COLLECTION AND ANALYSIS OF CLIMATIC MEASUREMENTS FOR THE ASSESSMENT OF SNOW LOADS ON STRUCTURES

Sadovský Zoltán

ÚSTARCH SAV (Inst. of Construction and Architecture of the Slovak Academy of Science), Bratislava, Slovakia

Faško Pavol, Pecho Jozef, Bochníček Oliver, Mikulová Katarína, Šťastný Pavel

SHMÚ (Slovak Hydrometeorological Institute), Bratislava, Slovakia

Keywords
climatic measurements, snow load, structural reliability

Abstract
Climatological measurements for the assessment of snow loads on structures as practiced in Slovakia are discussed in the light of methodologies described in the relevant backgrounds to Eurocodes. The database of yearly snow load maxima based on the weekly measurements of water equivalent of snow cover on 660 rain-gauge stations in Slovakia recorded during the last 52 winter seasons is analysed. Special interest is focused on the influence of heavy snowfalls in the winters 2004/2005 and 2005/2006, particularly on the extreme cases observed.

1. Introduction

Snow loads are of importance for the reliability of structures in the major part of European territory. Particularly, they are determining actions for light roofs of industrial buildings made of structural steel and wood.

The basic input for the design of structures subject to the actions of snow loads is the value of ground snow load at relevant site. Further step represents the definition of the relation between ground snow loads and snow loads on roofs. The present paper deals with the collection and analysis of climatic measurements for the assessment of snow loads on the ground.

A directly useable climatological record is the water equivalent of snow cover, i.e. the weight of melted snow cover. However, it has been measured only in a few countries. The most often available record is only depth measurements. Several models have been suggested for transformation of the depth of snow cover into loads taking possibly into account also other climatological measurements as density, humidity, temperature, etc.

In order to harmonise the methodologies of measurements and their analysis and evaluations of snow loads for the design of structures across European countries, a research program was launched by an international project team; see the preliminary report of Del Corso et al. [1]. The works were completed issuing the Final Reports Sanpaolesi et al. [8]-[10]. Based on the reports, the European norm EN 1991-1-3 „General Actions - Snow loads" 2003 was elaborated. The European snow map does not include the newly integrated states.

In the present paper, the methodologies of collection and analysis of climatic measurements for the assessment of snow loads in [8]-[10] are discussed from the viewpoint of the regional climate and practice applied in Slovakia and former Czechoslovakia. Particularly, the influence of the heavy snowfalls in the winters 2004/2005 and 2005/2006 on the choice of an extreme value probability distribution and the assessment of characteristic values of snow loads is studied. The study employs database of yearly snow load maxima based on the weekly measurements of water equivalent of snow cover on 660 rain-gauge stations in Slovakia, which have been recorded during 52 years since the winter 1954/1955. Finally, probabilistic snow load models for reliability calculations of structures taking into account seasonal occurrence of snow cover are briefly outlined cf. [6].

Because of high time and spatial diversity of climate conditions, the assessment of snow loads on structures necessitates an integrated effort of structural engineers and climatological experts [2]-[4], [13].

2. Measurements and evaluations of the water equivalent of snow cover

Snow cover can significantly influence the processes, which are explored as a subject of interest by climatology, hydrology, biology and some other earth sciences. The changes of snow cover during the wintry season affect the runoff of atmospheric precipitation from river-basin (watershed). The snow cover effect on surface layer of atmosphere is well known. The presence of snow on the ground represents not only important water storage but also a protective layer of vegetation against strong frosts. Conditions of snow cover of involved region are considered for selection of its recreational utilization as well as for protection against avalanches.

Climatological observations of snow layer are mostly confined to measurements of the depth of accumulated snow cover. Measurements of water equivalent of snow cover, which is required for the assessment of snow loads on structures, are rather scarce. The water equivalent of snow cover, expressed in mm of melted snow cover or in kN/m2, is directly measured only in some countries as Germany, Finland, Switzerland, partially UK [8] and among the new member states of EU also in Czech Republic and Slovakia. For example, in Finland the water equivalents are recorded twice each month, and daily values are calculated by using daily precipitation and air temperature measurements, cf. [8].

