The Guidelines for Internal Daylighting Design Based on Global Daylight Index (GDI)

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ABSTRACT: Daylight distribution inside the building is a function of daylight transmission, distribution and utilisation. All the factors mentioned above, determine the amount of daylight entering from the outside and transferring to a given point in the room. This amount is determined by glazing/opaque ratio, glazing properties, interior shapes, finishing materials, etc. Global Daylight Index is a function of transmission, distribution and utilisation and should be in specific range to assure required internal visual comfort level. The main purpose of our study was to formulate the definition of Global Daylight Index which can be a technical parameter for daylight design. The second goal of this work was to determine the values of GDI which assure the required level of daylight in buildings. The analyses were done using advanced numerical techniques based on Backward Ray Tracing Method, including Turbidity Coefficient individually calculated for each month and selected sky conditions. As a result of our study the required GDI values were presented.

Keywords: daylighting, comfort, guidelines

1. INTRODUCTION

Daylight utilization in a healthy building design is a crucial point, not only from the point of view of indoor environment quality but also from energy point of view. Present recommendations mainly depend on a building type, function, occupation etc. They are based on visual criteria and three of the main parameters are [1,2]: daylight factor, horizontal illuminance on the working plane, luminance ratio.

A great amount of daylight coming into the buildings is determined mainly by architectural ideas and vision. Usually, the first part of a design process is oriented towards esthetic requirements and deprived of technical analysis. It is almost impossible to apply advanced engineering techniques at such an early design level. Any simulation tools based on split-flux method, radiosity or ray tracing methods required detailed descriptions of the building (geometry, construction and materials) and the system (shading, light leading and transport devices). Therefore, at this stage any technical adjustments using accurate methods are difficult to obtain, laborious and strongly approximated. The second part of the project is more often supported by advanced numerical techniques to estimate precisely the features of the project and apply final corrections. However, first estimation at the initial design step can often determine further characteristics of a building and its components. It must be done as precisely as possible but in a relatively easy way. The initial guidelines (at the conceptual design phase) should be formulated clearly, explicitly and comprehensively. They should be based on and determine only the main features of the building (e.g. building geometry, material properties) taking into consideration the character of external environment, localization, etc. They should be functionally diverse according to the type of the building and its occupation.

A friendly, general and initial methodology for daylight utilization in buildings is proposed in the paper. It is based on the total amount of daylight getting to the working plane inside the rooms. Daylight illuminance inside the building is changeable and depends on external conditions (weather, time, season and urban development) and internal factors (surface properties – transmission and reflection characteristics, architectural design).

2. EXISTING METHODOLOGY

Visual comfort is the main determinant of lighting requirements. Nowadays, the starting point for daylight design are some simple guidelines giving first but not precise approximation. This approximation is based on a percentage of transparences, the ratio of glazing area to floor area or the maximum depth of the room which should not be exceeded. It is a relatively easy but not precise enough approximation. During the conceptual design most often the requirements have a inferior limit of e.g. a minimum ratio of glazing/floor area. On the other hand, the lack of superior limit often leads to crucial corrections at further design stage. It comes not only from visual but also from thermal and acoustic point of view. At a more advanced stage the minimum daylight factor, illuminance on the working plane or luminance ratio are recommended. All of these factors are checked during the design phase and final planning. Analytical or more advanced numerical methods support the design process of the elements of the facades and interior finishing. Moreover, they facilitate selecting and integrating of systems and services (including artificial lighting), selecting materials, products and final details. Additionally, all these daylighting strategies must be developed for different parts of the building separately. Detailed analyses are time-consuming, expensive and useless if the conceptual design was false. Therefore, a relatively easy but precise method should be developed to guide the architects towards proper conceptual design from the point of view of daylight utilization.

3. NEW APPROACH

Total Daylight Index (TDI) is the first step indicator for architects and engineers at the conceptual design phase to consciously create the buildings and building interiors at an early design stage. TDI is a dimensionless product of daylight transferring (T) and distribution (D) on the way from the sky to the point on the working plane and it ranges from 0 to 1. TDI should be individually estimated for one localization, standard climatic parameters (weather, time and season) but without any urban and architectural obstructions. Further particularities are realized by the correction factor (C) taking into account remaining external and internal conditions.

