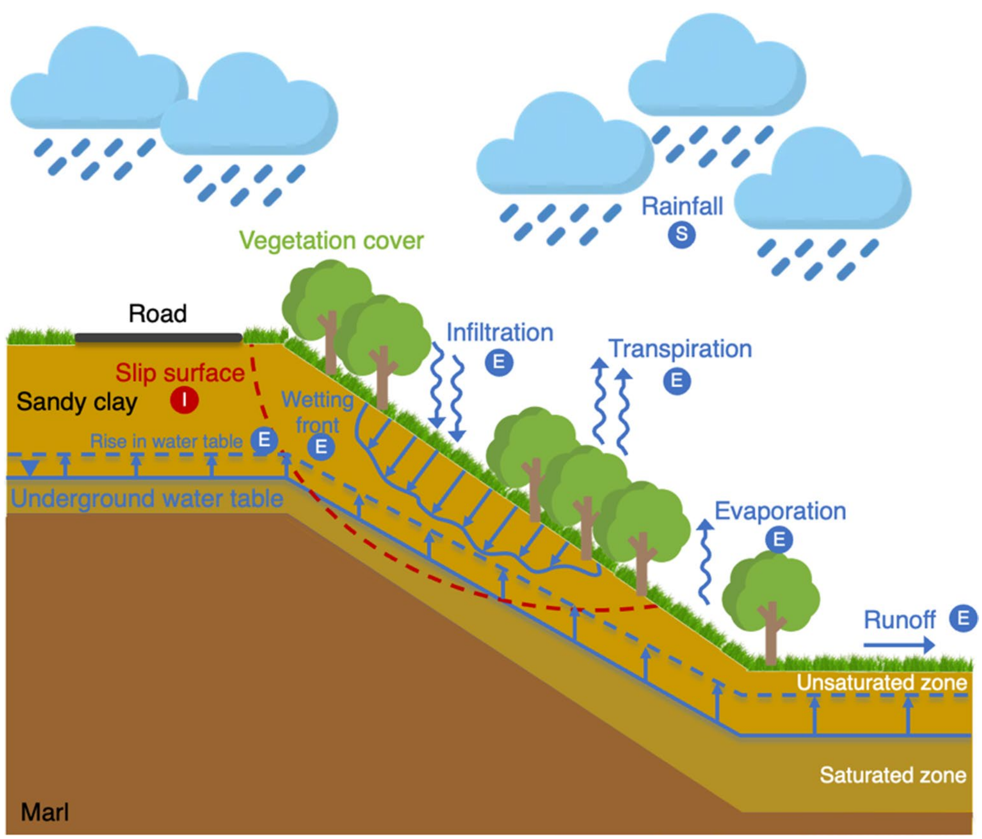

Fig. 6 Conceptual geoengineering model of the slope under analysis (S=signal; E=effect; I=impact)

2018). The obtained porewater pressure distribution was then employed as input for the LEM analysis, performed with the Morgenstern and Price method (1965) in Slope/W (GEOSLOPE International 2018). Therefore, it was possible to calculate the factor of safety for all simulation time steps to model the effects of climate change.

Phase IV: data acquisition

Having verified the available geological-geotechnical information and selected the modelling approach, in this phase it is possible to plan and carry out a quantitative geotechnical site characterization to collect the missing information needed to perform the LEM analysis. For this reason, the investigation included field testing (Standard Penetration Tests) and laboratory testing (soil classification, unit weight, direct shear test, permeability test, oedometer test). The geomechanical and hydraulic properties of the soil cover and bedrock are listed in Table 3, along with the material properties for the scenario after remediation, which will be introduced in Sect. 4.7. A Mohr-Coulomb elastic perfectly plastic constitutive model is used for the geomaterials involved. The soil model considers the peak friction angle and zero angle of dilation. The saturated permeability, saturated volumetric water content and compressibility were taken from literature (Leij et al. 1996; Budhu 2011).

