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Climate change effects on structural reliability in the Carpathian Region

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Abstract—Climate change affects not only the natural but also the built environment. The latter comprises large part of societal wealth, and it is a crucial component of developed economies. The focus of this paper is the quantitative assessment of the reliability of load bearing structures in changing climate. Despite its significance, relatively few quantitative studies are available on this topic, and particularly the Carpathian Region has been analyzed insufficiently. Therefore, the aim of this paper is (*i*) to present two quantitative studies on structures and climate change for the Carpathian Region, and (*ii*) to give an overview about approaches in civil engineering in relation to climate sciences, thus to trigger and facilitate future cooperation. The first part of the study is about the carbonation-induced corrosion of reinforced concrete structures analyzed considering six climate change scenarios. The results show that the depassivation probability can double from the beginning to the end of the 21st century. For structures executed in 2000, the effects will be subtle within the first half of the century, whilst the considerable changes are expected in the other 50 years. The second part of the study is about ground snow load and its effect on structural failure probability. It focuses on probabilistic models and statistical uncertainties, and draws attention to the significance of uncertainties arising from the insufficient number of observations. These uncertainties are typically neglected in current civil engineering practice, and they are especially important for climate change, for which the historical observations are not representative of the future environment. Bayesian statistical approach is used to handle these uncertainties. The analyses show that statistical uncertainties can have several order of magnitude effect on failure probability, thus their neglect is not justified. Additionally, long-term trends in historical snow observations are analyzed using stationary and non-stationary generalized extreme value distributions. Statistically significant decreasing trends ($p < 10\%$) are found for numerous locations, but they are practically significant only for a few in respect of structural reliability. The results of both studies indicate that climate change can have significant practical consequences on structures and should be considered by civil engineering profession. Revision of design standards and further research in cooperation with meteorologist seem to be needed to explore and reduce the impacts of climate change on load bearing structures in the Carpathian Region.

Key-words: climate change, civil engineering, reliability, probabilistic analysis, Bayesian statistics, snow action, non-stationary models, concrete carbonation, durability, Carpathian Region

1. Introduction

The basic objective of civil engineering is to design, build, and operate facilities which serve societal needs. This is to be accomplished among various uncertainties, e.g., uncertain material properties, uncertain future usage, very rare natural or manmade hazards. The designers must then ensure that the frequency of failures does not exceed a level acceptable by society. A major source of uncertainty is associated with actions such as wind, snow, earthquakes, traffic which should be reliably predicted and anticipated during the design process. Currently applied models for representation of these actions are prevalently based on historical experience and on the assumption of stationarity. However, observations of the past decades and sophisticated climate models imply that relying solely on past experience may be misleading. It is expected that climate change will (and very likely already did) considerably alter environmental conditions and extremes (*IPCC,* 2012; *Milly et al.*, 2008; *Retief et al.*, 2014). Thus, there is an urgent need to revise current design provisions and to incorporate the predicted effects of climate change.

Since engineering works are crucial components of industrialized societies and intended to be used by many generations – their service life is often over 100 years –, it is imperative to consider the expected effects of climate change. It is substantially cheaper to reduce the impacts of climate change today by designing resilient structures rather than to cope with more severe impacts by rehabilitations of existing structures in future. It is estimated that in 2010, climate change had already contributed to economic losses about 1% of global GPD; a considerably increase is expected in the future (*DARA*, 2012).

The potential adverse effects of climate change on structures are recognized and investigated for several regions and countries, e.g., Ireland (*CIACC*, 2009), Canada (*ACC*, 2008), and the United Kingdom (*IECCA*, 2011). These studies mainly focus on identifying and enumerating the effects and possible issues. Only relatively few quantitative numerical studies are available. Numerical researches are conducted in Australia within the framework of a national flagship program (*Nguyen et al.*, 2010; *Stewart* and *Wang*, 2011; *Wang et al.*, 2010).

To the authors' knowledge, few studies have been focused on construction works in the Carpathian Region and most of them intended to draw attention to the issue of climate change without any quantitative analysis (*Lenkei*, 2007; *Timár*, 2010; *VAHAVA*, 2010) or focusing on building physics and energetics (*Medgyasszay et al.*, 2007). A study by *Horváth* and *Pálvölgyi* (2011) is quantitative but not focused on structural or reliability aspects. That is why the authors conduct quantitative analysis of climate change on load bearing structures to provide first insights and to support decision making. The aims of this paper are:

- to present two quantitative studies dealing with typically neglected though important aspects in civil engineering;
- to give a broader view about relation of civil engineering with meteorology, thus to facilitate cooperation between experts, and to bridge the gap between engineering and climate sciences;
- to draw attention of civil engineers to challenges related to climate change.

The contribution summarizes the main findings of the previous conference contributions by the authors (*Rózsás* and *Kovács*, 2013a; *Rózsás et al.*, 2015; *Rózsás* and *Vigh*, 2014), and extends them by providing a broader perspective. The first study is dealing with carbonation induced corrosion of concrete structures considering six climate change scenarios. The second study is focused on modeling of extreme snow events, long-term trends in meteorological observations, and their effect on failure probability with special focus on statistical uncertainties. Both topics seem to be underestimated and often neglected in the present practice.

2. Climate change and civil engineering

2.1. Impacts of climate change on civil engineering structures

There is a virtually unanimous consensus among climate scientist that climate change is an ongoing process, largely caused by human activity, and urgent, large-scale measures are needed to avoid dangerous, irreversible, practically uncontrollable consequences (*Anderegg et al.*, 2010; *IPCC*, 2014; *Leshner et al.*, 2009; *UNFCCC*, 2010).

Climate change response strategies can be divided broadly into two categories: mitigation and adaptation (*IPCC*, 2001). These two strategies are often interrelated, i.e., by enhanced corrosion protection of bridges, future durability issues are moderated (adaptation) along with decreasing the green-house gas emissions by reducing traffic congestion and detours due to reduced maintenance (mitigation). Given the predicted severe consequences of climate change (*Warren*, 2011), surprisingly few studies are focused on large scale mitigation only. A notable exception is the research group of Mark Jacobson, which demonstrated that transition to renewables in the US of the all-purpose energy system (for electricity, transportation, heating/cooling, and industry) is economically and technologically feasible by 2050 (*Jacobson et al.*, 2015).

Table 1 summarizes some effects of climate change which bear relevance to construction works.

Corrosion related issues deserve special attention, since durability requirements and regulations are typically underdeveloped in standards. Furthermore, the corrosion related effects and costs are enormous but they are typically considerably underestimated, partially as they are not accompanied by singular catastrophic events. The most costly natural disaster in history, the 2011 Tōhoku earthquake and tsunami with \$235 billion damage as high estimate (*WB*, 2011), is only one-fourth of the annual corrosion related losses in the US (over \$1 trillion). The latter number is estimated using the 2013 level GDP of the US and approximating the sum of direct and indirect corrosion costs to be 6% of the GDP (*Koch et al.*, 2001).