The methodology required only general information about the building, usually available at this leg. It is based on the concept of exterior envelope, building function and basic dimensions.

3.1 Transferring factor

First part of the information concerns the properties of exterior envelope. This characteristic is described by the daylight transferring factor (T). It is defined as an amount of daylight entering the building interior space to the amount of daylight falling on the building envelope. The T factor is a glazing daylight transmission. Boundry partial coefficient C_b (p.3.3) takes into account the glazing/opaque ratio (window area) and window position. For a single indoor space, bounded by *n* external, transparent daylighting openings it is estimated according to the equation (1):

$$T = \sum_{i=1}^{n} g_i \times \frac{A_{ti}}{A} \qquad (1)$$

where:

g_i – is the total daylight transmission of surface *i* ;
A_{ti} – is the area of transparent surface *i* ;
A – is the total area of external transparent surfaces bounding the analysed space.
The T factor changes from 0 to 1 and in extreme cases it can be:
T=1 – for a fully glazed external façade and daylight glazing transmission equals 1 (only in theory);
T=0 – for a fully opaque façade or daylight glazing transmission equals 0.

3.2 Distribution factor

The second part of the information concerns the properties of interiors. This characteristic is described by the daylight distribution factor (D). It is defined as an amount of daylight coming from the window to the assumed working plane. On the other hand, the distribution factor also determines the weakness of the daylight inside the building space. The D factor is always described by the average reflectance of the surfaces in the room. For a single indoor space, bounded by *m* internal surfaces it is estimated according to the equation (2):

$$D = \sum_{i=1}^{m} S_i \times R_i \times \frac{A_{si}}{A_i} \qquad (2)$$

where:

A_{si} – is the area of surface *i* in the analysed space ;
A_i – is the total area of the surface in the analysed indoor space;
R_i – is the daylight reflection of surface *i* ;
S_i – is the surface coefficient taken from figure 1;
The D ranges from 0 to 1 and in extreme cases it can be:
D=1 – for ideally reflected surfaces and no other internal obstructions (only in theory);
D=0 – for no reflected surfaces (100% of daylight is absorbed).

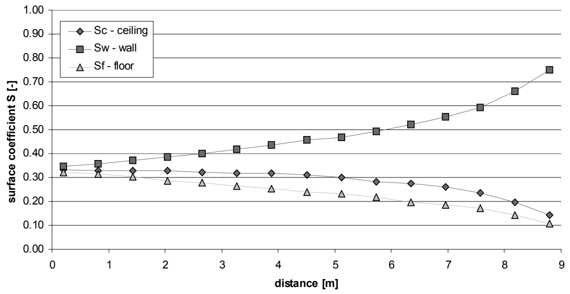

Figure 1: The surface coefficient S_i for walls S_{iw}, floors S_{if} and ceilings S_{ic}.

3.3 Correction factor

The values of Total Daylight Index calculated according to the procedure presented in paragraph 3 are valid only in some particular cases. Firstly, the daylight that reaches the building is not disturbed by the elements of external environment. It means that the analysed building and the glazing elements are fully exposed. The second assumption is that the daylight spreads out symmetrically to the interior space (the window is placed centrally in the external surface). It means that the daylight is distributed symmetrically from the outdoors to the building space. Finally, the third limitation concerns building interiors. It is assumed that the daylight is reflected in the same way by the floor, the ceiling and the walls except the wall opposite the window. This assumption does not delimit the depth of the room, but in reality the daylight reflected on the surface at the rear of the room changes the illuminance level in the deepest areas. Also, individual surfaces have different properties, reflect dissimilar amount of daylight inside the building space.