In Slovakia weekly measurements are carried out, each Monday at the time of morning measurement at 7.00 a.m. within the whole snow cover profile (depth). In the late 1940s, during 1950s and in early 1960s water equivalent of snow cover measurements have been executed regularly at the beginning of each month decade, similarly at 7.00 a.m. in the morning. The measurements are practised in two ways; in the first case water equivalent of snow cover is carried out by means of rain-gauge and in the second one balance snow gauge is used.

The water equivalent of snow cover measurement by using the rain-gauge is similar to solid precipitation gauging. The captured water quantity from melted snow is gauged by measuring cup analogous to liquid precipitation gauging. Measurements are carried out at a place of uniform snow distribution with the same depth as at a snow-stake. This technique is often applied in the lowland regions of Slovakia, where the snow cover usually reaches low depth values.

In the mountain regions where the snow cover depth is evidently higher than in lowlands, the balance snow gauge is used. Its system functioning mechanism is based on non-uniform lever weights tenet. Within the Slovakian rain-gauge network, the balance snow gauge is being used since 1956. The sample weight is received in grams. The water equivalent of snow cover H is received in millimetres by the formula:

$$H = p/q, \tag{1}$$

where p is the weight of sample in grams and q the cross-section area of snow gauge in square centimetres (50 cm^2).

Total rainfall, and mainly the form in which it falls out on the surface, significantly influences the water equivalent of snow cover. Higher precipitation totals and lower air temperature in higher situated regions and on the other hand, frequent snow cover duration discontinuances in lower situated locations cause significant differences in the water equivalent value of snow cover even within small regions.

Specific water equivalents of snow cover in regions with different altitudes are incomparable. As regards the density of snow cover, which is a relative quantity, similar values ought to be registered in larger as well as more broken regions. During the wintry season the snow cover density varies depending on duration, atmospheric conditions, snowfall period occurrence, etc. Its characteristics are affected by different physical changes within the layer.

Generally, solid precipitations increase the value of the water equivalent of snow cover. This is not the case for liquid precipitations. There have been observed significant increases of water equivalent of snow cover due to rainfalls. However, in some cases the water equivalent of snow cover remained almost unchanged or occasionally decreased after rainfall.

The above-mentioned changes of the water equivalent of snow cover depend likely on type and structure of snow in the layer, possibly also whether the soil under the layer is frozen or thawed. If the snow is dry and less thick or if the rain water doesn't have possibility to runoff, it will stay on in the snow layer. But if the snow is saturated by the rain water and this water has possibility to runoff to soil, the water equivalent of snow cover value may stay without change or diminishes during the liquid or mixed precipitation period.

The measurements of precipitations and of water equivalent of snow cover can be affected by some specific influences of surroundings of a meteorological station. Particularly, the solid precipitation gauging is biased by serious errors. Consequently, it holds generally that during the wintry seasons with sporadic occurrence of liquid and mixed precipitations the water equivalent of snow cover should be higher than weekly precipitation totals. We shouldn't forget about the wind affect, which is very important for snowdrift formations and of course makes the measurements of snow cover characteristics more difficult. Under ideal conditions, assuming that the precipitation gauging hadn't been biased by errors and evaporation, runoff, blowing away and blowing on or other snow cover changes, the curves representing cumulative precipitation totals and water equivalents of snow cover would have had a similar course in a graph figuration. Because of the non-ideal conditions in the nature, the differences between the above-mentioned curves are more or less obvious.

Because of the non-existence of a reliable physical model for conversion of snow depth empirical formulae are used. Then, the obtained daily values of snow load are used for the determination of the yearly maximum [1], [8]-[10]. Promising results offers the recently published formula of Němec et al. [4] employing daily measurements of: precipitation total, height of new snow cover, total height of snow cover and mean water vapour tension.

3. Characteristic values of snow loads and extreme value probability distributions

The definition of characteristic values of snow loads is based on probability analysis of annual maxima. The statistical distribution of these extreme values may be approximated by one of the extreme value distribution functions. Following the backgrounds to Eurocodes [1], [8], the characteristic value of snow load is defined by a probability of 0.02 of being exceeded within any one year. This corresponds to the so-called mean recurrence interval of 50 years. The characteristic value is thus expressed as the 98% fractal of the extreme value probability distribution of annual snow load maxima.

