DOI:10.22337/2587-9618-2022-18-4-23-38

NUMERICAL MODELLING OF SNOW DEPOSITS AND SNOW TRANSPORT ON LONG-SPAN ROOFS FOR STEADY AND UNSTEADY FLOW

Nikita A. Britikov [1,2]

[1] National Research Moscow State University of Civil Engineering, Moscow, RUSSIA
[2] Russian University of Transport (RUT-MIIT), Moscow, RUSSIA

Abstract: This paper presents the methodologies for numerical modelling of snow deposits and snow transport on long-span roofs for steady and unsteady flow. The calculation of snow loads on long-span roofs is a complex problem, solving which often involves deviating from the building code recommendations. Experiments in wind tunnels, although widely used, do not allow reproducing the full-scale effects of all snow accumulation processes. At the same time, the continuous improvement of mathematical models, numerical methods, software and computer technologies makes the development and implementation of numerical modelling technologies in real construction practice and regulatory documents inevitable. In this paper it is shown that the use of the well-known erosion-deposition model, supported by field observations and experimental data, allows reproducing reasonably accurate snow distributions on long-span roofs. The importance of the "synthesis" between physical and mathematical modelling and the application of the building codes is emphasized, as only the joint use of approaches can comprehensively describe modelling of snow accumulation and snow transport and provide better solutions to a wider range of related problems.

Keywords: computational fluid dynamics, numerical modelling, snow accumulation, snow deposits, snow transport, structure roofs, numerical methods.

МЕТОДИКА ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ СНЕГООТЛОЖЕНИЙ И СНЕГОПЕРЕНОСА НА ПОКРЫТИЯХ БОЛЬШЕПРОЛЁТНЫХ ЗДАНИЙ И СООРУЖЕНИЙ В СТАЦИОНАРНОЙ И НЕСТАЦИОНАРНОЙ ПОСТАНОВКАХ

Бритиков Н.А. [1,2]

[1] Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ
[2] Российский университет транспорта (МИИТ), г. Москва, РОССИЯ

Аннотация: В данной работе представлена методика численного моделирования снегоотложений и снегопереноса на покрытиях большепролётных зданий и сооружений в стационарной и нестационарной постановках. Расчёт снеговых нагрузок на большепролётные покрытия является сложной задачей, для решения которой часто недостаточно одних лишь рекомендаций строительных норм. Эксперименты в аэродинамических трубах, хотя и применяются повсеместно, не позволяют воспроизвести полномасштабные эффекты всех процессов снегонакопления. В то же время, постоянное развитие математических моделей, численных методов, программного обеспечения и вычислительной техники делает безальтернативным развитие и внедрение технологий математического моделирования в реальную строительную практику и нормативные документы. В данной работе показано, что использование известной модели уноса-отложения, подкреплённое натурными наблюдениями и экспериментальными данными, способно воспроизводить достаточно точные картины распределений снега на большепролётные покрытия. Отдельно подчёркнута важность «синтеза» между физическим и математическим моделированием и применением нормативных рекомендаций, поскольку только совместное использование подходов способно всесторонне раскрыть проблему моделирования снегоотложений и снегопереноса и дать наилучшее её решение для широкого спектра задач.

Ключевые слова: вычислительная аэродинамика, математическое моделирование, снегонакопление, снегоотложения, снегоперенос, покрытия сооружений, численные методы.

1. INTRODUCTION

Calculating the snow load on the roofs of large-span buildings and structures, including unique ones, often involves deviating from the building code recommendations for the shape coefficient and using experimental methods to determine the possible location of snowdrifts. Due to the fact that snow accumulation is a complex, highly non-linear and multi-scale phenomenon, the simulation of which is subject to different approaches depending on the problem in question, the development of a unified, verified and validated methodology for its numerical modelling is non-trivial. However, for most construction problems, the main interest is the snow transport, the greatest contribution to which (according to [4], from 50% to 75%) is made by saltation. In this regard, a methodology has been developed that allows to model snow transport and snow accumulation on large-span roofs of by means of numerical simulation of saltation, the results of which can then be used in combination with the building code recommendations for determining the design roof shape coefficient μ. Based on our previous studies ([1, 2, 3]), a decision was made to use the erosion-deposition model to simulate saltation. Since it describes the change of the height of the snow surface in time, the methodology was initially developed for unsteady flow. Then, to reduce resource intensity and increase efficiency, the methodology was developed for steady flow. The results of the verification and validation of the methodologies showed that, due to the extremely stochastic nature of the snow accumulation process, the use of modelled snow distribution maps alone is not sufficient to set the design shape coefficient μ. Nevertheless, numerical modelling makes it possible to identify areas of snow accumulation dangerous from the point of view of mechanical safety of the building, which cannot be predicted by the building code recommendations. Therefore, the symbiosis of the numerical modelling with the guidelines from the building code makes it possible to obtain the most crucial snow distributions on a particular roof.