The correction factor C should be used in order to generalize the proposed methodology. It is a product of three partial coefficients: exterior (C_e), interior (C_i) and boundary (C_b) factors.

$$C = C_e \times C_b \times C_i \qquad (3)$$

The exterior correction factor C_e includes the mitigation of the daylight caused by urban development, building geometry and any other obstructions around the transparent parts at building envelopes. The boundary correction factor C_b takes into account the size and the position of the window in relation to the reference case, when the façade is fully glazed and placed centrally in the external surface. Any vertical movement of the sill above the level of the working plane changes the daylight distribution inside the building. The third component of the correction factor (C_i) concerns the influence of the light reflected by the opposite (to the window) wall. It can cause various intensity of light transfer through reflectance by the ceiling, the walls or the floor. As it is well known, the amount of light reflected by the ceiling is crucial for the illuminance at the upper side of the horizontal plane.

The correction factor ranges from 0 to 1 and:

C=1 – is for ideal conditions: no external obstructions, centrally fixed window and identical properties of all internal surfaces;

C=0 – when one of the factors (outside, inside or at boundary layer) presents total barrier for daylight transportation (only in theory).

4. INTERIOR DAYLIGHT DISTRIBUTION

The initial numerical calculation has been done using RADIANCE-based methodology [3]. The analysed part of the building located at central Europe climatic conditions (longitude, latitude and meridian respectively 52.25N, 21.0E,–15.0) was assumed to be south oriented. The luminance of the sky was assumed according to the Standard Overcast Sky Distribution developed by the Commision Internationale de l"Eclairage (CIE) [4]. The mean value of Linke Turbidity Factor obtained from other works for the city is T_L=3,75 [5].

For the purpose of first analysis, the representative types of transparences have been selected. The visible transmittance for ten materials rises gradually by 0.1 from 0 to 1. The properties of internal surfaces also rose gradually by 0.1 from 0 (totally absorbing surface) to 1 (ideally reflected) – the same for all surfaces (the walls, the floors and the ceiling).

The test cell analysed here was 3m high, 3m wide and 9m deep. The external surface is 9m^2 and the total amount of internal surfaces is 117m^2. The whole external surface is treated as a transparent area which is 1/3 of the total floor area.

The results presented in fig. 2 and 3 show the daylight distribution inside a hypothetical room along a central line at the level of a typical working plane. All analyses presented in that paper were done for a 21st of March at noon (12:00AM).

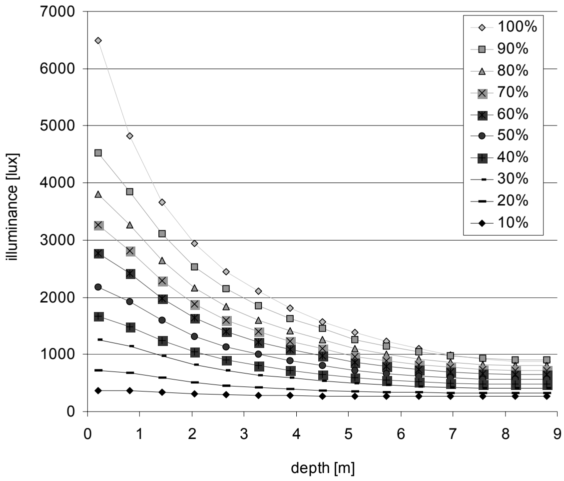

Figure 2: Daylight illuminance profiles in the room with different transferring (T) properties at external surface.

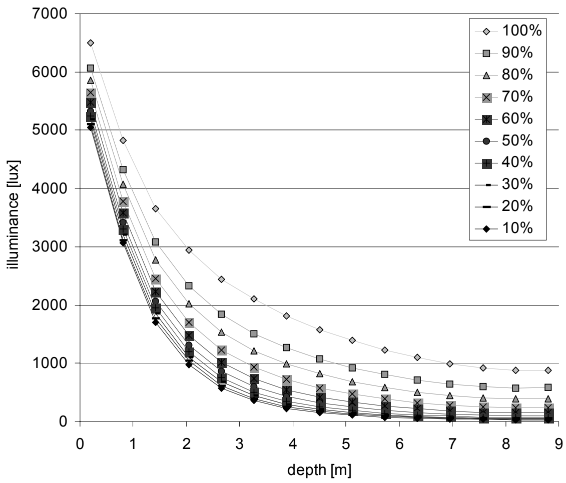

Figure 3: Daylight illuminance profiles in the room with different distribution (D) properties of a building interior.