The aging and deteriorating bridges are common and urgent issue worldwide. As an example, in Hungary 60% of the bridge population is over 50 years old (*KKK*, 2012), and 25% of highway bridges are rated with local or global deficiencies (rating 4 or 5 on a 5 scale measure with 5 as the worst) (*Tóth*, 2012); similar figures apply for the Czech Republic. Moreover, the infrastructure comprises a great amount of national wealth in every country, e.g., in the UK at least 50% (*Long*, 2007). In Hungary, the transportation infrastructure is about one-fifth of the total national wealth, and it generates 5–6% of the GDP. 2–3% of GDP is annually devoted to its development (*KKK*, 2008).

2.2. Design standards – Eurocodes

Standards and design provisions are the main instruments of everyday engineering practice, aiming to design and construct reliable structures. Practicing engineers have typically insufficient knowledge or lack of time to conduct advanced analyses beyond provisions in standards; therefore, it is largely the responsibility of the research community to address challenges and needs of society. The importance of this task is well illustrated by that the built environment comprises about 80% of the national wealth of developed nations (*Sarja*, 2005).

Table 1. Selected projected impacts of climate change with relevance on load bearing structures.

Description	**Climate**	**Struct. eng.**
For the Central European region, the mean recurrence time of the current (1981–2000) 20 years return period daily precipitation maxima is expected to reduce to 16–10 years for 2046–65 period, and to 16–7 years for 2081–2100 period. The ranges are covering 50% of the considered climate models and corresponding to B1, A1B, and A2 scenarios (*IPCC*, 2012).	Precipitation	Floods, slope stability, landslides, scours
For the Central European region, the mean recurrence time of the current (1981–2000) 20 years return period daily temperature maxima is expected to reduce to 10–2 years for 2046–65 period, and to 6–1 years for 2081–2100 period. The ranges are covering 50% of the considered climate models and corresponding to B1, A1B, and A2 scenarios (*IPCC*, 2012).	Temperature	Expansion joint, rail track buckling, increased stresses
Using the 1951–80 period as reference, the monthly temperature during northern hemisphere summers are expected to increase significantly. The percentage of global land area with over 3 and 5 sigma reference thresholds are predicted to increase from less than 1% to 19% and from less than 1% to 2–3%, respectively, by 2100 for RCP2.6 scenario. The percentage of the global land areas in the same order for RCP8.5 scenario are 87% and 58% (*Dim* and *Alexander*, 2013). The former scenario or concentration pathway (RCP2.6) is very likely already unattainable, and the latter (RCP.8.5) represents the most severe, business-as-usual case with increasing greenhouse gas emission to the end of the 21st century.		
The probability of mega-heatwaves, such as the 2003 and 2010 summer extremes in Europe, are predicted (A1B scenario) to increase 5 to 10 times within the next 40 years (*Barriopedro et al.*, 2011).		
For some regions in Australia (Cairns, Townsville, Rockhampton, and Brisbane), climate change induced mean wind damage losses can increase by \$2.8, \$7.1 and \$15 billion by 2030, 2050, and 2100, respectively. For new constructions, the increase of the wind pressure design value is a cost-effective adaptation measure (*Stewart* and *Wang*, 2011).	Wind	Roofs, claddings
For reinforced concrete structures, *Stewart et al.* (2011) found that in Australia the carbonation-induced corrosion damage risk can increase by 40–460% at the end of the 21st century, compared to year 2000 as reference. The same study demonstrated that chloride ion induced damage risk can increase by 6–15%.	Combined*	Corrosion
Nguyen et al. (2013) studied the atmospheric corrosion of metal fasteners in timber construction for Australia under the A1FI scenario (most severe among considered scenarios) using the most severe global circulation models, and found 40% and 20% increase in corrosion rate for Brisbane and Melbourne, respectively, by 2100 comparing with 1990 as reference.		

*The combination of multiple meteorological changes can be important for corrosion, where typically the interplay of multiple factors is crucial, e.g., wet-dry surface alteration and temperature change.

To illustrate where and how climate change and climate research are connected to standards, the conceptual framework of standardization and its relation to engineering practice is depicted in *Fig. 1*. The process starts with gathering theoretical and empirical information to identify the physical and probabilistic models required to represent the behavior of various structures and their loads. These coupled physical-probabilistic models are applicable to structural design. However, they are excessively complex for everyday use. Therefore, the probabilistic models are replaced with approximate deterministic methods, where sufficient reliability is achieved by application of safety factors. These factors are calibrated to more advanced probabilistic models to ensure the target reliability, which should represent an optimum value for the whole society considering human, environmental, and economic aspects (*Steenbergen et al.*, 2015). This procedure is conceptual since the subject is overly complex and uncertain, thus these calculations cannot be precisely completed. The acceptable level of failure probability is typically expressed in terms of target reliability, which is based on expert judgement, comparative analysis of human risk acceptance and perception, and limited quantitative analysis. In Europe, for a typical building, the annual target failure probability of 10^{-6} is selected for structural failure. It should be noted that this is a nominal value for decision making, and does not correspond to actual failure rates that are typically governed by uncertainties not covered in standards such as human errors and negligence. These account for about 80% of the observed failures (*Melchers*, 2002; *Melchers et al.*, 1983).

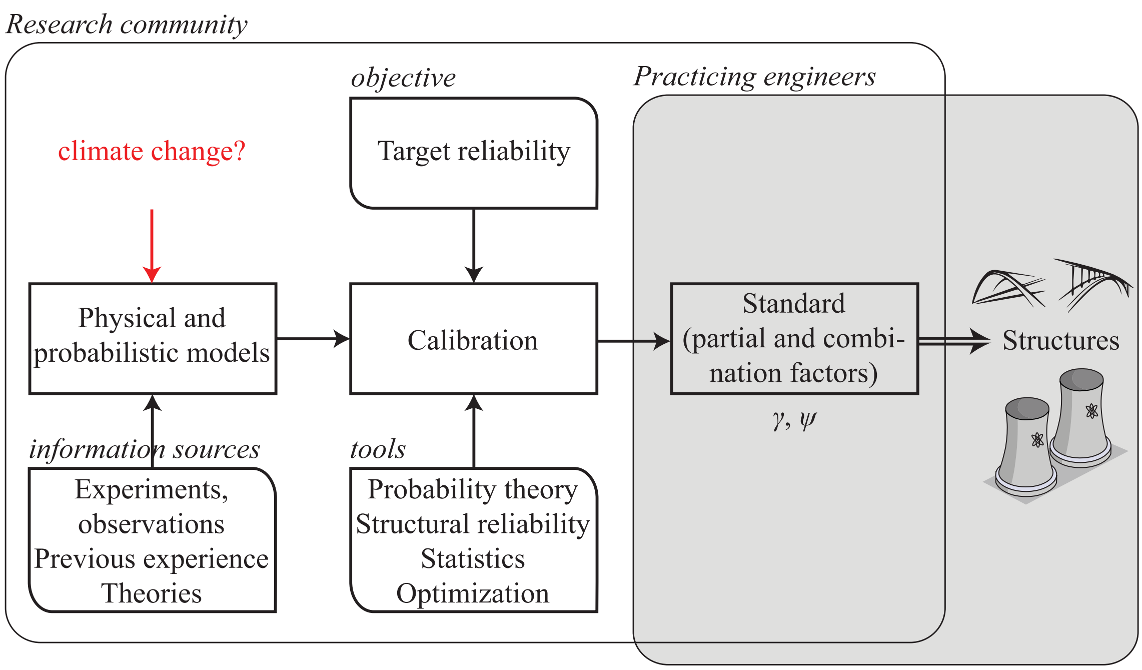


Fig. 1. Conceptual framework of standard calibration and its connection to engineering practice.

