

Analysis of Methods for Determining Climate Loads at a Specified Territory Point by Meteorological Data

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Abstract: Methods for determining the characteristic values of climate loads at the location of a building have been perfected. Based on comparative analysis, the method of levelling the values of climate loads with an exponential or triangular weight function is recommended. For four climate loads, appropriate equalization intervals are determined, ensuring the maximum amount of weather data taken into account, while maintaining their uniformity. In construction, the determination of the climate load is important for the location of the building. When prescribing building standards, the values of the climate load are determined according to the data of weather stations in relative proximity, which provides values within the limits of reliability. Such an approach can lead to an overestimation of the characteristic values of climate loads and consequently increase the consumption of the construction materials of the building or, in the opposite case, decrease the unnecessarily high-energy consumption to condition the space inside the building.

Keywords: characteristic values; climate loads; load values at a given project point; meteorological data; territorial variability

1 INTRODUCTION

When designing load-bearing building structures, the calculated values of climatic loads are determined according to the norms [1, 2, 3]. As a rule, zone maps are given in norms, in which the territory of the country is divided into several regions with determined load values for the area of the region. When standards are prescribed, district load values are determined according to the data of individual weather stations in such a way that for certain parts of the region, they provide certain values within the confidence limits. In many cases, this leads to an overestimation of the characteristic values of climate loads and consequently an increase in the consumption of the construction materials of buildings.

A more accurate determination of the characteristic values of climate loads in the area of a certain construction site is possible on the basis of statistical processing of the results of meteorological observations, which is allowed by the norms [1]. Most often, samples of the annual maximums of the respective climatic parameters are used for this, which can be described by the Gumbel distribution [4]. The methodology of such calculations is described in [5, 6]. Determining the characteristic and design values of climate loads from actual meteorological data may in some cases lead to a reduction in the consumption of the building materials of newly designed buildings. Likewise, appropriate climate loads during the checking of the calculation of exploited structures may in some cases make it impossible to perform or reduce the laborious and costly work of reconstruction.

In the simplest case, the desired calculated climate load parameter is determined by the weather station located near the construction site. In the absence of such a weather station, data from several nearby weather stations are used, which can also increase the accuracy of the results by increasing the amount of the meteorological data used. Various methods for determining the estimated climate load parameters at a

particular geographical point according to the local weather station network are outlined in [7, 8].

The purpose of this article is to improve and comparatively analyse different methods for determining the characteristic values of climate loads at a particular geographical point according to the data of the local network of weather stations.

2 PRELIMINARY ANNOTATION

This article analyses methods for determining the characteristic values of climatic loads at a specific point in the territory (hereinafter referred to as the project point) according to the data of weather stations in the region. The problem is solved by the example of meteorological observations in the territory of Ukraine. For the study, a meteorological database has been formed for 172 flat weather stations, the network of which quite fully and evenly covers the territory of Ukraine. When forming the database, information was used [9, 10], which shows the sample sizes of annual maximums, their mean values and standards, as well as the characteristic values of the loads corresponding to the generally accepted repetition period $T = 50$ years. The duration of the observation is generally 25 to 50 years, with only 70 cases out of 688 using shorter series of 10 to 25 years.

The used meteorological data have a stochastic nature, which determines their random variability in time and space. In addition, there are some changes of load values due to the influence of geographical and climatic factors. Differences in the periods of meteorological observations at different weather stations increase the heterogeneity of these data. Therefore, the methods that are used for the evaluation of the loads at a given point of the territory should provide verification of the uniformity of the data of meteorological stations.

For each weather station, latitude and longitude in degrees, altitude in meters and the statistical characteristics and characteristic values of four climate loads are known:

snow cover weight, ice weight, maximum wind pressure and wind pressure with ice. For each load, the number of observation years, the average value of the sample of the annual maxima, the standard of the annual maxima sample, and the characteristic value of the load are given in the database.

Statistical characteristics of the snow cover weight on the earth's surface were obtained by processing samples of the annual maximum snow cover weights formed according to [9]. Average values and norms for the ice weight, maximum wind pressure, and wind pressure with ice were taken from [10]. Characteristic values are calculated in [9, 10] by the formula

$$Q_0 = M + 2.6S \quad (1)$$

based on the description of the annual maximums' pattern by the Gumbel distribution law [4, 5] with an average value of M and a standard of S , and what is also taken into account is the average repetition period of the characteristic load value $T = 50$ years. The approximate formula (1) gives results that are quite close to the exact values [4, 5].

The meteorological database described below is used for the comparative analysis of the methods for determining characteristic values of climatic loads at a specific geographical point according to the data from a local weather station network.