The up to date database of annual snow load maxima in Slovakia is based on weekly measurements of water equivalents of snow cover. It comprises data from the winter 1954/1955 to the winter 2005/2006 at 660 rain-gauge stations. For the selection of suitable extreme value distribution function, eight representative stations and four distribution functions, namely the gamma, Gumbel, Weibull for minima and lognormal distributions have been chosen [7].

The computational procedure using RCP software STATREL [5] included checks of probability papers (where available), estimation of distribution parameters: the method of moments, the maximum-likelihood optimiser method (ML-opt) and the least squares estimation; and distribution tests: the Kolmogorov-Smirnov test and the χ^2-test at the critical significance level of 0.05. More weight has been posed on the former test as being theoretically more satisfying. Visual tests of upper tails of empirical and theoretical distribution functions and tests for outliers were also included. The conclusion has been to apply the Gumbel distribution and the moment method for subsequent calculations.

Special issue investigated in [7], which will be further pursued in this section, is the study of how the heavy snowfalls in the last two winters 2004/2005 and 2005/2006 influenced the characteristic values calculated using annual maxima since the winter 1954/1955. The differences obtained by deducting the value corresponding to the shorter period of 50 years from the other one of 52 years have shown in a number of stations significant increases of characteristic values. Specifically, at 415 stations the differences were negligible – between -0.05 to +0.05 kN/m^2, at 110 stations the observed interval was 0.05 to 0.1 kN/m^2, at

101 stations 0.1 to 0.2 kN/m^2, at 25 stations 0.2 to 0.3 kN/m^2 and at 9 stations the values ranged from 0.3 to 0.56 kN/m^2.

In this paper we focus on the data of two stations from the class of top differences. At Oravská Lesná station, which is one of the eight representative stations, the characteristic value increased by 0.34 kN/m^2 and the slope of regression line changed from negative to positive, see *Figures 1* and *Figure 2*. Despite of this, the test results gave very high scores of significance levels, confer *Table 1*. However, visual check of *Figure 2* suggests a gradual increase of maxima, not obeying the form of a "steady state" process assumed in statistical evaluations of snow load data [8].

For the data at Handlová-Nová Lehota station, the highest increase of the characteristic values, being of 0.56 kN/m^2, has been found. Visual check of *Figures 3* and *Figure 4* and low significance levels of tests, see *Table 2*, show that the highest annual maximum of 3.72 kN/m2 attained in winter 2005/2006 does not fit the rest of the record. For the gamma and Gumbel distributions, using the maximum-likelihood optimiser method for parameter estimation, it has been detected as an outlier.

An exceptional snow load value has been defined in [8] as: "If the ratio of the largest value to the characteristic load determined without the inclusion of that value is greater than 1.5 then the largest load value shall be treated as an exceptional value". Such snow load values should be considered in design separately as accidental actions [8]. Thus, the characteristic values should be assessed without the exceptional snow load. Plot of 51 annual maxima and the corresponding regression line is in *Figure 5*. The results of distribution tests including the characteristic values are in *Table 3*. One can check that the ratio of the exceptional load 3.72 kN/m^2 to the majority of characteristic values from *Table 3* is about 2.