To evaluate net infiltration at the soil surface, it is essential to assess all components of the water balance (precipitation, evaporation, transpiration and runoff). For the past event, precipitation measurements were obtained from the Podčetrtek meteorological station (Fig. 5) located 1.7 km away from the landslide. Therefore, the multi-day average value of precipitation recorded during the landslide event was assumed, that amounts to 16 mm/day for the period 26–28 November 2021. Based on the study reported by Maček et al. (2018), evapotranspiration resulted to be around 17.9 mm for the month of November, i.e. 17% of the average 2008–2023 total precipitation in the same month. Assuming that no runoff occurred on the slope during the activation of the landslide, an average net water infiltration at the ground surface of 13.3 mm/day (equivalent to $1.54 \cdot 10^{-7}$ $m^3/m^2/s$) is obtained and used in the geomechanical analyses. The same reasoning was applied to the future precipitation scenarios. Although the assumptions on evapotranspiration and runoff for present and future scenarios are very simplistic, they were deemed appropriate for the purpose of the paper, i.e. that of illustrating the functioning of the framework.

Table 3 Mechanical and hydraulic parameters of the slope geotechnical units adopted in the seepage and LEM analyses

Property	Sandy clay	Marl	Rockfill
Saturated unit weight γ_{sat} (kN/m^3)	18.5	24	23
Effective cohesion c' (kPa)	2	200	2 (case A), 50 (case B)
Effective friction angle φ' (°)	20	45	20 (case A), 45 (case B)
Saturated permeability $k_{sat}=k_y=k_x$ (m/s)	$5 \cdot 10^{-7}$	$5 \cdot 10^{-11}$	$1 \cdot 10^{-3}$
Saturated volumetric water content $VWC=V_w/V_s$ (-)	0.38	0.005	0.42
Compressibility m_v (1/kPa)	$5 \cdot 10^{-4}$	$1 \cdot 10^{-8}$	$5 \cdot 10^{-6}$

In order to incorporate climate change in the geomechanical model, the projected precipitation at the landslide site needs to be taken into account. To this aim, no established procedures exist, and researchers are currently developing methods to define future climate scenarios (Manola et al. 2018; Hossain et al. 2024). In this study, intensity-duration precipitation data with different return periods were explored for the Slovenian context and, specifically, for the location of interest (Crossrisk 2024). Events with a return period of 50 years (the timeframe considered in this analysis based on the service life deriving from regulations) and durations of 24 up to 96 h were selected. Additionally, to account for climate change, a 10% increase to these values was applied (ClimateHub Interreg project n.d.; Environmental Agency of the Republic of Slovenia 2019). Nonetheless, this assumption requires further validation through consultation with climatological expertise in future research.

Phase V: analysis/design

The geotechnical model is built in this phase by incorporating the results of climate change modelling in the geoengineering model and into the analysis input. The commercial finite element code Seep/W (GEOSLOPE International 2018) is applied to a finite element mesh with 559 nodes and 505 quadrilateral/triangular elements characterized by lengths and heights of around 1 m (Fig. 7), and the soil parameter values in Table 3. As a hydraulic boundary condition at the ground surface, a water flux condition was assumed equal to net infiltration, while an impervious condition was assumed at the bottom. The right boundary was set as a potential seepage face. The model is assumed initially dry.

Based on the computed pore pressures from the FEM seepage analyses, the slope stability conditions were evaluated through limit equilibrium analyses with the aim to assess the change in the slope safety factor during rainfall. The analysis results for the landslide event (without remediation) show that, initially, in dry conditions, the factor of safety is 1.16. Following precipitation, it decreases over time dropping to 0.95 on the third day. Such results closely align with the slope instability observed on-site and validate the model. Results for the future scenario based on precipitation