2. UNDERLYING PRINCIPLES

Both methodologies utilize the erosion-deposition model (described in [6]), developed on the basis of some previous works of the early 1990s. The aforementioned model is based on the assumption that snow mass entrainment is the result of aerodynamic forces, while deposition is the result of settling and attachment of snow particles brought by wind flow. The change in snow cover height over time is described by the expression:

$$\frac{\partial h}{\partial t} = \frac{q_g}{\gamma}, \tag{1}$$

where h is the height of the snow surface, t is time, and γ is the bulk density of snow.
The snow mass exchange flux between air and snow cover q_g is given by:

$$q_g = q_+ - q_- \tag{2}$$

$$q_+ = Cw_f\left(1 - \frac{u_*^2}{u_t^2}\right)\theta(u_t - u_*) \tag{3}$$

$$q_- = A\rho_a(u_*^2 - u_t^2)\theta(u_* - u_t), \tag{4}$$

where q_+ is the deposition flux, q_- is the erosion flux, C is the snow concentration in the air near the snow accumulation surface, w_f is the average snowfall velocity, A is the coefficient depending on the degree of cohesion (snow particles intergranular bonding), ρ_a is the air density, u_* is the friction velocity, u_t is the threshold friction velocity, and θ is the Heaviside function. The friction velocity is determined by the following formula:

$$u_* = \sqrt{\frac{\tau_w}{\rho_a}} \quad (5)$$

where τ_w is the local shear stress on the surface calculated by numerical simulation of wind flows over the surface in question. Threshold friction velocity u_t is determined experimentally. If the friction velocity u_* is lower than the threshold velocity u_t, deposition is observed, otherwise, erosion is observed.

3. METHODOLOGY FOR UNSTEADY FLOW

The flowchart of the methodology for unsteady flow can be represented as the following list:

1. Analysis of the object
Analysis of climatic characteristics at the location, identification of possible snow accumulation and snow drift zones.
2. Problem statement
Selection of blowing directions and velocities, specifying the flow characteristics for each phase (snow concentration, friction velocity, etc.).
3. Computational model generation
Creation of a geometric model of the computational domain and a computational mesh that takes into account the points of interest of the object.
4. Selection and tuning of the turbulence model
Bearing in mind the computational optimization considerations.
5. Definition of the calculation parameters
Initial and boundary conditions, timestep size, numerical schemes and solvers.
6. Aerodynamic analysis
Transient analysis which utilizes custom code to calculate the change in snow height.
7. Engineering analysis of the calculation results
The equation (1) is solved at each timestep Δt with help of custom code, where $\partial t = \Delta t$, and the snow-surface mesh is deformed by moving each node in z direction by $\partial h = \Delta h$ provided by the equation. The problem is solved until a satisfactory result has been achieved.

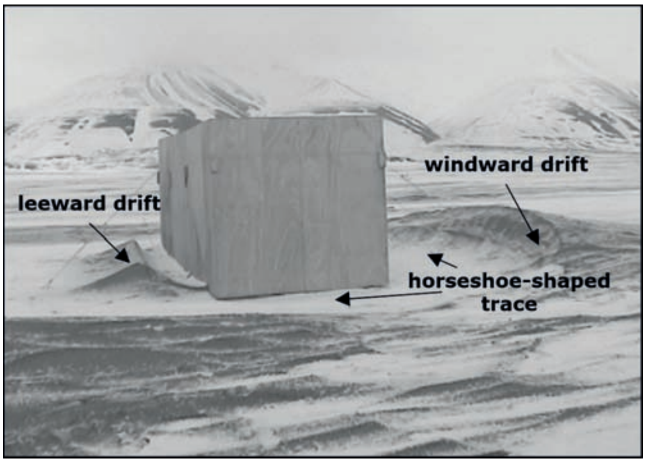
4. VERIFICATION OF THE METHODOLOGY FOR UNSTEADY FLOW

Two problems were considered as verification problems:
1) The model problem (flow around a cube), for which snow accumulation is investigated qualitatively, with the formation of characteristic structures (windward and leeward snowdrifts and a horseshoe-shaped trace);
2) The building code problem (snow distribution on a gable roof), for which snow accumulation is investigated both qualitatively and quantitatively, with calculation of the shape coefficient μ for each slope.