Hereafter, we focus mainly on the common European standard for basis of design – EN 1990 (hereafter 'Eurocode' for brevity). It is based on the limit state concept, i.e., the boundary between meeting (safe) and failing to fulfill a demand (failure) is sharp, characterized by a sudden change in performance. This is illustrated in *Fig. 2* along with the requirements and limit states of the Eurocode. The three principal requirements that a structure should fulfill are:

- structural resistance (avoid partial or full collapse);
- serviceability (not to impede usage, operation);
- durability (limit deterioration).

These are treated in the framework of ultimate (ULS) and serviceability limit states (SLS). The basic approach to verification of the limit states in the Eurocode is the partial factor method.

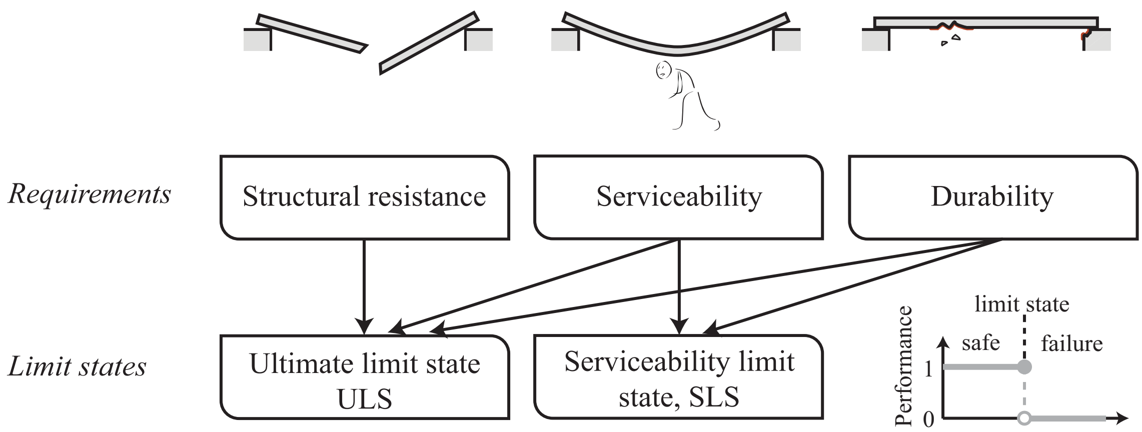


Fig. 2. Illustration of the requirements and limit states of Eurocode.

As other design standards, Eurocodes are more advanced in respect of physical models for structural resistance, and most of the research efforts are still devoted to these. The probabilistic and durability models are less developed; however, this biased focus is not justified. The disproportional development of physical and probabilistic models renders the advances in the former less effective (*McRobie*, 2004), e.g., the impact of 10% improvement in a resistance model of steel members is overweighed by the uncertainties in the probabilistic load models. Regarding durability, the economic cost of corrosion is enormous, typically much larger than those associated with structural failures, e.g., in the US the total cost of weather-related disasters for 22 years ($380 billion) is comparable to the annual direct cost of metallic corrosion ($276 billion, 3% of the US, GDP). Moreover, the indirect costs, associated with the loss of productivity, are estimated to be equal of direct costs (*Koch et al.*, 2001). In respect of climate change, these findings suggest that probabilistic analysis and durability issues are of utmost importance.

2.3. Methodology

Analysis and plan of responses to climate change are inherently probabilistic and interdisciplinary issues. This probabilistic nature is in-line with engineering work, which has to cope with numerous uncertainties by means of the probability theory, statistics, and structural reliability. In reliability analyses, the failure probability of structures and structural elements is estimated using the limit state concept. A limit state function ($g(\mathbf{X})$) is typically formulated as the difference of capacity and demand:

$$g(\mathbf{X}) = capacity - demand, \tag{1}$$

thus $g(\mathbf{X}) < 0$ describes exceedance of the limit state (*Fig. 3*). All relevant basic variables ($\mathbf{X}$) are represented as random variables with their probability density functions. The failure (violation of limit state) probability then can be calculated as the integral of the joint density function $f_{\mathbf{X}}(\mathbf{x})$ of basic variables over the $g(\mathbf{X}) < 0$, failure region:

$$P_{\mathrm{f}} = P\left(g\left(\mathbf{X}\right) < 0\right) = \int_{g(\mathbf{X})<0} f_{\mathbf{X}}(\mathbf{x}) \cdot d\mathbf{x}\,. \tag{2}$$

The above – typically high-dimensional – integral is usually approximated by numerical techniques especially tailored for the particular features of structural reliability problems (*Lemaire et al.*, 2010; *Melchers*, 2002). The design point (*Fig. 3)*, associated with the highest density value on the failure surface ($g(\mathbf{X}) = 0$) is an important element of reliability analysis, that provides information about the importance of random variables and failure probability. Although in this paper the comparisons and conclusions are solely based on the failure probabilities, structural reliability analyses are often extended to risk-based decision making problems considering economic and environmental consequences, and human safety as well (*Köhler*, 2011).

Both in civil engineering and climate sciences, coupled physical-probabilistic models are used to represent complex systems and to propagate uncertainties. In climate sciences, estimates of the first two moments (mean, standard deviation) of random variables are typically sufficient, in civil engineering, full specification and propagation of random variables are necessary to calculate low failure probabilities.

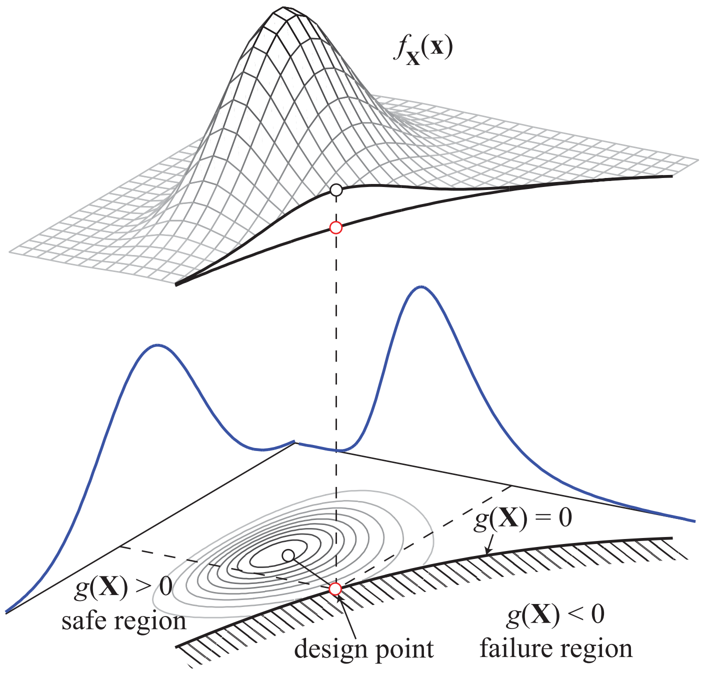


Fig. 3. Illustration of the limit state function, design point, and the safe and failure performance regions.