Figure 2 presents illuminance profiles for 10 different Transferring factors T. All the values were measured at the level of 90cm. The character of the charts shows significant differences in illuminance values at the distance of 3m from the window.

Close to the window face the illuminance is 20 times higher for an ideally transferring envelope (T=1) compared with the wall transferring only 10% of daylight (T=0.1). At the distance of 3 meters from the window the illuminance differs about 5 times, while at the rear of the room it differs about 2 times only. The gradient of the illuminance depends on transferring properties. For T=1.0 it is more than 5 000 lux between opposite sides of the room, when for T=0.1 the illuminance is constant at the level of 400 lux.

Figure 3 presents illuminance profiles in the room with different distribution factors D. The function graphs of daylight profiles are the same for all D values. The largest differences between extreme profiles were observed at the distance from 1st to 3rd meter. In the front of the room the illuminance varies about 1 500 lux, while at the rear it is about 1 000 lux.

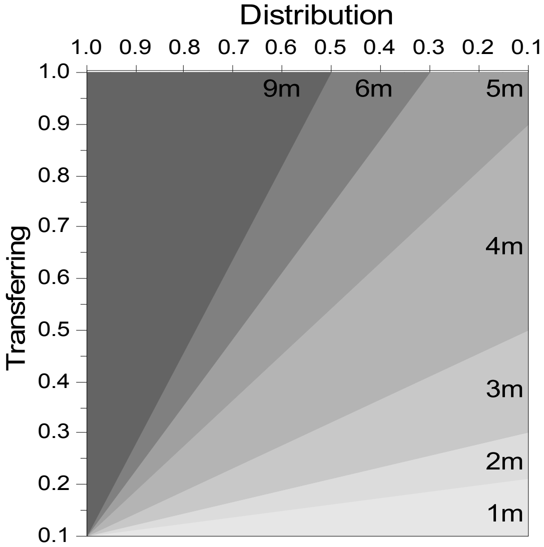

Figure 4: Diagram for 100 Lux

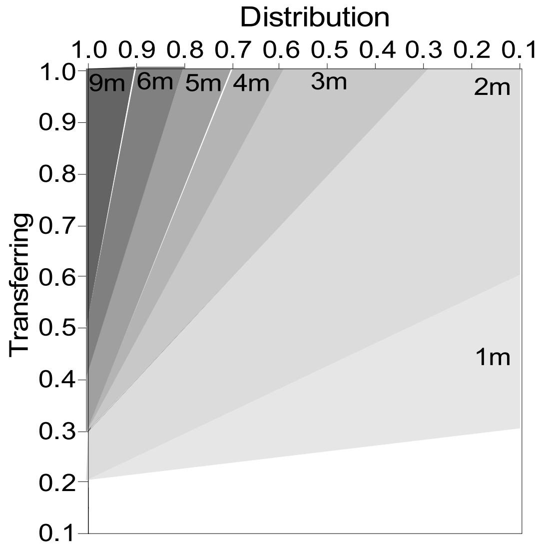

Figure 7: Diagram for 500 Lux

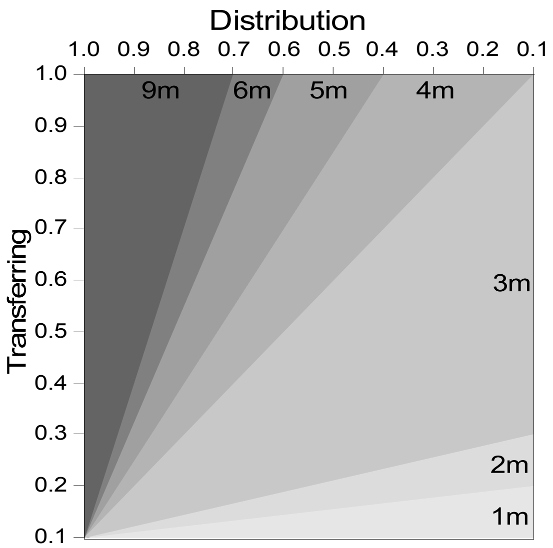