3 METHODS FOR DETERMINING THE CLIMATE LOAD AT A PROJECT POINT

3.1 Definition based on the Actual Data of a Particular Weather Station

The simplest way to get a characteristic load value from real-time weather data is to directly use the observation results at a weather station located close enough to a specific project point. Due to this, it is necessary to create a sample of the annual maximums of the appropriate climate load and to perform its statistical processing. The characteristic value is calculated using the approximate formula (1) or its more exact versions given in [4, 5]. Such a method can give false results due to accidental observation errors or the influence of the mesoclimatic characteristics of the weather station used. In addition, this method is not generally applicable in the absence of a weather station in the immediate vicinity of the project point, as it happens in most cases of site selection.

3.2 Combining Data from nearby Weather Stations

To obtain more reliable and accurate results, it is necessary to use data from several weather stations near the project point. The accuracy of the results is increased by increasing the amount of the meteorological data used, and the reliability is increased by averaging the mesoclimate characteristics of several nearby weather stations. Generalized results thus characterize a particular area along the area of the project point.

Observation results on weather stations L are shown by known sample sizes N_k , their average values of M_k and variance $D_k (k = 1, \dots, L)$. Differences in the available data may be due to random fluctuations in the results of observations at neighboring weather stations, as well as due to regular differences in climatic characteristics. Therefore, to make the decision to combine the data from a selected group of weather stations, it is advisable to use a one-way variance analysis [11].

The classic formulation of the analysis of variance with respect to the comparison of the data of several weather stations can be formulated on the basis of [11]. We consider L weather stations closest to the project point with the numbers $k = 1, \dots, L$, for each of them there are samples of different contents of N_k meteorological observations X_{ki} , $i = 1, \dots, N_k$. The possibility of combining all available data into one common sample should be checked.

$$N = \sum_{k=1}^L N_k \quad (2)$$

To do this, average values and variances are calculated for each sample compared.

$$M_k = \frac{1}{N_k} \sum_{i=1}^{N_k} X_{ki} \quad (3)$$

$$D_k = \frac{1}{N_k - 1} \sum_{i=1}^{N_k} (X_{ki} - M_k)^2$$

The average value of the combined sample is

$$M = \frac{1}{N} \sum_{k=1}^L \sum_{i=1}^{N_k} X_{ki} \quad (4)$$

Within-group variation, which on average characterizes the random spread of data within a single weather station, is calculated

$$D_{\text{wg}} = \frac{\sum_{k=1}^L D_k (N_k - 1)}{(N - L)} \quad (5)$$

Between-group variation, which depicts the scattering of data between weather stations and thus characterizes the influence of the deciding factor (specific weather station) on the total variance of the combined sample, is calculated

$$D_{\text{bg}} = \frac{\sum_{k=1}^L N_k (M_k - M)^2}{(L - 1)} \quad (6)$$

The statistics of the Fisher's variation comparison criterion are calculated by the formula

$$F = \frac{D_{bg}}{D_{wg}} \quad (7)$$

and it compares with the critical value of the Fisher's $F_{cr}(k_{bg}, k_{wg})$ statistics from the F-distribution tables for the selected significance level (usually $\alpha = 0.05$ or $\alpha = 0.01$) and the number of the degrees of freedom $k_{bg} = L - 1$ and $k_{wg} = N - L$. If $F > F_{cr}$ is obtained, a second set of weather stations near the project point should be selected and the calculation repeated by using the above algorithms.

For $F \leq F_{cr}$, the data samples of all L weather stations can be considered homogeneous. They need to be combined into a total volume sample (2) and statistically processed. The desired characteristic value of the test load at the project point is determined by the formula (1) or its more accurate analogous data based on the Gumbel distribution, taking into account the statistical characteristics of the combined sample.

The second variant of the task of combining data from the nearest weather stations assumes the absence of the patterns of observation results, which are represented by the known values of N_k , mean values of M_k and variants of D_k , $k = 1 \dots L$. For these purposes, the analysis of the variance procedure modified by the authors is used. The total volume of the combined sample N is determined by the expression (2) and its average value is calculated by the formula

$$M = \frac{\sum_{k=1}^L M_k N_k}{N} \quad (8)$$

The within-group variation D_{wg} (5) and between-group variation D_{bg} are calculated by the formula (6). The statistics of the Fisher criterion (7) are compared with the critical value $F_{cr}(k_{bg}, k_{wg})$ for the selected level of meaning and the number of the degrees of freedom $k_{bg} = L - 1$ and $k_{wg} = N - L$.