3. Probabilistic analysis of reinforced concrete structures exposed to carbonation

3.1. Carbonation of reinforced concrete structures

Concrete is the most widely used manufactured material worldwide as its constituents are widely available, it can be casted into almost any shape, and it has favorable physical properties to work together with steel reinforcement. A particularly important property is that concrete provides an alkaline environment, which prevents the atmospheric corrosion (oxidation) of the embedded steel elements, i.e., ensures the passivation of steel. Carbonation of concrete is a chemical process which leads to lower pH value and corollary to the depassivation of steel. Since the oxidation product (rust) has smaller density than the steel, the process leads to cracking and spalling of concrete (*Fig. 4* - the numbers of states are related to those in *Fig. 5*), and ultimately can induce serviceability and structural resistance problems.

3.2. Probabilistic analysis

Carbonation is the most common corrosion cause of reinforced concrete that affects almost every structure. It is mainly driven by the CO_2 concentration of the surrounding air which diffuses into the concrete and reacts with it (*Fig. 4*); thus, the expected increase of CO_2 in the future might considerably accelerate the process. To investigate this, time-variant probabilistic analysis (*Melchers*,

2002) is performed considering six climate change scenarios. For simplicity, only the depassivation period is taken into account, which is typically longer than the propagation period (*Fig. 5*), and it is expected to give good indication of the possible changes regarding the entire corrosion process.

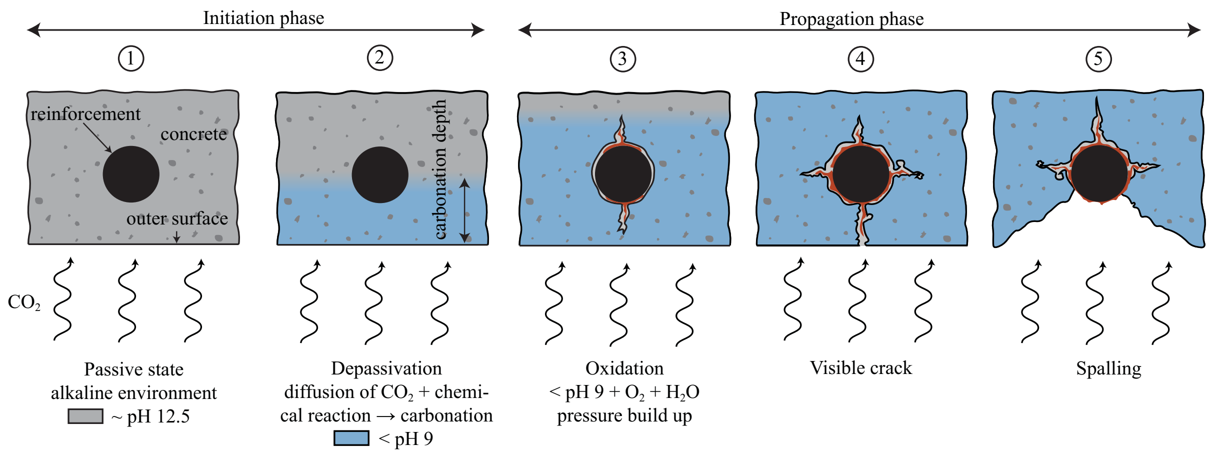


Fig. 4. Carbonation process of reinforced concrete, illustration of initiation and propagation phases.

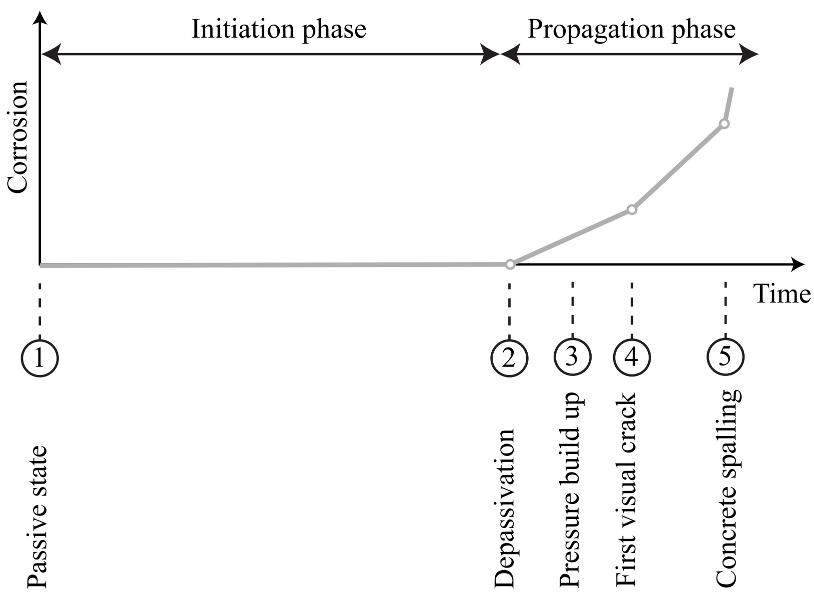


Fig. 5. Evolution of carbonation-induced corrosion in time.

The corrosion model and probabilistic description of basic variables provided by *fib* - the International Federation for Concrete Structures is adopted (*CEB/fib*, 2006). The corrosion model based on Fick's law of diffusion was extended by the authors to the case of time-varying CO_2 concentration (*Rózsás* and *Kovács*, 2013b). Six SRES climate change scenarios are considered: three scenarios within the rapid economic growth family A1: the A1FI (fossil intensive), A1T (predominantly non-fossil), and A1B (balanced) scenarios, and additionally the A2 (regionally oriented economic), B1 (global environmental sustainability), and B2 (local environmental sustainability) scenarios (*IPCC*, 2007) with probabilistic representation of CO_2 level, number of rainy days, and relative humidity. Additionally, a reference scenario corresponding to a constant CO_2 level for the year 2000 is considered as representing the provisions solely based on past experience.

Reliability analyses are completed for a hypothetical structure built in 2000, assuming 100 years design working life. The structure is thus expected to operate without major structural maintenance within this period. The minimal durability provisions of EN 1992-1-1 for design of concrete structures and the superseded Hungarian national standard (*ÚT*, 2002) are analyzed. The latter is motivated by the fact that significant portion of the Hungarian bridge inventory is constructed according to the pre-Eurocode national standards. It is anticipated that the neighboring countries in Central Europe had similar provisions, thus the results are indicative for their conditions as well.