Figure 5: Diagram for 200 Lux

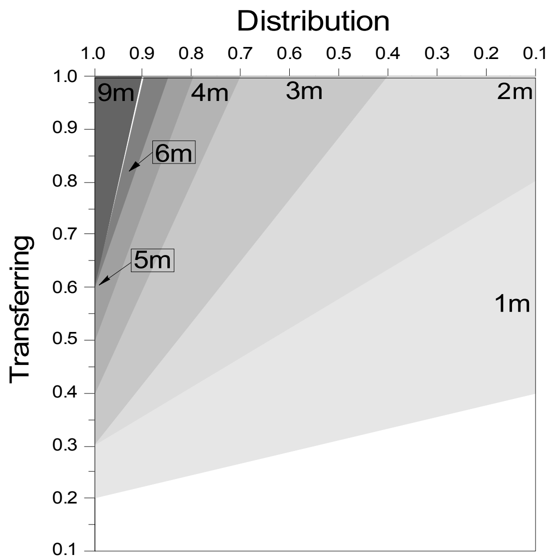

Figure 8: Diagram for 750 Lux

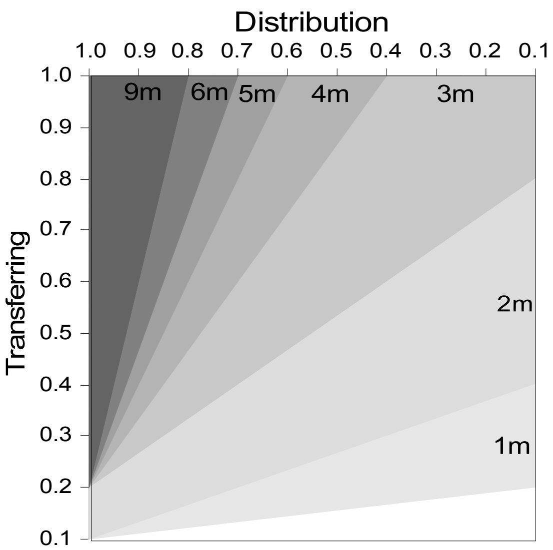

Figure 6: Diagram for 300 Lux

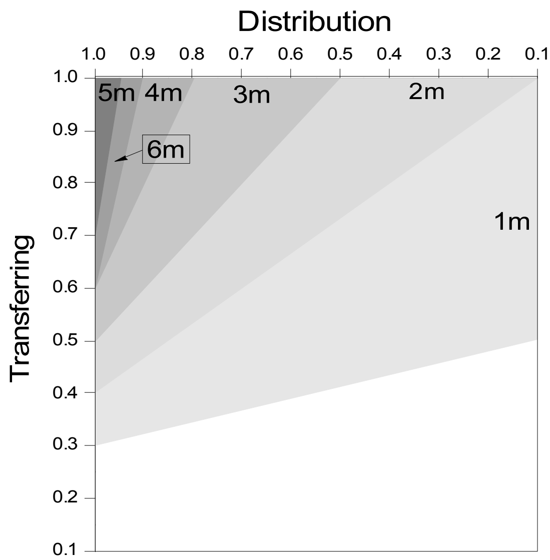

Figure 9: Diagram for 1000 Lux

For D>0.9 the illuminance level at the back of the room is over 500 lux, whereas for D<0.2 the illuminance dropped almost to 0 lux. Based on the presented results the initial guidelines were formulated and presented below.

5. THE GUIDELINES

The first approximation of Global Daylight Index has been done for ideal conditions. The correction factor C was assumed to be 1. It means that:

- the surrounding of the building is empty, without any obstruction or reflection elements around,
- the openings are placed centrally in the wall and the light spreads symmetrically into the room space,
- the ceiling, the walls and the floors have the same reflectance.

The influence of different external conditions is very difficult to standardize. At the further stage of our research project we formulate the C_e values for different urban development and obstructions at the elevations of the building. The interior factor mainly depends on the type of finishing and its mean value can be estimated proportionally. The effect of boundary correction C_b was estimated individually and presented in paragraph 6.