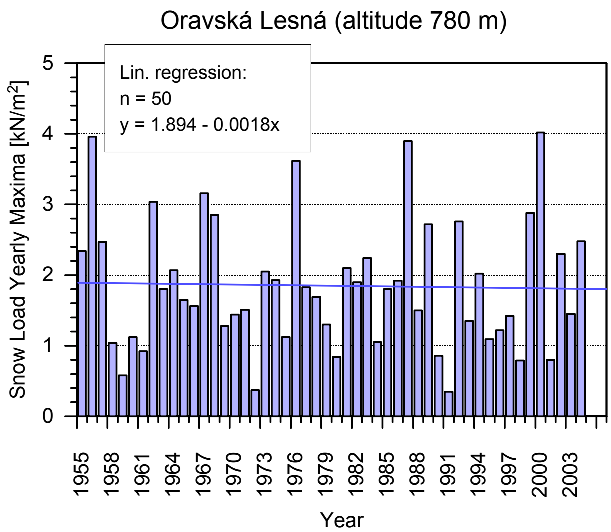

Figure 1. Snow load yearly maxima at Oravská Lesná station, 50 years period

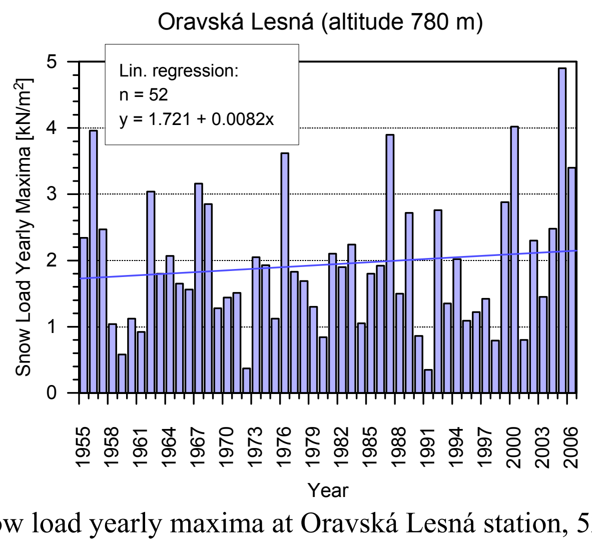

Figure 2. Snow load yearly maxima at Oravská Lesná station, 52 years period

Table 1. Test results at Oravská Lesná station (alt. 780 m), 52 years period

Probab. distrib.	Params estimate	Kolmog.-Smirnov	Chi-square	Char. val. 98%
Gamma	Moments	0.99997	0.904	4.53
	ML-opt	0.99997	0.904	4.55
Gumbel	**Moments**	**0.99996**	**0.974**	**4.57**
	ML-opt	0.99996	0.974	4.55
	Least sqs	0.997	0.974	4.84
Weibul min	ML-opt	0.997	0.857	4.42
Log-normal	Moments	0.995	0.904	4.71
	ML-opt	0.967	0.860	5.38
	Least sqs	0.974	0.813	5.93

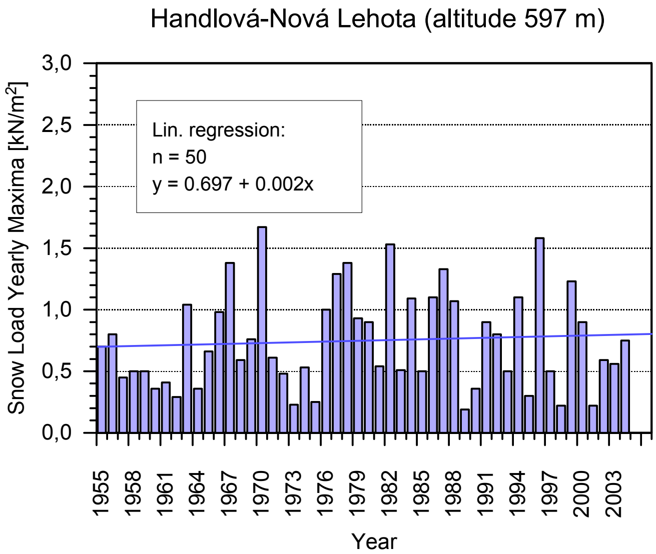

Figure 3. Snow load yearly maxima at Handlová-Nová Lehota station, 50 years period

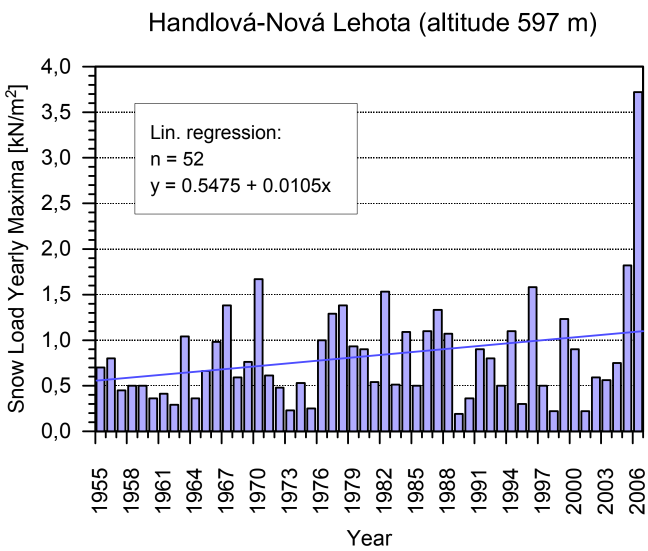

Figure 4. Snow load yearly maxima at Handlová-Nová Lehota station, 52 years period

