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Statistical Investigation of Extreme Weather Conditions

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ABSTRACT: Structures are exposed to an ensemble of natural hazards. Earthquakes and flooding's are the most recognized natural hazards, but structures also have to be safe under extreme weather conditions such wind and hurricanes, heat periods and colds, extreme rainfalls, hail and freezing rain. Some of this hazards are usually not investigated in detail, however based on statistical investigations, hazard curves and representative values of hazards can be defined, if required. They can be applied in probabilistic computations to achieve the probability of failure of the structures. Although major efforts have been undertaken in recent years to estimate the hazards and the representative values, we have to notice, that the validity of the provided natural hazards estimations by means of statistical investigations is limited due to confined sample populations. One of this causes is the recently increased knowledge using data with extreme values from non-instrumental periods, which heavily influences the outcome of the statistics, if considered. Newer statistical methods and the inclusion of historical data can, but need not necessarily improve results under all conditions. This development has also been observed in seismic loading estimation and in flooding hazard prognosis.

1. INTRODUCTION

Structures are not only exposed to technical live and dead loads, they are also heavily exposed to natural loadings. Such loadings can reach extreme values, as known for seismic loading or flooding loads of water or sea exposed structures. However many other natural loadings exist, such as wind and storm loading, snow and ice loading, loadings from hail and rainfall or temperature loadings. Usually their contribution to the overall hazard figure is limited. Figure 1 shows the different natural hazards for a structure in a relative size related to rough generic risk values.

In the field of structural engineering, representative loading values for most hazards, such as wind and snow, have been developed and are based on statistical investigations (Handbuch Eurocode, but see also Lieberwirth 2003 and Proske & Van Gelder 2009). This studies mainly focus on the characteristic loading values with a return period of 50 years (98 % fractile), but some accidental loads are based on 10 000 year return period values (see Table 1).

The allowed extrapolation time of statistics is in range of 3 to 4 of the covered observation time (Pugh 2004). This would yield to a required observation time of 2500 to 3300 years for the accidental load value. Of course, such measurement series do not exist. Therefore not only data from measurement times should be used, but also non-instrumental data. This development is currently extended from seismic hazard assessment to all other natural hazards for structures.

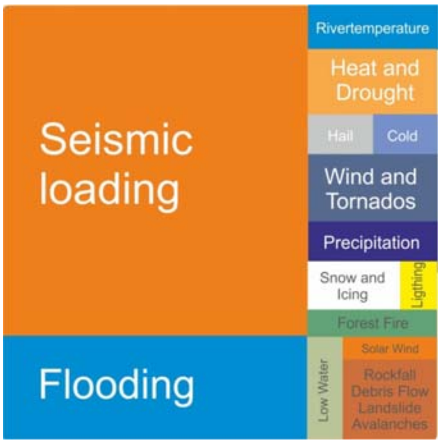

Figure 1: Classification of several natural hazards.

Table 1: Return periods of certain load combinations or load values(mainly based on Curbach & Proske 2002).

Load combination/ load value	*Return period*
Quasi-static	*50 percent of the time of the year*
Non-Frequent (DIN 1055)	*1 day (300 times per year)*
Non-Frequent (DIN FB)	*1 week*
Frequent	*1 year*
Rare	*10 years*
Characteristic (natural loading)	*50 years*
Accidental (earthquake)	*350 years*
Characteristic (traffic load)	*1000 years*
Accidental load	*10000 years*

2. AVAILABLE DATA

Observation periods for data can be distinguished into instrumental and non-instrumental periods. Non-instrumental periods can reach extreme times frames, for example in the field of seismicity. In Anatolia, based on geological investigations, about 60 earthquakes over a certain magnitude were identified for a time period of 4000 years (Gore 2000). Using written documents in some regions Mountain risk events can be identified over a period of 2000 years.

Non-instrumental data has been discussed so far in Austria and Switzerland for seismic hazards (Schwarz-Zanetti & Fäh 2011 a/b), for flooding (Tetzlaff et al. 2002, Wetter et al. 2011) and for Mountain risks (Totschnig & Hübl 2008, Disalp 2008). Many techniques exist for non-instrumental data observations, for example biological proxys, written documents, marks on structures and others (for an overview see Behringer 2011). However in most cases, the accuracy and density of the data points decreases, further one looks into the past.

In the last decades, climate history has provided non-instrumental data for a variety of climatological parameters. This research was mainly based on the discussion of climate change, see for example the discussion about Manns Stick. Results with different spatial resolutions mainly for Switzerland have been published by Pfister 1999, Behringer 2011, Dobrovolny et al. 2010, Ahmed et al. 2013, Z'graggen 2006.