The depassivation probabilities for each decade in the 2000–2100 period are calculated using crude Monte Carlo simulation. Various exposure classes (XC2, XC3, XC4) and cement types (CEM I 42.5 R, CEM I 42.5 R+FA) are considered to cover a large range of reinforced concrete structures. The exposure classes correspond to different environmental conditions differentiated by the duration and frequency of wet and dry phases (*CEN*, 2000, 2004). For example, XC2 class belongs to wet, rarely dry environment which is typical for industrial floors and building foundations, and XC4 represents cyclic wet and dry environment which is applicable for bridge piers, piles, and bridge superstructures.

4. Results

The time-course of the depassivation probabilities are illustrated in *Fig. 6*, the blue lines are representing the six climate change scenarios, while the yellow stands for the reference model.

The SRES scenarios are unanimously predicting increase in the depassivation probability compared with the reference model. The difference between the climate change scenarios and reference model becomes more substantial with increasing time. With the exception of EC-XC4, the durability provisions yield to greater depassivation probability than the selected 10% target (*CEB/fib*, 2006). The deficiency in the ÚT provisions is particularly apparent for CEM I 42.5 R cement, for which the target probability is reached within 30–40 years, even with the reference model, and the depassivation probability at 2100 is about 0.4 (*Fig. 6*). This means that for 4 out of 10 such structures, the depassivation of the reinforcement can be expected. The expected changes in carbonation depth (*Fig. 4*) and depassivation probability for the 2000–2100 reference period are summarized in *Table 2*. The numbers show that although the smallest relative changes are expected for the ÚT provisions, in absolute terms they are performing the worst (*Fig. 6*). Additionally, albeit the EC-XC4 provision has the largest relative increase (>100%), it still complies with the 10% limit value.

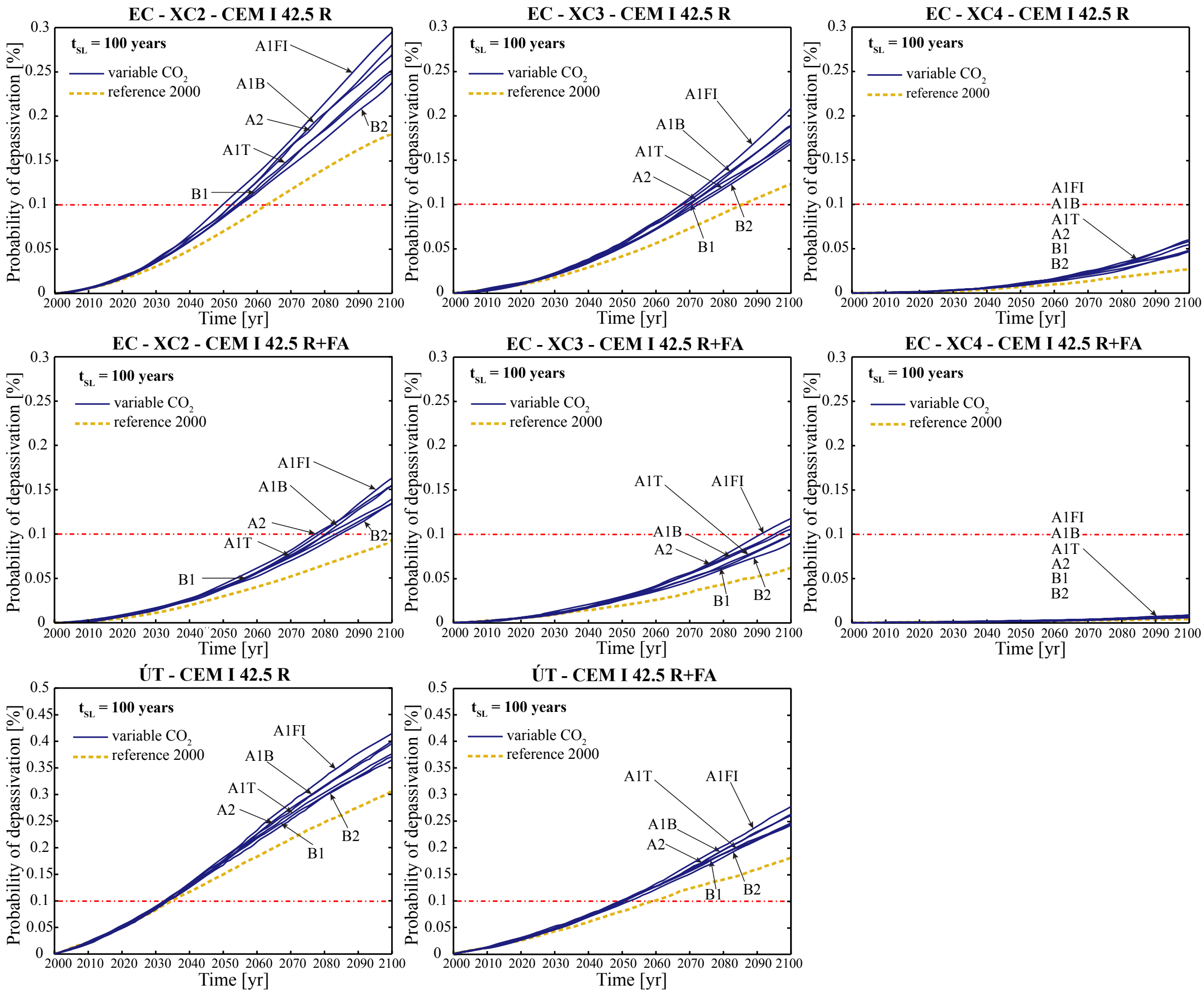


Fig. 6. Probability of depassivation corresponding to a hypothetical structure built in 2000 with 100 years design working life (t_{SL}), and using the provisions of Eurocodes (EC) and the superseded Hungarian national standard (ÚT) for multiple exposure classes (XC2-4), cement types (CEM I 42.5 R, CEM I 42.5 R+FA), and climate change scenarios (A1FI, A1T, A1B, A2, B1, B2). The selected target probability is 10% (*Rózsás* and *Kovács*, 2013a).

Table 2. Increase in carbonation depth (x_c) and depassivation probability (P_f) compared to the reference model, the intervals cover the considered six climate change scenarios (*Rózsás* and *Kovács*, 2013a).

		CEM I 42.5 R		CEM I 42.5 R+FA	
Standard	**Exposure class**	**Δx_c [%]**	**ΔP_f [%]**	**Δx_c [%]**	**ΔP_f [%]**
Eurocode	XC2	11 – 20	33 – 61	13 – 21	55 – 90
	XC3	12 – 21	44 – 73	12 – 20	50 – 82
	XC4	12 – 20	70 – 115	10 – 19	65 – 100
ÚT	–	11 – 20	21 – 36	13 – 21	33 – 55

The following conclusions are drawn from the probabilistic analysis:

- It is expected that the increased CO_2 concentration will lead to practically significant increase of depassivation probability compared with the reference model based on concentration corresponding to year 2000. The probability can increase by 115% until the end of the 21st century (*Table 2*).
- Most of the analyzed EC and ÚT durability provisions do not meet the considered 10% target probability, not even for the reference scenario (no climate change). By 2100, the EC and ÚT regulations can yield to 2.5 and 4.0 times greater depassivation probability, respectively, than the target, considering the most commonly used CEM I 42.5 R cement type (*Fig. 6*).
- For structures built in 2000, the effect of climate change is expected to be subtle till the middle of the 21st century, the practically significant effects are predicted for the second half of the century.