Table 2. Test results at Handlová-Nová Lehota station (alt. 597 m), 52 years period

Probab. distrib.	Params estimate	Kolmog.-Smirnov	Chi-square	Char. val. 98%
Gamma	Moments	0.767	0.100	2.41
	ML-opt[1*]	0.837	0.444	2.15
Gumbel	**Moments**	**0.641**	**0.170**	**2.34**
	ML-opt[1*]	0.660	0.338	2.01
	Least sqs	0.205	<0.05!	2.61
Weibul min	ML-opt	0.741	0.166	2.41
	Least sqs	0.100	<0.05!	5.36
Log-normal	Moments	0.906	0.188	2.49
	ML-opt	0.911	0.230	2.45
	Least sqs	0.935	0.138	2.71

1* in index position denotes detection of one outlier

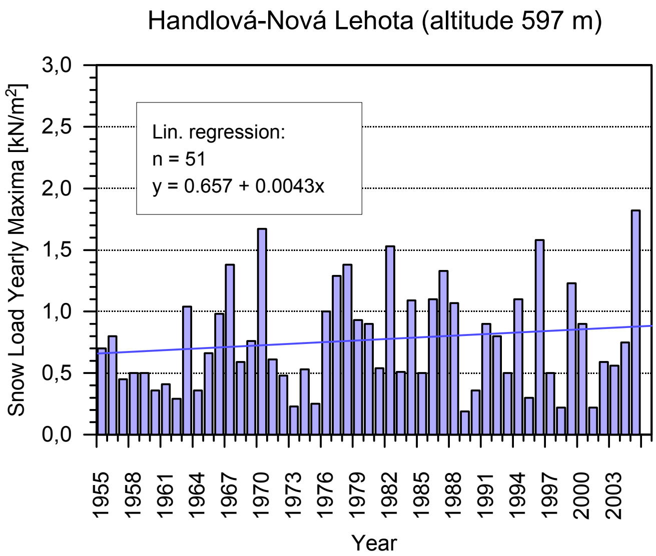

Figure 5. Snow load yearly maxima at Handlová-Nová Lehota station, 51 years period

Table 3. Test results at Handlová-Nová Lehota station (alt. 597 m), 51 years period

Probab. distrib.	Params estimate	Kolmog.-Smirnov	Chi-square	Char. val. 98%
Gamma	Moments	0.895	0.248	1.85
	ML-opt	0.905	0.248	1.86
Gumbel	**Moments**	**0.781**	**0.522**	**1.86**
	ML-opt	0.831	0.401	1.85
	Least sqs	0.865	0.274	1.98
Weibul min	Least sqs	0.083	<0.05!	5.08
Log-normal	Moments	0.625	0.248	1.93
	ML-opt	0.719	0.148	2.18
	Least sqs	0.871	0.615	2.40

Figures 6 to *8* illustrate importance of parallel visual checks of upper tails of theoretical (here lognormal) and empirical distribution functions. The best test results, *see Table 3*, are obtained for parameter estimation by the least squares method, however, the worst tail approximation accounts for an unrealistically high characteristic value of snow load. Generally, the application of the least squares method leads to higher characteristic snow loads [7], [8].

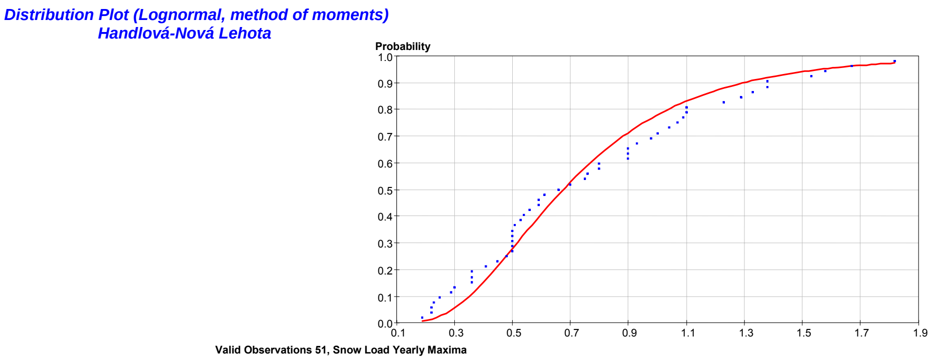

Figure 6. Lognormal distribution of snow load yearly maxima at Handlová-Nová Lehota station, method of moments, 51 years period