In many cases instrumental data is available for a certain time period, mainly in the region of years, decades and sometimes a century. First measurements of temperature range from the 18th century (Pfister 1999, Behringer 2011). For example, the measurement time series from Central England with daily data is available from 1772. However, local effects such as the color of neighboring houses, the type of the measurement device housing and other effects can change the maximum measured temperature up to 4 Kelvin (Z'graggen 2006). Therefore measurement data is nowadays intensively reviewed and checked (Füllemann et al. 2011, Begert et al. 2003, Begert et al. 2005). One can summarize: we need to extend our observation time, but quantity (see figure 2) and quality decrease looking further into the past. Both, instrumental and non-instrumental data include certain drawbacks.

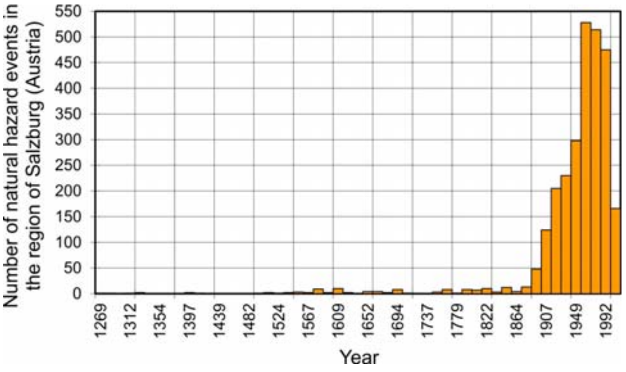

Figure 2: Mountain risk events of several natural hazards (based on Totschnig & Hübl 2008) using non-instrumental data for the Salzburg region in Austria

3. STATISTICAL INVESTIGATIONS

Major studies were undertaken to probabilistically quantify natural hazards and to provide detailed information in Switzerland in the last decade. For example, for seismic loading the PEGASOS and PRP Studies were carried out, running over more than 10 years. The studies are planned to reach the SSHAC Level 4 (Budnitz et al. 1997), the highest quality level on scientific seismic studies. The SSHAC (Senior Seismic Hazard Analysis Committee) gives rules and recommendations to provide seismic hazard estimations. SSHAC level techniques spend major efforts to include uncertainty of data and methods. Currently several SSHAC Level 3 projects are running worldwide (U.S. East cost study) to update and improve the quality of seismic hazard estimations.

The same trend can be seen for flood hazard estimations, especially after some major floods occurred in central Europe in the last decade of the 20th century. Some flooding hazard analysis already in 2009 include historical data. Currently the PLATEX/EXAR (BAFU 2014) project is running in Switzerland, which uses comparable quality standards as used for the seismic study.

One of the latest projects in this frame is the project extreme weather conditions. In this project several extreme weather parameters have been investigated, such as rain, hail or snow. Again, studies have been carried out before, for example for the preparation of the SIA-codes. However in the latest study data from non-instrumental periods were heavily discussed.

Besides that, extreme efforts were made during the statistical investigation. For example, for the rain data, the block maxima method was used and a generalized extreme value distribution was applied. The precipitation was investigated for seasonality, since rain shows maxima during the summer time. Therefore only data from May to September was used. Additionally to avoid time varying threshold levels, the distribution was used with time varying parameters. The following seasonality trend was assumed in the fitting of the distribution:

$$\mu(t) = \mu_0 + \mu_1(t - t_0) + \sum_{j=1}^{L} \left\{ c_j \cos(2\pi jt/365) + s_j \sin(2\pi jt/365) \right\} \tag{1}$$

with $\mu(t)$ as statistical time depend parameter, here as mean value, μ_0 as statistical parameter for a reference year, μ_1 as linear trend of the statistical parameter, t as time, t_0 as reference time (mainly in years) and c_j and s_j as constants for the consideration of seasonal variability.

Both, shape and scale parameter of the generalized extreme value distribution were adapted in the same way. Also the data was checked for annual changes over time.

Without going very much into detail, the above paragraph just shows the amount of deepness of the statistical analysis. Major efforts were undertaken to achieve robust and high quality hazard curves for the different hazards.

4. PROBLEMS

Non-instrumental data should allow an extension of the data pool by including rare event data. However based on the rather low quality standards for early measurements and the indirect indicators for non-measurement values, it is difficult to merge both, data from instrumental and non-instrumental time periods in the field of extreme weather parameters. Whereas in flooding and seismic loading, extreme values are usually well documented by existing structures at the time of the event, for extreme temperatures non such evidence exists.