For $F > F_{cr}$, it is necessary to reduce the number of weather stations closest to the project point in order to obtain $F \leq F_{cr}$. In this case, the data of all L weather stations can be considered homogeneous and combined into the total distribution of meteorological observations (2), whose mathematical expectations are equal to (8), and the variance is calculated by the formula

$$D = \frac{D_{wg}(N-L) + D_{bg}(L-1)}{N-1} \quad (9)$$

The presence of the statistical characteristics (8) and (9) allows us to determine the desired characteristic load value at the project point according to the formula (1) or a more accurate formula.

For the more reliable determination of the characteristic value of the load at the project point, it is advisable to use the largest possible number of weather stations closest to it and, accordingly, a large set of initial meteorological data. The analysis of variance should begin at all weather stations located within a radius of about 100 km from the project

point. For $F > F_{cr}$, the outermost weather stations should be removed from this set to obtain $F \leq F_{cr}$, which allows the data of all recorded weather stations to be combined into a single sample or into a common distribution.

3.3 In-Plane Interpolation Method

The method proposed in [10] for determining the calculated climate load parameters at a given point in the territory (project point) is based on the use of a plane that connects the value of the desired parameter to the three nearest weather stations. The characteristic value of the load at the project point Q is determined from the equation of the plane passing through the characteristic values of this load Q_1, Q_2, Q_3 at the three nearest weather stations. The weather stations that form the interpolation triangle are selected by the decision of the designer or researcher based on the minimum distance from the project point and their orographic area so that the project point is usually located within the interpolation area. Experience shows that for the same project point, several different interpolation triangles can be selected.

After transforming formulas [10] from a local coordinate system into a global one, we obtain the desired value of the characteristic value of the climate load at the project point with the coordinates x, y .

$$z = \frac{D}{C} - \frac{A}{C}x - \frac{B}{C}y \quad (10)$$

The coefficients of the formula (10) are determined by the coordinates x_i, y_i and the characteristic load values z_i for the three stations that form the interpolation triangle:

$$\begin{aligned} A &= (y_1 z_2 + y_2 z_3 + y_3 z_1 - y_3 z_2 - y_2 z_1 - y_1 z_3) \\ B &= (x_2 z_1 + x_3 z_2 + x_1 z_3 - x_2 z_3 - x_3 z_1 - x_1 z_2) \\ C &= (x_1 y_2 + x_2 y_3 + x_3 y_1 - x_3 y_2 - x_1 y_3 - x_2 y_1) \\ D &= (x_1 y_2 z_3 + x_2 y_3 z_1 + x_3 y_1 z_2 - x_3 y_2 z_1 - x_2 y_1 z_3 - x_1 y_3 z_2) \end{aligned} \quad (11)$$

To perform the calculation in a spread sheet, it is enough to enter the coordinates of the project point and select the interpolation triangle, after which the calculations are automatically performed according to the formulas (10), (11). The position of all weather stations and the project point can be set both in latitude and longitude in degrees, as well as in the selected rectangular coordinate system.

In order to analyse the stability of the described method, the examples of determining the characteristic values of the snow cover S_0 , maximum wind pressure W_0 , ice weight G_0 and wind pressure with ice W_{0G} for five project points located in different regions of Ukraine were considered (such cities as Kropyvnytskyi, Lviv, Nizhyn, Kharkiv, and Kherson). A local network of 9 ... 10 weather stations located at a distance of 120 km from the project point was used. From these weather stations, 10 different interpolation triangles were formed, from which the characteristic values were calculated

by using (10). As an example, Tab. 1 shows the results for the city of Kropyvnytskyi.

Tab. 1 shows that the results of calculations using different interpolation triangles have an unacceptably large spread. The mean value of the 10 options gives more stable results, approaching the values of certain weather station data in Kropyvnytskyi. For other project points, qualitatively close results were obtained, which together indicate a significant dependence on a sufficiently subjective choice of the interpolation triangle.

Table 1 Variability of characteristic load values in Kropyvnytskyi, calculated using 10 different interpolation triangles

Characteristic load values	S_0 (Pa)	W_0 (Pa)	G_0 (N/m)	W_{0G} (Pa)
the smallest of 10 options	1161.9	306.4	10.5	186.3
the highest of 10 options	1348.6	394.4	22.5	236.5
the average of 10 options	1248.3	356.1	16.4	213.4
Meteorological data for Kropyvnytskyi	1210.6	350.0	13.7	210.0

In order to increase the stability of the results, some authors proposed to modify the considered method for determining the characteristic values of climatic loads by plane interpolation. The improvement is that the possibility of using interpolation triangles is checked by using the above mentioned analysis of variance, and the final result is determined by the average of the results of multiple interpolation triangles.