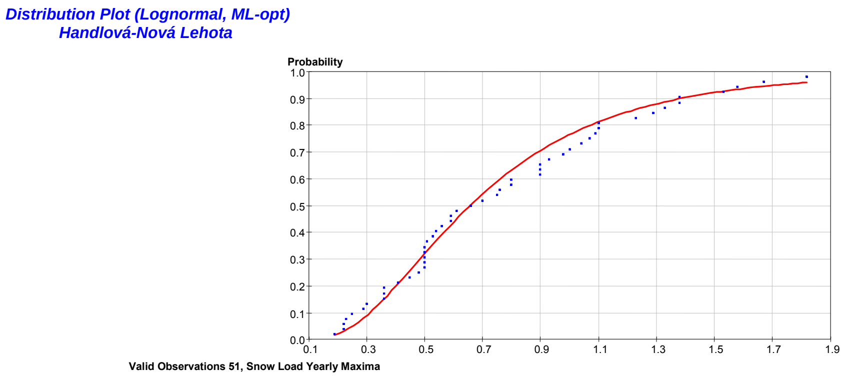

Figure 7. Lognormal distribution of snow load yearly maxima at Handlová-Nová Lehota station, Maximum-Likelihood optimiser, 51 years period

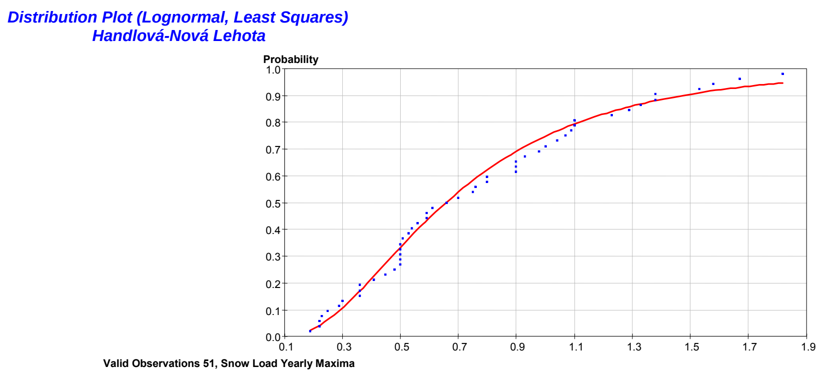

Figure 8. Lognormal distribution of snow load yearly maxima at Handlová-Nová Lehota station, least squares, 51 years period

4. Snow load models for reliability calculations

An exact description of snow loads can be obtained using time-dependent processes. Less involved options are the event-based maxima approach and annual maxima approach [8]. The former can be used in climates, where snowfalls occur as discrete events and between the events the snow cover completely melts, e.g. in Denmark [8]. In continental climates with continuous and longer lying periods of snow cover and resulting snow layer accumulation in wintry season the latter approach applies.

In majority of European countries the characteristic values of snow load are assessed by the probability distribution function of annual snow load maxima. As a rule the Gumbel distribution is applied:

$$F_1(x) = \exp\{-\exp[-\frac{\pi}{\sigma\sqrt{6}}(x-\mu)-\gamma]\} \tag{2}$$

where μ and σ denote the mean value and standard deviation of the yearly maxima. For a probabilistic analysis of structures in a lifetime of n years, the adjusted distribution function $F_n(x)$ can be used:

$$F_n(x) = F_1(x)^n. \tag{3}$$

However, the distribution function (2) or (3) does not take into account the seasonal occurrence of snow cover. In paper [11], the intermittent occurrence of snow cover has been considered for a probabilistic design of industrial buildings. This idea has been further applied to calibrations of safety factors by probabilistic optimisation, cf. [6].
Denoting by p_{snow} the expected relative frequency of snow presence in a year, the yearly mixed distribution is obtained as [6]

$$F_{1,mix}(x) = (1-p_{snow})\mathbf{1}_{0\le x} + p_{snow}F_1(x), \tag{4}$$

while for the lifetime of n years it is

$$F_{n,mix}(x) = (1-p_{snow})\mathbf{1}_{0\le x} + p_{snow}F_1(x)^n. \tag{5}$$

The distribution functions (4 and 5) are less severe than those given by equations (2 and 3). Despite of this, the optimisation of safety factors for industrial buildings considering seasonal occurrence of snow cover by (4 and 5) led to partial factor for snow of 2 [6], in contrast to the standardised value of 1.5. The use of distribution functions (2 and 3) would yield even higher snow factor, which may imply an unnecessarily cost increase if applied.