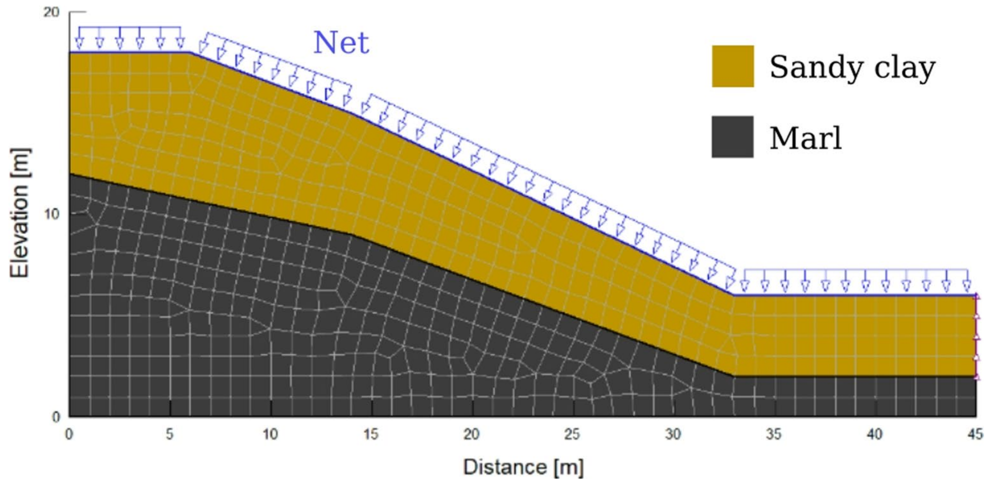

Fig. 7 Geometry, mesh and applied hydraulic boundary conditions of the geomechanical model

data from the Crossrisk website are not reported since they are expected to lead to instability even earlier given the increase in the infiltration intensity.

Phases VI-VII: evaluation and treatment

Following the output in Phase V, the analyses carried out allow to conclude that the analyzed slope is not climate-adaptive. This proves that adaptation measures are needed, especially in view of future increases in precipitation intensity. Hence, a critical review of the design has to be undertaken, going back to phase III. Possible remediation measures to ensure the slope will be stable in the future against climate change include the installation of retaining structures with drainage systems, management of water run-off from the road, and soil and water bioengineering (Preti et al. 2022).

Phase III-VII after remediation

In accordance with the framework, the analysis of slope stability with respect to ultimate limit states (ULS) is reiterated by altering the geo-structure through upgrading, e.g. by remedial measures. The objective is to achieve compliance with performance criteria to ensure that the slope remains stable against the backdrop of climate change, with a global safety factor of at least 1.3.

As a way to adapt to the potential effects of climate change, in the conceptual model the presence of counterfort drains (around 2 m wide and 6 m deep) was accounted for, to validate the effectiveness of the remedial measures in enhancing slope stability under varying conditions, ultimately ensuring long-term climate adaptivity. Counterfort drains, also known as deep trench drains, are commonly used as emergency remedial works on slope landslides. They provide both surface and groundwater drainage for slopes, reducing pore pressure. A collector pipe is installed at the base to ensure water is conveyed out of the slope as readily as possible to prevent the possibility of increased pore pressures. Moreover, when counterforts are backfilled with rock fill, or other relatively high shear strength materials, they can be used to mechanically improve stability when they intersect the failure surface, increasing the mobilized shear resistance along the latter (Lee and Clark 2002).

The geotechnical model is thus adapted to analyze the new scenario including the implementation of counterfort drains (Fig. 8 and last column in Table 3). For the current study, two different cases have been considered in order to evaluate the hydraulic and mechanical functions of counterfort drain separately:

- case A deals only with groundwater drainage, without any increase in shear strength. For that purpose, zero pore water pressure was applied at the bottom of the counterfort drain (water collection pipe). The permeability of the material constituting the counterfort drain was increased, while the shear strength remained constant as per the property of sandy clay.
- case B considers both groundwater drainage and increased soil shear strength. In this case, zero pore water pressure is applied at the base of the counterfort drain, too. However, in addition to case A, rock fill mechanical properties are assigned to the material constituting the drain, which enhances both the shear strength and permeability of the counterfort drain.