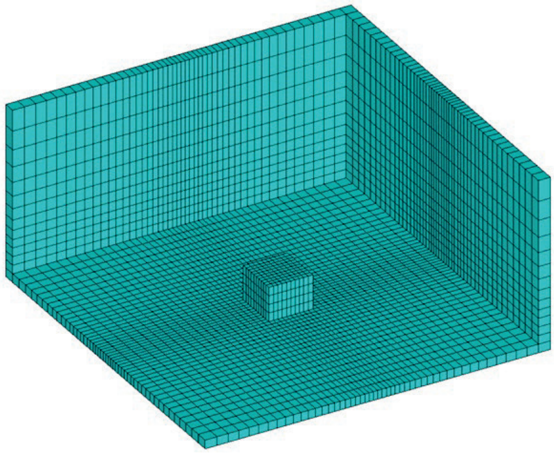
4.1 Solution of the model problem for unsteady flow: a two-phase flow around a cube

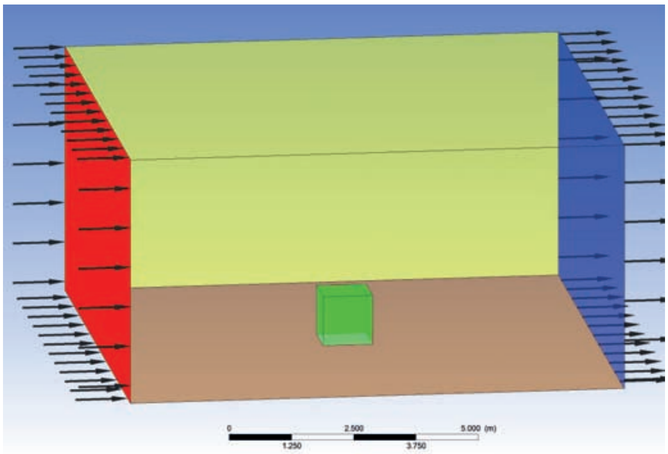
In a rectangular computational domain of 10×10×5 m a Eulerian two-phase flow around a 1×1×1 m cube (primary phase is air, secondary phase is solid particles) with a logarithmic velocity profile at the inlet is simulated for 60 min with timestep of 1 s. In this problem the density of the secondary phase is 150 kg/m^3. An aerodynamic domain (Fig. 1c) is formed from the finite-volume mesh (Fig. 1b). A series of additional steady-state calculations were carried out to select the initial value of the snow volume fraction at the inlet and the initial friction velocity. Based on the results, they were set to $1 \cdot 10^{-4}$% and 0.3 m/s, respectively. Realizable *k-ε* model was used for turbulence modelling.
The calculated snow accumulation (Fig. 1d) in general agrees with the field experiment (Fig. 1a): two characteristic drifts on the windward and leeward sides and a horseshoe-shaped trace of the erosion flow are observed. The results suggest that the application of the erosion-deposition model for the saltation is sufficient to produce

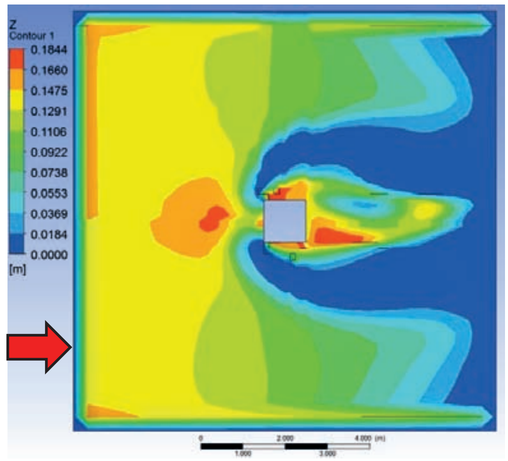
snow drifts of characteristic shapes and to simulate snow transport. However, they also demonstrate the stochasticity of the snow accumulation and the resource-intensive nature of the modelling itself, for a very small timestep is required for problem's adequate convergence.



a) snowdrift around a low-rise construction (from [8])


b) outer layer of the finite-volume mesh (~35.8k cells)


c) layout of the aerodynamic domain



d) snowdrift around the cube at the end of the simulation (t = 3600 s)

Figure 1. Unsteady numerical modelling of snow accumulation and snow transport around a cube