5. Conclusion

The long-term practice in collection of climatological measurements in Slovakia shows up their good standard and suitability for the assessment of snow loads on structures.

The analysis of the influence of heavy snowfalls in the winters 2004/2005 and 2005/2006 on the characteristic values calculated using annual maxima since the winter 1954/1955 led to detection of an exceptional snow load in the sense of [8], which has to be treated separately within an accidental design case.

For the reliability studies of structures in continental climates a probabilistic snow model with mixed distribution function taking into account the seasonal occurrence of snow cover together with the distribution function of annual maxima is recommended. Of course, the characteristic snow loads result from the in European countries harmonised methodology based on an extreme value distribution function of annual maxima derived without the seasonal issue.

Acknowledgements

This work was supported by the Slovak Research and Development Agency under the contract No. APVV-51-024505.

References

[1] Del Corso, R. et al. (1995). New European Code for Snow Loads. Background document. *Proc. Dept. Structural Engng Univ. Pisa,* No.264, Pisa, 76p.

[2] Faško, P. & Lapin, M. (1996). Snow cover and precipitation changes in Slovakia in the 1921 – 1995 period. *Proceedings on the 24 th ICAM 96.* HMI of Slovenia, Bled, 259 – 266.

[3] Handžák, Š., Faško, P. & Nejedlík, P. (2000). Selected snow cover characteristics change during the period 1921 – 2000 in Slovakia. CD, ICAM 2000, Innsbruck, Session 6.

[4] Němec, L., Květoň, V., Setničková, I. & Škáchová, H. (2003). Estimation of the Water Equivalent of Snow Cover from the Other Meteorological Instruments, *ICAM Conference, Brig,* www.map2.ethz.ch/icam2003.

[5] Consult, (2003). RCP Reliability Consulting Programs: STRUREL: A Structural Reliability Analysis Program System, STATREL User´s Manual: Statistical Analysis of Data for Reliability Applications, München. RCP

[6] Sadovský, Z. (2006). Climatic loads and reliability of light roof industrial buildings. In C. Guedes Soares & E. Zio (eds.), *Safety and Reliability for Managing Risk*; *Proc ESREL 2006,* (vol. 2, 1535-1539). London: Taylor & Francis.

[7] Sadovský, Z., Bochníček, O., Faško, P., Mikolová, K. & Šťastný, P. (accepted for ESREL 2007). Revision of snow load data for structural design in Slovakia.

[8] Sanpaolesi, L. et al. (1998). *Phase 1 Final Report to the European Commission, Scientific Support Activity in the Field of Structural Stability of Civil Engineering Works: Snow Loads*. Department of Structural Engineering, University of Pisa, 170p.

[9] Sanpaolesi, L. et al. (1999)[a]. *Phase 2 Final Report to the European Commission, Scientific Support Activity in the Field of Structural Stability of Civil Engineering Works: Snow Loads*. Department of Structural Engineering, University of Pisa, 341p.

[10] Sanpaolesi, L. et al. (1999)[b]. *Annex B to the Final Report - European Ground Snow Loads Map.* Department of Structural Engineering, University of Pisa, 41p.

[11] Schleich, J.B., Sedlacek, G. & Kraus, O. (2002). Realistic Safety Approach for Steel Structures. *Proc. 3[th] European Conference on Steel and Composite Structures.* Eurosteel, Coimbra, 1521-1530.

[12] Tichý, M. et al. (1987). *Loads on Structures* (Zatížení stavebních konstrukcí – in Czech). TP 45, SNTL, Praha, 466p.

[13] Vojtek, M., Faško, P. & Šťastný, P. (2003). Some selected snow climate trends in Slovakia with respect to altitude. *Acta Met. Univ*. Comenianae, Vol. XXXII, 17-27.