As anticipated, four precipitation events with a return period of 50 years were analyzed. These events, characterized by a duration of 24, 48, 72, and 96 h, correspond to precipitation amounts of 125 mm, 144 mm, 155 mm, and 164 mm, respectively (retrieved from CrossRisk). However, it is reported that, due to the anticipated impacts of climate change, Slovenia will experience a 10% increase in precipitation amounts by the end of the 21 st century (ClimateHub

Fig. 8 Geometry and mesh of the geomechanical model with counterfort drains

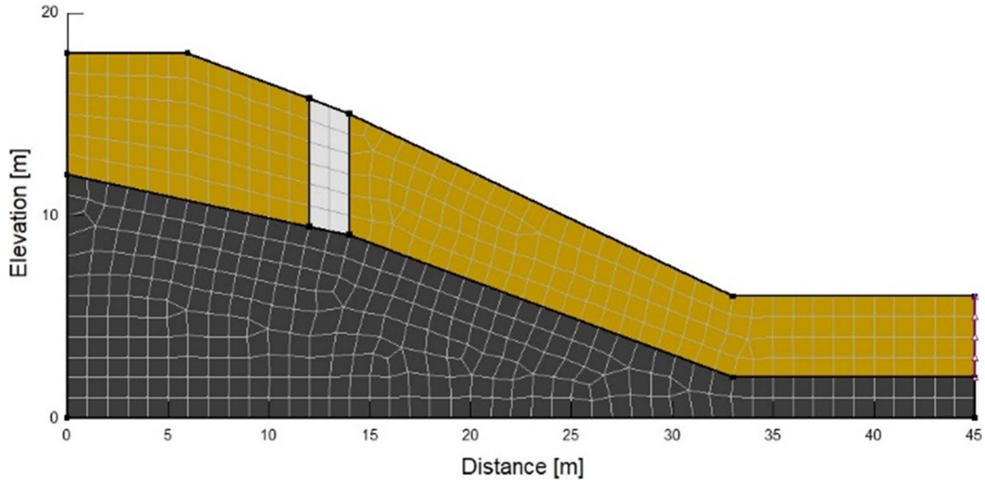

Table 4 Precipitation amounts, adjusted for climate change, and corresponding water net infiltration values for a 50-year return period over different time intervals

Event #	Duration (h)	Current rainfall intensity		Future rainfall intensity		Net infiltration (mm/d)
		Total (mm)	Daily (mm/d)	Total (mm)	Daily (mm/d)	
1	24	125.0	125.0	137.5	137.5	114.1
2	48	144.0	72.0	158.4	79.2	65.7
3	72	155.0	51.7	170.5	56.8	47.2
4	96	164.0	41.0	180.4	45.1	37.4

Table 5 Factor of safety evolution over time obtained from the LEM analyses

Event #	Duration (h)	Factor of safety	
		Case A	Case B
-	0	1.16	2.05
1	24	1.13	2.02
2	48	1.11	2.00
3	72	1.10	1.99
4	96	1.09	1.98

Interreg project; Environmental Agency of the Republic of Slovenia 2019).

To estimate water net infiltration, as explained in Sect. 4.4, it is assumed that 17% of the precipitation is lost to evaporation and transpiration. After accounting for this reduction, the water infiltration values for each event were calculated and are presented in Table 4.

Table 5 presents the variation in the safety factor corresponding to the four different rainfall events modelled. In Case A, the factor of safety is 1.16 before the onset of rainfall. In event 1, after 24 h of intense rainfall, it reduces slightly to 1.13. In event 4, after 96 h of sustained rainfall at a lower intensity compared to event 1, the factor of safety further declines to 1.09. Despite being lower than the target factor of safety, accounting for the hydraulic role of counterfort drains does enhance slope stability, which is evident by comparison with simulation in Sect. 4.5, where the factor of safety was 0.95 after three days of less intense rainfall. For Case B, the initial factor of safety is higher, 2.05 before the onset of rainfall. After 1 day of intense rainfall (event 1), the factor of safety reduces slightly to 2.02. When the rainfall is prolonged for 4 days at a reduced intensity (event 4) the factor of safety further reduces to 1.98. The results obtained show that by accounting for the increased shear strength in the analyses, the remediation measure can guarantee that performance of the slope is compliant with design requirements at all temporal scenarios considered, i.e. the geo-structure will be climate-adaptive throughout its service life.

This study represents a preliminary and simplified application of the proposed framework to a case study characterized by limited data availability (e.g., absence of groundwater level information). Furthermore, the framework was tested on a single geo-structure type (a slope), highlighting the need for future applications across a broader range of geo-structures.