Unfortunately, mistakes and uncertainty of proxy-data can heavily influence all hazards and therefore all the results of the statistical investigation. For example in Switzerland the intensity of the Lindau Earthquake from December 20 1720 was overestimated by a translation error from the original written documents. Also historical spatial relations can be misleading: an earthquake in the “Welschland” in 1152 was related to “Neuenburg” in Switzerland. However, the term „Welschland“ was not related to the French speaking Switzerland before the 19. century, but to Italy. Therefore the earthquake was related to a wrong location based on a wrong interpretation of written proxies. (Schwarz-Zanetti & Fäh 2011 a/b)

In table 2 and figure 3 we try to visualize such problems. Figure 3 shows the temperature anomalies for Switzerland from 1444 to 2003 (Wetter & Pfister 2013). First of all, the development of this diagram is an excellent work. However, whether this diagram can be used for extreme temperature hazard estimation can be easily detected by the comparison of the results from the non-instrumental period with instrumental data. Table 2 gives the official maximum temperature measurements for different locations in Switzerland. Based on table 2 the temperature anomaly in figure 3 for 2003 can be confirmed for the Swiss lowlands. However, the second largest temperature occurred for most measurements locations in 1983. In figure 3 the temperature anomaly for 1983 is pretty close to the confidence range, but does not seem to be an extreme value. Even further, the 1983 temperature values are the maximum values in many temperature measurement data series for instrumental time periods. Furthermore for Basel, on of the longest temperature measurement data series (from 1864), the third largest measurement occurred in 1921, whereas in figure 3 the 1945- and the 1934-anomalies are extremer than the 1921 value.

One can summarize, the comparison of local temperature measurements with the reconstruction of non-instrumental based temperature anomalies may be misleading. However, an solution would be to create an spatial and temporal average, for example for the Swiss lowlands for three month, based on the local instrumental data series (this was partly done by Wetter & Pfister). After comparing this values for instrumental and non-instrumental periods, we could disassemble the anomalies from non-instrumental time to achieve local extreme values. Such comparisons show indeed, that in general spring temperatures increase in Switzerland. This explains the change of anomalies and the limitation of the annual maximum temperatures.

This effects indicate, that data from non-instrumental periods require enormous proofing. Wetter & Pfister 2012 summarize in the discussion paper: “In summary, it is concluded that biological proxy data may not properly reveal record breaking heat and drought events in the pre-instrumental past. Obviously, such assessments need to be complemented with the critical study of contemporary documentary evidence being widespread in such situations and providing coherent and detailed narratives about weather patterns and climate induced impacts.” However, Totschnig & Hübl 2008 have also found major bias in written documents about historical events.

Table 2: Maximum annual temperatures in Switzerland according to MeteoSwiss (Z’graggen 2006).

Station	2003	1983	1947	1921
Grono	41.5 [1]			
Locarno-Monti	37.9	37.3		
Piotta	34.0	32.8		
San Bernadino	27.6	27.9		
Basel	38.6 [2]	38.4 [4]		38.4 [4]
Zürich	36.0	35.8 [5]	35.8	
Bern	37.0		35.9	
Altdorf	36.5			
Chateau d Oex	33.4	35.0		
Gstaad-Grund	32.0	34.0		
Adelbode	29.4	32.2		
Mürren (1638 m)		30.4		
Elm/ Engelberg	32.6	32.7		
Napf	29.7	30.4		
Pilatus	22.3	27.3		
Gütsch o. Andermatt	22.8	25.1		
Säntis	18.8	20.8		
Sion	37.2			
Ulrichen	30.5	32.2		
Montana	30.0	30.6		
Zermatt	30.1	31.9		
Grächen	29.5	31.5		
Chur	37.1	37.5		
Disentis	32.6	32.9		
Davos	27.3	29.0		
Arosa	26.2	26.5		
Weissfluhjoch	19.6	22.8		
Sta. Maria	29.7	30.6		
Robbia	32.9	33.3		
Scuol	33.1			
Genf	37.8			38.5

[1] Record of Switzerland: Grono is located on the border to Italy
[2] Record in the Northern Alp region
[3] Value is challenged
[4] 38.4°C from July 1983 and July 1921, the former maximum value was 39°C from July 2nd 1952, but was corrected to 37.3°C
[5] The former maximum value of 37.7°C from July 29 1947 was corrected to 35.8 °C.
[6] Foehn