3.4 Method of the Equalization of Characteristic Values

Changes in the characteristic values by a territory can be represented as an unstable random field [5, 11] represented by a surface of mathematical expectation showing regular climatic changes of the load in the territory and a random component due to the geographical characteristics of individual weather stations and measurement errors. Levelling this field with a weight function, which reduces the importance of weather stations as they move away from the project point, allows for the alignment of random components and thus the detection of regular load changes in the study area. The levelling process can be considered as a modification of the method described above for combining the data from a network of weather stations, taking into account the reduction of the role of weather stations as it moves away from the project point. In this paper, the levelling method [5] is improved by taking into account the sample sizes from which the characteristic values of the climate load and the mathematical justification of the levelling interval values are determined based on variance analysis.

Taking into account the methodology described above to evaluate the possibility of combining the data from neighbouring weather stations by using variance analysis, a modification of the data levelling technique [5] has been developed, which is described by the following algorithm (12) to determine the characteristic value of the climate load at a given project point. The initial data are the characteristic values of the load Q_k and the sample size N_k , according to

which they are determined for all L weather stations in the territory. The dispersions of characteristic values are estimated using the approximate formula obtained in (12):

$$D_{Qk} = \frac{0.36 Q_{0k}^2}{N} \quad (12)$$

For each of the L weather stations, a weight function is calculated that takes into account the distance d_k from the weather station with the number k to the project point, according to one of the formulas:

$$C_k = \exp\left(-\frac{d_k}{a}\right) \quad (13)$$

$$C_k = 1 - \frac{d_k}{a} \text{ when } d_k < a \quad (14)$$

$$C_k = 0 \text{ when } d_k \geq a$$

Where a is the levelling interval, expressed in the units of distance.

The equivalent observation volume N_{ek} for the k^{th} weather station and the total equivalent observation volume, which determine the characteristic value at the project point, are:

$$N_{ek} = C_k \times N_k$$

$$N_e = \sum_{k=1}^L N_{ek} \quad (15)$$

The characteristic value of the load at the project point is:

$$Q = \sum_{k=1}^L \frac{N_{ek} \times Q_k}{N_e} \quad (16)$$

The within-group and between-group variation for determining the F-criteria are calculated using the formulas:

$$D_{wg} = \sum_{k=1}^L \frac{N_{ek} \times D_k}{N_e} \quad (17)$$

$$D_{bg} = \sum_{k=1}^L \frac{N_{ek} (Q_k - Q)^2}{L}$$

The observed value of the Fisher criterion statistics $F = D_{bg}/D_{wg}$ is compared with the critical value $F_{cr}(k_{bg}, k_{wg})$ for the selected level of significance and with the number of the degrees of freedom, depending on the equivalent number of weather stations and the data taken into account.

For small values of the levelling interval, when considering the small amount of meteorological data, the Fisher criterion statistics do not exceed the critical value: $F < F_{cr}$. The increase in the levelling interval leads to an increase in between the group variance. Until $F > F_{cr}$ occurs,

indicating that it is impossible to combine the selected meteorological data. The longest levelling interval is optimal, at which the condition $F \leq F_{cr}$ is fulfilled, thus ensuring that the maximum possible amount of temporal data is used while maintaining their uniformity.

In order to select the best type of the weight function (13) or (14) and to determine the optimal value of the levelling interval according to the described methodology, the calculation was performed for each of the four climate loads at five project points located in the cities of Kropyvnytskyi, Lviv, Nizhyn, Kharkiv and Kherson. Variance analysis was performed at the significance levels of $\alpha = 0.05$ and $\alpha = 0.01$. The levelling intervals gradually increased until $F > F_{cr}$ was obtained, which allowed their optimal values to be identified for each load type at each of the five project points.

The results of the calculations showed the closeness of the characteristic load values obtained on the basis of the exponential (13) and triangular (14) weight functions. The difference between them does not exceed $\pm 3\%$. Therefore, for practical use, we can recommend the weight functions (8) and (9) with the levelling intervals given in Tab. 2.

Table 2 Recommended levelling intervals values

	Levelling intervals (km) in formulas	
	(13)	(14)
Weight of snow cover	50 - 55	130 - 150
Maximum wind pressure	30 - 35	70 - 80
Weight of ice	15 - 25	40 - 70
Wind pressure with ice	40 - 45	110 - 120

The levelling intervals listed in Tab. 2 are obtained by summing the calculation results for the five project points.

The smaller values of the levelling intervals correspond to a significance level of 0.05 and the large ones to 0.01. The lowest levelling interval values were obtained for the weight of the ice and the highest for the snow load. The analysis showed a tendency of the narrowing of the levelling area with increasing territorial variability of loading. The deviation of the levelling interval from the optimal value in Tab. 2 within 10 ... 20% changes the result by 1 ... 2%.