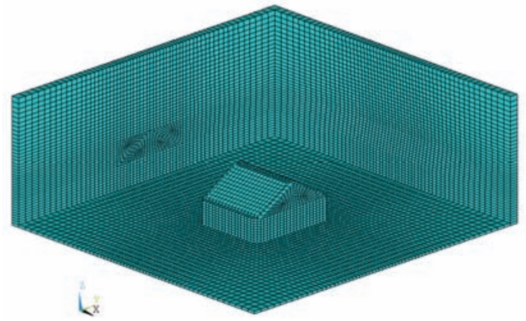
4.2 Solution of the building code problem for unsteady flow: a two-phase flow around a gable roof

In a rectangular computational domain of 40×38×15 m, a Eulerian two-phase flow around a 10×8×6 m building with the same characteristics as given in paragraph 4.1 is simulated for 50 min with timestep of 1 s. An aerodynamic domain (Fig. 2c) is formed from the finite-volume mesh (Fig. 2b). In this problem, a series of additional steady-state calculations were also carried out to select the initial value of the snow inlet volume fraction and the initial friction velocity. Realizable *k-ε* model was used for turbulence modelling, as well.

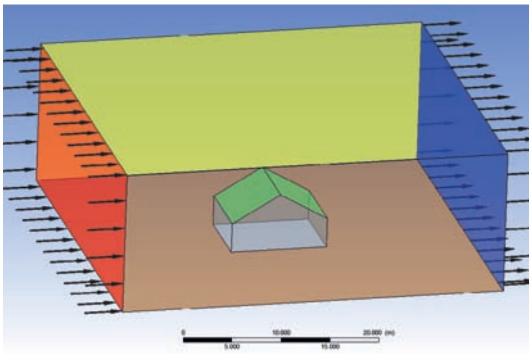
The calculated snow accumulation (Fig. 2d) allows to conclude that *qualitatively* snow erosion was obtained on the windward side of the roof, snow deposition was obtained on the leeward side, and a horseshoe-shaped trace was obtained around the building, but *quantitatively* the result does not agree with the building codes, because snow erosion is almost complete (in contrast to the expected μ = 0.75 according to the code).

In conclusion, based on the results of the verification, it is demonstrated that the erosion-deposition model can be applied to simulate snow accumulation and snow transport for unsteady flow and allows to obtain a *qualitative* result; however, obtaining adequate *quantitative* result requires multiple calculations with varying initial conditions and analysis of intermediate results, which are special cases of snow accumulation.

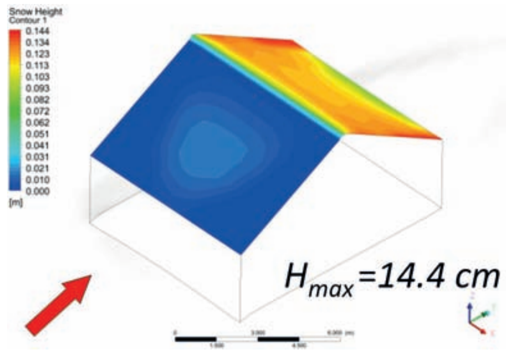
a) snow distribution on a gable roof (from [9])



b) outer layer of the finite-volume mesh (~143k cells)



c) layout of the aerodynamic domain



d) snow distribution on a gable roof at the end of the simulation (t = 3000 s)

Figure 2. Unsteady numerical modelling of snow accumulation and snow transport on a gable roof

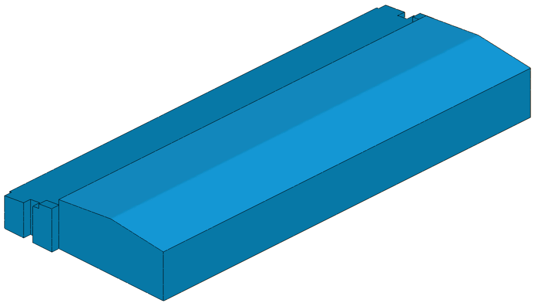
5. VALIDATION OF THE METHODOLOGY FOR UNSTEADY FLOW

The validation is performed for a real building under construction for which snow accumulation on the roof is to be investigated.

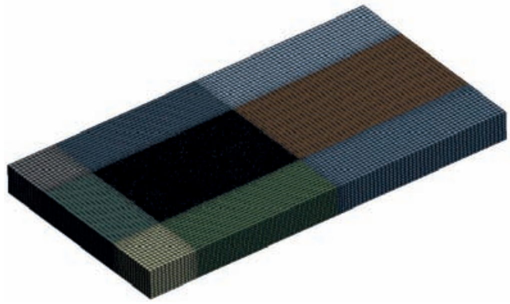
In a rectangular computational domain of 519×953×125 m, a two-phase flow around an industrial building with the same characteristics as in paragraph 4.1 is simulated for 40 min with timestep of 1 s. In this problem the density of the secondary phase is 300 kg/m^3. An aerodynamic domain (Fig. 3c) is formed from the finite-volume mesh (Fig. 3b & 3d). Initial conditions, the inlet velocity and snow volume fraction, were varied to obtain different snow accumulation patterns on the roof. The parameters are presented in Table 1.