Finally, the required value of the illuminance can be determined by specific Total Daylight Index, as a result of both: transferring and distribution properties. The initial calculation has been carried out for the working plane located at the distance of 1, 2, 3, 4, 5, 6 and 9 meters from the window or other openings. Figures 4-9 present visual diagrams for six levels of the illuminance. The illuminance values were assumed according to existing requirements. The illuminance values and related types of work are presented in table 1.

Table 1. Minimum illuminance at the working plane

[lx]	Type of work
100	Temporary work
200	Limited visual requirements
300	Medium visual requirements
500	Normal visual requirements
750	Long time work and high requirements
1 000	Long time and detailed work

For temporary work (100 lux) visual requirements can be complied in a whole room, but the distribution factor must be higher than 0.5, while for 200 lux the minimum D value is 0.7. If we need to obtain 300 lux the transferring factor must not be lower than 0.2 and the minimum distribution factor equals 0.8. In order to provide the illuminance at the level of 500 lux at the working plane located 3 m from the window, the minimum Total Daylight Index should be:

TDI>0.42 for D=0.6 (T=0.7)

TDI>0.30 for T=1.0 (D=0.3)

For higher illuminance (750 lux) the requirements are met in the whole room only for very high TDI values, close to 1.0 and similarly to the previous case the transferring factor T can not be lower than 0.2. The highest illuminance, at the level of 1 000 lux, is provided at the distance of 6 meters from the window but only for the highest TDI. Relatively low TDI values guarantee the required daylight level not deeper than 2 meters.

6. CORRECTION AT BOUNDARY

The correction factor C_b should be estimated for selected depth of the room. The exemplary results for 3 and 6 meters are presented in table 2 and 3 respectively. The presented C_b factors are valid only for a room with the ratio $h_0/d_0<1,5$, where d is the width and h is the height of the room. The factor includes moving of the window compared with the central place. Figure 10 presents the vision of this idea.

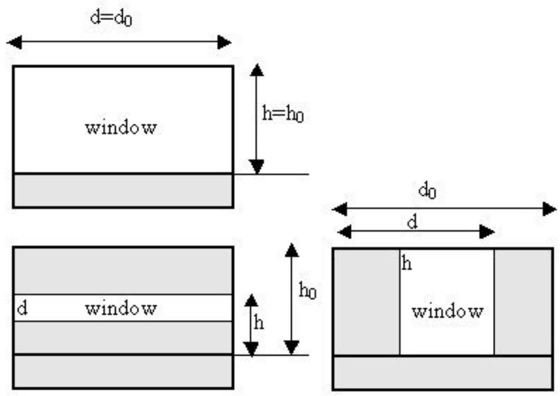

Figure 10:The geometry of the external wall with openings and main dimensions.

7. CONCLUSIONS

The required TDI value relates to the illuminance level inside the building and can be easily used as the first guideline during the architectural design process. The initial results show that the Transferring factor (the amount of daylight entering the building space) determined the luminance distribution in the whole room space. The lowest values of T (below 0.2) do not guarantee minimum lighting conditions. The highest values of T (above 0,6) caused excessive lighting close to the window but on the other hand, provide enough daylight in the deepest space. Different daylight Distribution factors D show greatest differences at the distance from 1 to 3 meters.

At the distance of 3 meters from the window the illuminance value is above 500 lux regardless of D. At the rear of the room the Distribution factors must be 0.9 or more to sustain the illuminance at the level of 500 lux.