The findings indicate that the revision of the current durability provisions would be timely. To select appropriate adaptation measures, the analysis should be extended with the propagation phase of the corrosion and with economic cost analysis. These findings are deemed indicative, even if the presented analysis is intentionally simplified. For large structures, spatial variability in material and geometry characteristics needs to be taken into account, and the optimum target reliability may be different from the level indicated by the *fib* bulletin (*Holický*, 2011; *Sýkora* and *Holický*, 2013).

5. Snow extremes and structural failure probability

5.1. The effect of statistical uncertainties

In contrast with the serviceability and durability requirements, the target failure probability for ultimate limit states – associated with partial or full collapse of structures or structural members – is several orders of magnitude smaller. It is typically determined by distribution fractiles to which no observations are available (
Fig. 8). For example, for meteorological extremes, commonly 50–100 years of observations are available, but failure probabilities of about 10^{-4} in 50 years should be calculated and justified. Therefore, it is of crucial importance to account for statistical uncertainties which arise from the scarcity of available information. It is alarming that the current practice in civil engineering commonly neglects these uncertainties and uses 'best' point estimates such as maximum likelihood estimates, thus leads to deceptive confidence.

Coles et al. (2003) report the 'embarrassingly frequent' occurrence of events believed to be quasi-impossible, and partially attribute this to the neglect of statistical uncertainties in probabilistic models. Statistical uncertainty is composed of parameter estimation uncertainty and model selection uncertainty. The former is the uncertainty in the identification of the parameters of a particular probabilistic model, while the latter is the uncertainty in the identification of the generating model type. Both of these uncertainties are illustrated in *Fig. 7*, parameter estimation uncertainty by confidence bands, and the model selection uncertainty by considering multiple models. *Fig. 7* shows the annual ground snow maxima for two representative locations of the Carpathian Region: Budapest represents low-land areas with Fréchet-like distribution (skewness$<$1.14), and the Slovakian Tatra Mountains represents mountainous areas with Weibull-like distribution (skewness$<$1.14). The data are obtained from the CARPATCLIM project as snow water equivalents in daily temporal resolution covering the 1961–2010 period (*Szalai et al.*, 2013).

The interval coloring in *Fig. 7* and
Fig. 8 is 'ink-preserving', i.e., the same 'amount of ink' is used for every vertical section, hence creating a linear transition from the narrowest (dark blue) to the widest interval (white). In a particular 2×2 figure, equal ranges have the same color on each subplot, thus the models are directly comparable based on coloring as well. *Fig. 7* shows that moving away from the observations, the confidence bands are substantially widening. The difference between the models is remarkable, especially the narrow confidence band of the Gumbel distribution, which often does not encompass the largest observations.

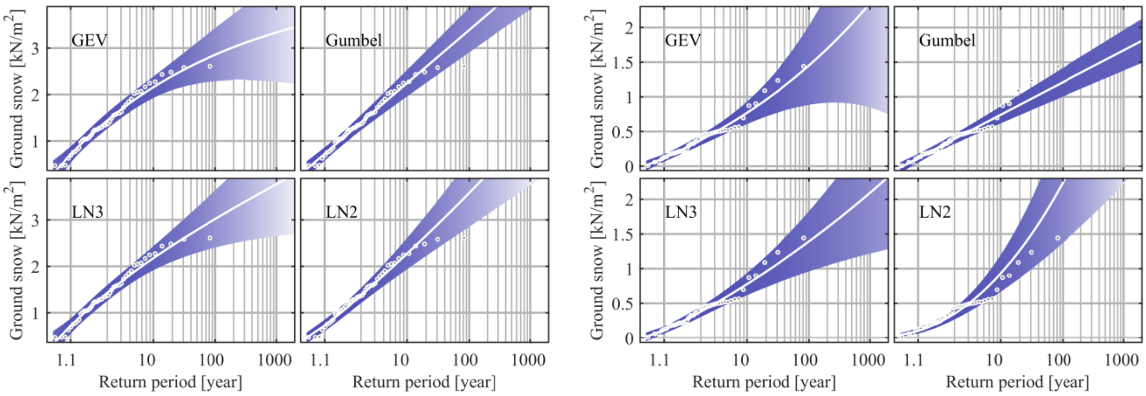
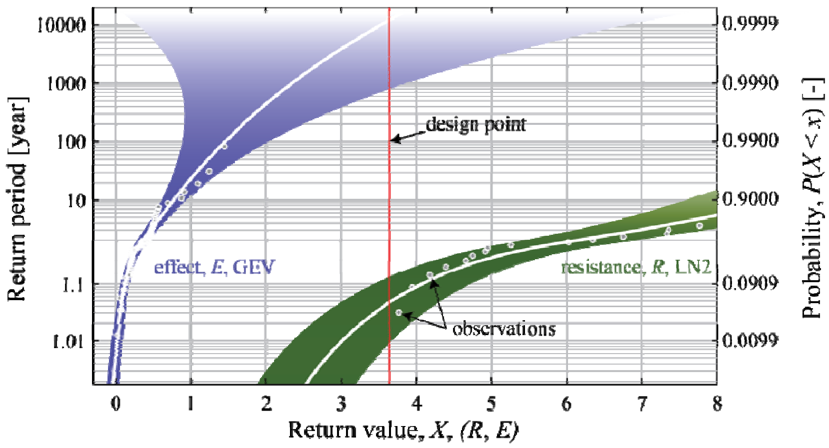


Fig. 7. Illustration of statistical uncertainty for annual maxima of ground snow load in Gumbel space, maximum likelihood fit with 90% confidence band (delta method). Slovakian Tatra Mountains (left), Budapest (right). GEV – generalized extreme value distribution, LN3 – three-parameter lognormal distribution, LN2 – two-parameter lognormal distribution.



$g = R - E$

$R \sim \mathrm{GEV}$; $E \sim \mathrm{LN2}$

	mean	CoV	n_{obs}
R	6.4	0.3	20
E	0.4	0.7	49

$P_{\mathrm{f}} = 1.8\times10^{-5}$

Fig. 8. Illustration of parameter estimation uncertainty and its relation to design point for a simplified reliability problem, maximum likelihood fit with 90% confidence band (delta method). E is inferred from the annual ground snow maxima of Budapest, also used in *Fig. 7*.