In general, the results of the analysis showed that for practical use in load normalization for the territory of Ukraine it is possible to recommend an exponential (13) or triangular (14) weight function with levelling intervals from Tab. 2. The desired characteristic load value at a given project point is calculated by (16) considering equivalent amounts of data (15) and one of the weighting functions (13) or (14) without conducting the variance analysis. To determine the characteristic values of the load at the project points of other territories, it is necessary to first clarify the optimal values of the levelling intervals listed in Tab. 2 by performing the variance analysis by using the method described above.

4 COMPARISON OF THE ACCURACY OF THE CALCULATION METHOD

In order to select the best method for the considered determination of the climate loads at a given project point, the characteristic value of four climate loads for the five

project points located in the cities of Kropyvnytskyi, Lviv, Nizhyn, Kharkiv and Kherson is compared. The characteristic values for each project point are determined by the methods described above:

1) According to the actual data of the weather station located at the project point;

2) Combining the characteristics of the samples of the annual maximum loads according to the results of the variance analysis;

3) Plane interpolations by selecting interpolation triangles according to the results of the analysis of variance and the average of several results;

4) Equalization of characteristic load values with an exponential weight function (13);

5) Levelling of characteristic load values with a triangular weight function (14).

As a result of the calculation, 100 characteristic values were obtained, the analysis of which allowed us to evaluate the accuracy of these calculation methods. The problem of benchmarking the methods used to determine the characteristic load values at a particular project point is the lack of fully reliable benchmarks with which to compare results. Using the calculation results based on actual meteorological data obtained at the project point (method 1) as a benchmark is incorrect, as the data of an individual weather station may have some random deviations due to the measurement errors and mesoclimatic characteristics of each weather station. Therefore, the used characteristic values are averaged over all five methods. The percentages of deviations of the characteristic values determined for each of the five methods from these averages are analysed, and the average percentage modules of the deviations for all project points are shown in Tab. 3. The logic behind such an analysis is that the closeness of the results obtained by different calculation methods indicates the reliability of these methods.

Table 3 Average modules of the percentage deviation of characteristic values, calculated by different methods

Method for determining the characteristic value	Percentages of the deviation of characteristic values				
	S_0	W_0	G_0	W_{0G}	Average
According to the weather station at the project point	11.59	11.92	14.68	8.67	11.72
Combined numerical characteristics of samples	9.21	8.78	21.33	7.25	11.64
Plane interpolation average results	4.73	8.91	16.51	6.44	9.15
Levelling with an exponential weight function	2.69	2.63	8.78	2.01	4.03
Levelling with a triangular weight function	3.18	3.01	9.01	2.76	4.49

It can be seen from Tab. 3 that the largest deviations for the ice weight load are obtained. For the remaining loads, approximately the same percentage deviations are obtained. The general accuracy characteristic of the method of calculating characteristic values is the percentage of deviations for individual loads, as well as their average values indicated in the last column of Tab. 3. Based on these data, it can be concluded that the calculations by the first two

methods for determining the characteristic values of the load at a given project point have the least accurate results. The third method (plane interpolation with the average of the results of several interpolation triangles) provides slightly smaller deviations of characteristic values, but it also has an excessively high complexity due to the need to "manually" select several interpolation triangles, perform the variance analysis and average the results. The mutual convergence of the characteristic load values obtained by these methods indicates sufficient accuracy and reliability of the results.

Therefore, methods 4 and 5 are recommended for practical use, based on the levelling of the characteristic load values with an exponential (13) or triangular (14) weight function, which provide sufficiently high accuracy in determining the characteristic values at a given project point.

5 CONCLUSIONS ON THE RESULTS OF THE RESEARCH

1. Based on the meteorological data from 172 weather stations in Ukraine on the snow cover weight, maximum wind pressure, ice weight and wind pressure with ice, the known methods have been improved and new methods have been developed to determine the characteristic values of the climate loads at a given project point.

2. Formulas have been obtained for a one-way variance analysis, which allows one to decide on the possibility of combining the statistical characteristics of the annual maximum loads in the absence of samples themselves.

3. Based on benchmarking, the methods based on the levelling of characteristic load values with an exponential or triangular weight function are recommended for practical use, which give the highest accuracy of all results.

4. Appropriate levelling interval values for four climatic loads have been established to ensure that the maximum amount of weather data is taken into account, provided that they are homogeneous. The deviation of the levelling interval from the recommended values by 10 - 20% changes the result by 1 - 2%.

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