ACKNOWLEDGEMENT

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Table 2. Boundary correction factors C_b for 3m

d/d_0 / h/h_0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
0,1	0,18/0,15	0,15	0,15	0,16	0,16	0,16	0,16	0,16	0,16	0,18
0,2	0,18	0,26/0,21	0,22	0,23	0,24	0,25	0,26	0,26	0,26	0,29
0,3	0,18	0,27	0,36/0,29	0,31	0,32	0,33	0,34	0,36	0,36	0,39
0,4	0,18	0,27	0,38	0,48/0,38	0,40	0,43	0,43	0,44	0,47	0,50
0,5	0,18	0,27	0,38	0,48	0,56/0,47	0,52	0,52	0,53	0,55	0,60
0,6	0,18	0,28	0,38	0,46	0,57	0,64/0,58	0,60	0,63	0,63	0,70
0,7	0,18	0,28	0,37	0,47	0,57	0,67	0,74/0,67	0,70	0,71	0,79
0,8	0,18	0,27	0,37	0,48	0,58	0,67	0,77	0,84/0,78	0,79	0,87
0,9	0,18	0,27	0,37	0,46	0,58	0,67	0,74	0,84	0,91/0,86	0,94
1,0	0,18	0,27	0,37	0,46	0,58	0,65	0,76	0,84	0,91	1,0/1,00

Table 3. Boundary correction factors C_b for 6m

d/d_0 / h/h_0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
0,1	0,26/0,25	0,25	0,25	0,26	0,26	0,26	0,26	0,26	0,26	0,26
0,2	0,26	0,33/0,30	0,31	0,31	0,31	0,32	0,32	0,32	0,32	0,34
0,3	0,26	0,33	0,40/0,35	0,36	0,37	0,38	0,38	0,39	0,39	0,39
0,4	0,26	0,33	0,43	0,47/0,43	0,43	0,46	0,47	0,47	0,48	0,50
0,5	0,26	0,33	0,42	0,50	0,58/0,52	0,55	0,55	0,55	0,56	0,58
0,6	0,26	0,33	0,42	0,47	0,58	0,67/0,62	0,62	0,64	0,65	0,68
0,7	0,26	0,33	0,41	0,47	0,60	0,69	0,75/0,70	0,71	0,72	0,77
0,8	0,26	0,33	0,40	0,50	0,59	0,68	0,77	0,84/0,80	0,80	0,88
0,9	0,26	0,33	0,43	0,50	0,58	0,67	0,74	0,84	0,90/0,88	0,94
1,0	0,26	0,33	0,42	0,48	0,58	0,67	0,76	0,84	0,90	1,0/1,0

Table 4. Interior correction factors C_i

D / h	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
3m	1,58	1,56	1,46	1,40	1,35	1,28	1,24	1,15	1,06	1,04
4m	1,59	1,57	1,48	1,46	1,40	1,37	1,28	1,26	1,14	1,05
5m	1,60	1,46	1,44	1,42	1,40	1,38	1,33	1,20	1,12	1,10
6m	1,50	1,47	1,30	1,29	1,27	1,24	1,21	1,20	1,19	1,09
7m	1,40	1,35	1,22	1,21	1,20	1,17	1,15	1,12	1,00	1,00
8m	1,30	1,35	1,24	1,23	1,21	1,20	1,10	1,08	1,00	1,00
3m	1,27	1,23	1,13	1,10	1,07	1,05	1,03	1,02	1,01	1,00
4m	1,35	1,31	1,18	1,15	1,10	1,08	1,07	1,03	1,00	1,00
5m	1,37	1,20	1,17	1,14	1,11	1,10	1,09	1,05	1,02	1,00
6m	1,34	1,31	1,15	1,14	1,12	1,07	1,06	1,03	1,02	1,00
7m	1,31	1,28	1,16	1,15	1,14	1,13	1,12	1,00	1,00	1,00
8m	1,22	1,20	1,04	1,03	1,02	1,01	1,00	1,00	1,00	1,00
3m	1,15	1,12	1,05	1,04	1,03	1,00	1,00	1,00	1,00	1,00
4m	1,18	1,14	1,08	1,05	1,04	1,00	1,00	1,00	1,00	1,00
5m	1,21	1,18	1,10	1,07	1,04	1,01	1,00	1,00	1,00	1,00
6m	1,25	1,20	1,09	1,06	1,05	1,02	1,00	1,00	1,00	1,00
7m	1,21	1,19	1,08	1,05	1,02	1,00	1,00	1,00	1,00	1,00
8m	1,18	1,15	1,02	1,01	1,00	1,00	1,00	1,00	1,00	1,00