5.2. Reliability analyses

Failure probability is determined by the very uncertain tail of distributions. *Fig. 8* shows cumulative distribution functions of resistance and effect random variables for a simple limit state function. The probabilistic models of the random variables are inferred from a limited number of observations, and the parameters are selected to represent a lightweight steel structure subjected to snow load. The parameter estimation uncertainty is substantial as the confidence bands at the design point (red line) show. This small example well illustrates that using only the point estimates (white lines) conveys false confidence in the models.

The confidence interval around the maximum likelihood point estimate (ML) illustrates the extent of parameter estimation uncertainty. However, this frequentist approach does not allow incorporating parameter estimation uncertainty directly into failure probability. This can be accomplished within the Bayesian paradigm, which bases the inference on the relative evidence of the parameter values given a dataset (*Spiegelhalter* and *Rice*, 2009). Additionally, it treats the distribution parameters as random variables, thereby enabling to integrate them into the failure probability. Herein Bayesian posterior predictive distribution (BPP) is chosen to take into account parameter estimation uncertainty (*Aitchison* and *Dunsmore*, 1980). For comparison, Bayesian posterior mean (BP) as Bayesian point estimate is also considered, this represents a model without parameter estimation uncertainty. For all Bayesian calculations, vague priors are used.

To compare these approaches and to further illustrate the effect of statistical uncertainties, a steel frame is analyzed in the following section (*Rózsás* and *Vigh*, 2014). Reliability of such lightweight structures is often dominated by snow load. The simple 2D steel frame, illustrated in *Fig. 9*, with a span of 12 m and bay width of 5 m is subjected to self-weight, permanent load, wind load, and snow load. The hypothetical structure is located in Budapest, the annual snow maxima presented in the right side of *Fig. 7* are used to infer the distribution parameters.

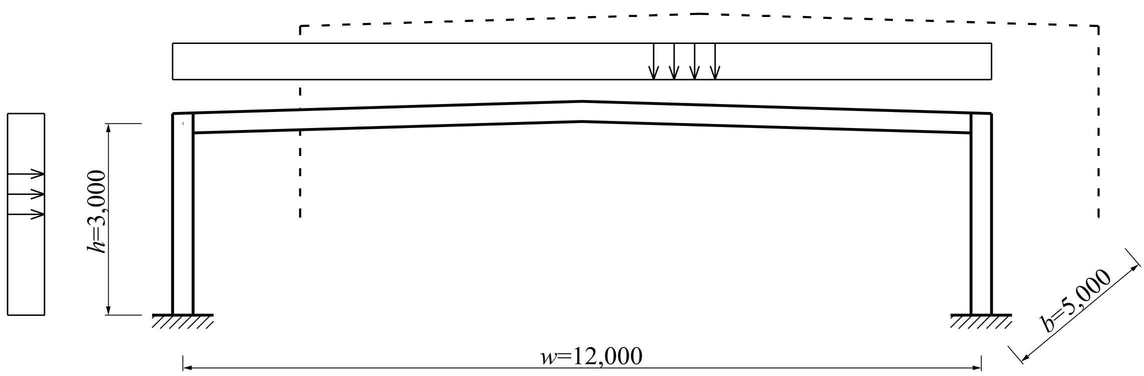


Fig. 9. Steel frame exposed to permanent, snow, and wind load (*Rózsás* and *Vigh,* 2014).

The structure (cross-section dimensions) is designed in accordance with Eurocode 3 (*CEN*, 2005) with full (100%) utilization. Parametric study is completed, in which:

- the ratio of the snow load to the whole load effect, χ, is varied and the structure is accordingly redesigned for each case;
- two distribution types and
- three distribution parameter estimation techniques are tested for annual maxima of the ground snow load.

6. Results

Left part of *Fig. 10* compares the annual failure probabilities calculated by different parameter estimation techniques, using Gumbel distribution. It appears that BP and ML may underestimate the statistical uncertainties and the failure probability of the structure. It is clear that this effect becomes more significant with an increasing snow load ratio.

For different distribution types and parameter estimations, right part of *Fig. 10* shows the failure probability in function of the snow load ratio. It is confirmed that the probability of failure may considerably increase if the snow load follows GEV distribution. It is also shown that GEV is more sensitive for the incorporation of parameter estimation uncertainty.

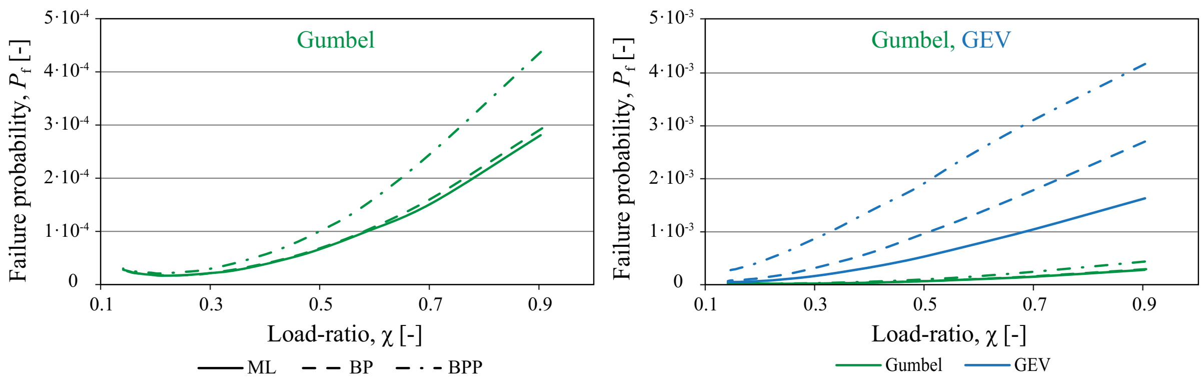


Fig. 10. Effect of distribution parameter estimation techniques on annual failure probability (P_f) in respect of load ratio (χ).
ML: Maximum likelihood, BP: Bayesian posterior; BPP: Bayesian predictive posterior.

Fig. 10 confirms that:

- The parameter estimation uncertainty in snow model has a significant effect on the reliability, in case of Gumbel and GEV distributions the incorporation of this uncertainty yields to about 1.4 and 5 to 6 times greater failure probability, respectively.
- The GEV-ML model leads to about 7 times greater failure probability than the Gumbel-ML model which is adopted in the Eurocode.

The consideration of these uncertainties can be especially important for safety critical facilities such as nuclear power plants.

6.1. Non-stationary extremes - long-term trends in time

The analyses in the preceding sections are based on stationary probabilistic models; however, some studies concerning snow precipitation found decreasing trend in Europe. *Birsan* and *Dumitrescu* (2014) have analyzed historical observations from Romania and detected decrease in snowfall days (82% of stations) with substantial decrease in snow depth (18% of stations) and snow coverage (29% of stations). *Marty* and *Blanchet* (2012) have found statistically significant (p<5%) decreasing long-term trends in annual maxima snow depth for the Swiss Alps.

Time trends in annual maxima of ground snow load and their effect on structural reliability have been insufficiently studied for the Carpathian Region so far. Therefore, the long-term trends in annual snow maxima are analyzed for the entire region using the data from CARPATCLIM database (*Szalai et al.*, 2013).