Conclusions

The article presents the research work carried out as part of the European Large Geotechnical Institutes Platform (ELGIP) Working Group on Climate Change Adaptation. The objective of the research is to propose guidelines for the consideration of climate change into geotechnical analysis and design of new and existing geo-structures. To this purpose, a causal chain between climate change signals, effects and impacts on geo-structures is provided as a basis for determining the potential consequences that climate signals may have on geo-structures. Then, a general, comprehensive framework for the design, planning and assessment of climate adaptation of geo-structures is developed. The framework provides operational guidance to enable the integration of climate change into geotechnical analysis and design. Operationally, it is defined according to a sequential scheme of seven modules and is general enough to be applied to different types of geo-structures.

The provided case study exemplifies, at a high level, the practical application of the framework to a real case study of a slope stability problem, showcasing its effectiveness in addressing current and future climate challenges. In particular, the case of a climate non-adaptive slope is considered to exemplify the likely most frequent case where the design needs to be iterated until finding a positive performance not only under current climate scenarios but also and especially under the future ones. This exercise also highlighted the need to develop methodologies to define reliable future climate scenarios to be used by geotechnical engineers during climate-adaptive design.

As a key takeaway, the study draws attention to the fact that climatic factors are typically not explicitly considered during geotechnical analysis and design stage—except in an indirect manner, such as by assuming a raised groundwater table to account for intense rainfall—nor is attention generally given to how future climatic changes may influence geotechnical performance. Accordingly, the regulatory framework should be revised to require the systematic integration of climate change considerations into design practice.

Future research will explore more specific examples, extending the applicability of the framework to various types of geo-structures, and enhancing its utility in engineering practice.

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Data availability Data will be made available on request.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors and Affiliations

Alessandra Insana[1] · Marco Uzielli[2] · Tamara Bračko[3] · Amirreza Pourfatollah[1] · Patrizia Vitale[4] · Bojan Žlender[3] · Marco Barla[1] · Vittoria Capobianco[5] · Primož Jelušič[3] · Elham Mahmoudi[6] · Leyla Nik[7] · Julia-Isabelle Ruopp[8] · Fabien Szymkiewicz[9] · Hauke Zachert[8] · Hjördis Löfroth[7]

✉ Alessandra Insana
alessandra.insana@polito.it

Marco Uzielli
marco.uzielli@unifi.it

Tamara Bračko
tamara.bracko@um.si

Amirreza Pourfatollah
amirreza.pourfatollah@polito.it

Patrizia Vitale
patrizia.vitale@ngi.no

Bojan Žlender
bojan.zlender@um.si

Marco Barla
marco.barla@polito.it

Vittoria Capobianco
vittoria.capobianco@ngi.no

Primož Jelušič
primoz.jelusic@um.si

Elham Mahmoudi
elham.mahmoudi@rub.de

Leyla Nik
leyla.nik@sgi.se

Julia-Isabelle Ruopp
julia-isabelle.ruopp@tu-darmstadt.de

Fabien Szymkiewicz
fabien.szymkiewicz@univ-eiffel.fr

Hauke Zachert
hauke.zachert@tu-darmstadt.de

Hjördis Löfroth
hjordis.lofroth@sgi.se

1 Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy

2 Department of Civil and Environmental Engineering, University of Florence, Florence, Italy

3 Faculty of Civil Engineering, Transportation Engineering and Architecture, University of Maribor, Maribor, Slovenia

4 Department of Offshore Energy, Norwegian Geotechnical Institute, Oslo, Norway

5 Department of Natural Hazards/Geotechnics and Environment, Norwegian Geotechnical Institute, Oslo, Norway

6 Safe and Resilient Infrastructure, Deltares, The Netherlands

7 Swedish Geotechnical Institute, Linköping, Sweden

8 Institute of Geotechnics, Department of Civil and Environmental Engineering, Technical University of Darmstadt, Darmstadt, Germany

9 Laboratoire Sols, Roches et Ouvrages Géotechniques, Université Gustave Eiffel, Lyon, France