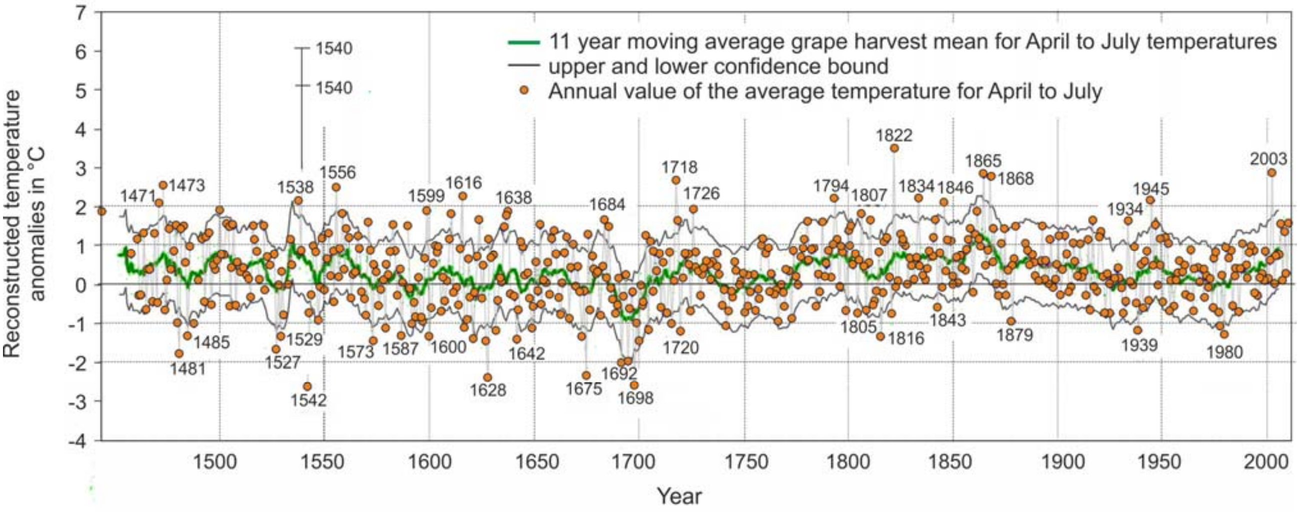

Figure 3: Temperature anomalies according to Wetter & Pfister 2013 for Switzerland

We can summarize, that instrumental data for the statistical estimation of extreme rare events is limited. The application of non-instrumental data is difficult, since different methods (biological proxy, written documents) may yield to different results and the results may not be transferable to the appropriate climatological parameter (extreme daily air temperature versus temperature anomaly over several month, peak wind gust speed versus description of storm etc.). Furthermore longer time periods, although adequate for statistical extrapolation of extreme accidental loads, may introduce changes of the population. The mentioned problems are not observed in this severity for seismic history, since here no change of population is assumed and geological artifacts are probably more robust than biological proxy's.

5. SUMMARY

The estimation of extreme rare events is required for design against accidental loads. Usually traditional statistical methods are applied for the estimation of the representative accidental loads. However, to extend the sample and observation time, the inclusion of non-instrumental data is currently state of the art (depending on the hazard type) to achieve accurate representative values. Besides the application of statistics in the sense of Fisher, Bayesian update techniques can and have been used to include the rough data from non-instrumental periods.

However, increased understanding of historical data (non-instrumental period) of extreme events may substantially change the results of the statistical investigation in rather short time periods and therefore limiting the lifetime validity of the probabilistic computation. Furthermore, the historical data may also not belong to the same population (Little Ice Age) and requires further adaptation. Besides, as mentioned above, the investigation of non-instrumental data usually results in regional and seasonal averages, neither local values nor values with a high temporal granularity are available.

With this drawbacks in mind, we have to accept, that the results of the statistical evaluation of extreme weather conditions using non-instrumental data has limited validity. This confirms the application of the so-called integral risk cycle, which is widely applied for mountain risk engineering and living probabilistic safety assessments, which are common in Nuclear Engineering. The statement may jeopardize also the application of probabilistic methods in structural engineering, because it limits the lifetime of the results as mentioned above. We have to accept, that major loadings are permanently changing not only due to climate change, but also due to permanently increased knowledge about events in non-instrumental times. This brings us back to the question, whether a deterministic approach simply choosing an appropriate safety factor is more sufficient than a full probabilistic computation. That is even further true, if we consider, that the design life time of structures is 50 or 100 years.

Whereas in Mountain risk engineering, improvements in terms of debris flow barriers or rockfall protections nets can be installed after information update and repeated risk assessment, it seems to be impracticable to permanently reconstruct houses simply by the sheer number of them. In Germany alone, about 23 million houses exist.

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