Initially, a straight line is fitted to the annual maxima in least square sense. The slope parameter (m) with a representative location is illustrated in *Fig. 11*. Decreasing trend in annual snow maxima is found for 97% of the studied region.

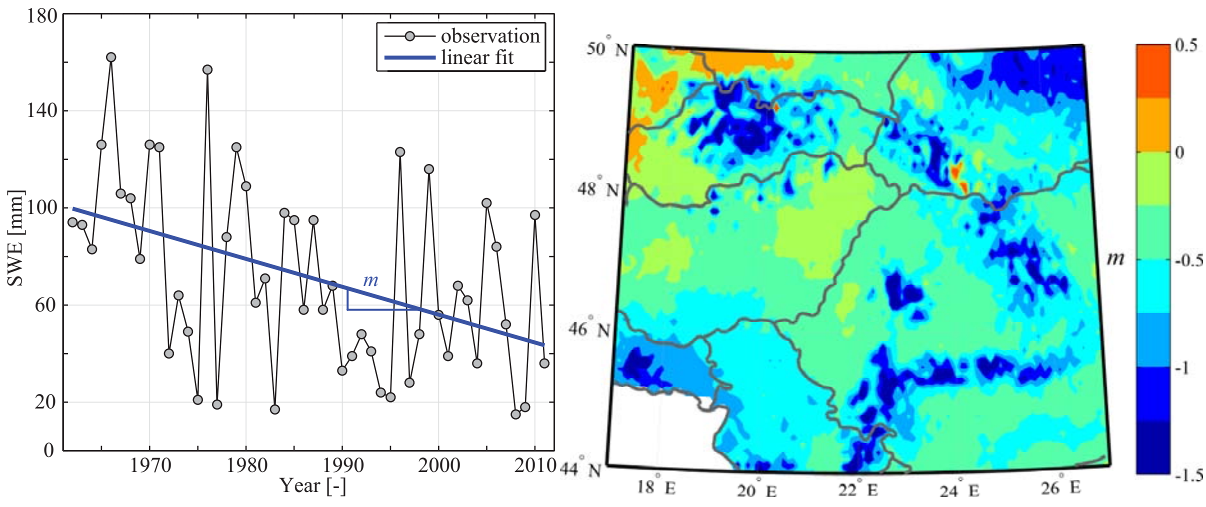


Fig. 11. A representative location with decreasing trend (left), and map of the linear trend line's slope parameter *m* in mm/year (right) (*Rózsás et al.*, 2015).

Then, stationary and various non-stationary univariate generalized extreme value distributions are fitted to each grid points. Maximum likelihood method is used for parameter identification, and likelihood ratio and Akaike information criterion based comparison are applied to detect statistically significant trends. The Akaike weight (*Burnham* and *Anderson*, 2002) based comparison of stationary and non-stationary (linear trend in location parameter) models are presented in *Fig. 12.* The likelihood ratio and Akaike weight based comparisons identified numerous locations with statistically significant ($p<10\%$) trends. However, further reliability analyses revealed that these trends are often not practically significant in respect of structural reliability. This is mainly attributed to the considerable uncertainty of the probabilistic snow model in the range of the design point. For locations where practically significant trend is identified the change is favorable, i.e., the increase of reliability can be expected.

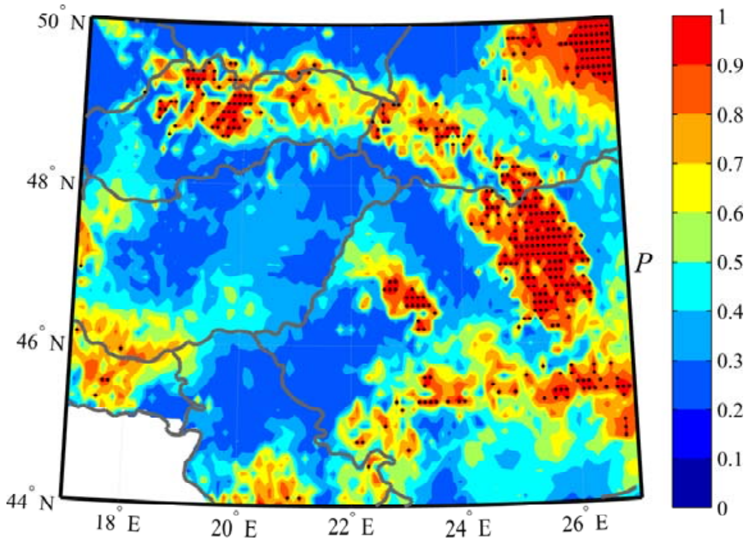


Fig. 12. Akaike weight based comparison of stationary and non-stationary (linear trend in location parameter) generalized extreme value distributions. $P>90\%$ locations are marked with black dots. P expresses the probability that the non-stationary model fits better the data than the stationary in Kullback-Leibler divergence sense (*Rózsás et al.*, 2015).

Similar calculations are completed for the Carpathian Region considering climate projection until the end of the 21st century. The preliminary results indicate decreasing trend in ground snow load and negligible effect on strucural reliability for some selected locations (*Kámán*, 2014). However, it requires further research to decide whether the results of global circulation models can reasonably predict such extremes which needed in structural reliability analyses.

7. Summary and concluding remarks

In this paper, we argued that civil engineering structures comprise great value and are crucial components of industrialized societies, thus the investigation of climate change impacts is necessary. An overview about civil engineering and its relation to climate change and climate sciences is given to facilitate future cooperation. Two numerical studies for the Carpathian Region suggest:

Concrete carbonation

- It is expected that the increased CO_2 concentration will lead to practically significant increase of depassivation probability compared with the reference model, with year 2000 level concentration. The probability can increase by 115% until the end of the 21st century.
- For structures built in 2000, the effect of climate change is expected to be subtle till the middle of the 21st century, the practically significant effects are predicted for the second half of the century.
- Uncertainty in projected environmental parameters affects significantly structural reliability estimates and improved quantification of this uncertainty by climate scientists and statisticians is needed.

Snow load

- Statistical uncertainties in probabilistic models of annual maxima of ground snow load can have significant effect and may considerably increase (with order of magnitude) the failure probability. Their neglect can lead to practically significant underestimation of failure probability.
- Analyzing historical observations, statistically significant decreasing trend ($p<0.1$, $P>0.9$) is found in annual maxima of ground snow load for numerous locations; however, practical significance is found only for a few, and the changes are favorable from reliability point of view.
- As the aforementioned conclusions can be generalized for other climatic actions, in particular for wind speeds, essential contribution of meteorologists and statisticians to civil engineering includes improved projections for trends and extremes in local weather events, and specification of uncertainties for large, 500-1000 years return period events.

Based on these findings, revision of design standards and further joint research of meteorologists and civil engineers are recommended to explore and reduce the impacts of climate change on load bearing structures. Steps are to be made as soon as possible due to the inertial effect of today decisions on climate system (*WBGU*, 2009).

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