As a result, three snow accumulation distributions were obtained on the roof. Although qualitatively they allow determining the direction of snow transport and quantitatively the height of snow cover, it is not possible to draw a general conclusion for the value of the design shape coefficient μ from them, as individual cases of snow accumulation are obtained.

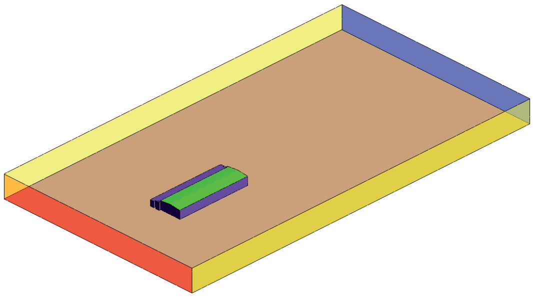
In conclusion, the results suggest that it is not possible to directly use the data from the unsteady flow modelling to determine the design shape coefficient μ.



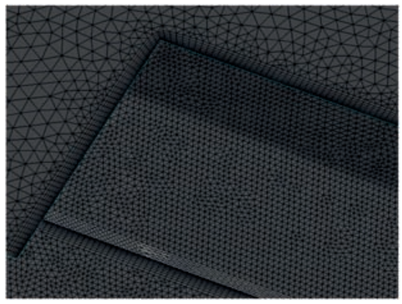
a) geometry of the industrial building



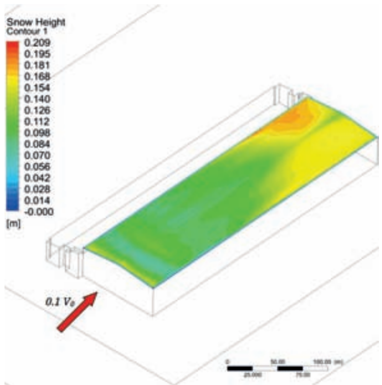
b) finite-volume mesh (~1.7m cells)



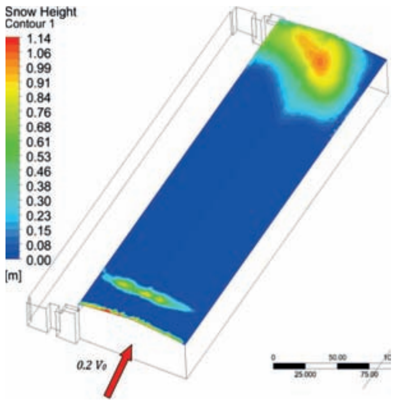
c) layout of the aerodynamic domain



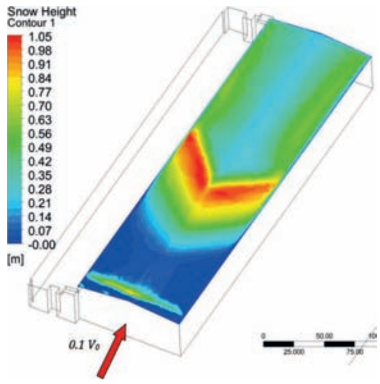
d) inflation in the boundary layer



e) final snow distribution for case 1 (see table 1 for details)



f) final snow distribution for case 2



g) final snow distribution for case 3

Figure 3. Unsteady numerical modelling of snow accumulation and snow transport around an industrial building

Table 1. Validation cases summary

Case number	***Simulated snowfall***	***Velocity at 10 m above ground [m/s]***	***Snow surface maximum height [cm]***	***Snow phase maximum concentration [%·10^{-3}]***	***Snow distribution***
1	Mild	0.84	20.9	0.19	Close to even
2	Mild	1.69	114	1.34	Uneven
3	Moderate	0.84	105	1.2	Uneven

6. METHODOLOGY FOR STEADY FLOW

Due to the problems identified during verification and testing of the methodology for unsteady flow, it was necessary to change the approach and develop a methodology for steady flow, reducing resource intensity but not losing accuracy.

For these reasons, the erosion-deposition model is supplemented by two hypotheses:

Hypothesis 1: There is initially some amount of snow $\mu_0 = const$ on the roof;

Hypothesis 2: The flux q_g and its constituent parameters are time-independent.

The *modelled shape coefficient* μ_m is also introduced to emphasize the difference between it and the design shape coefficient μ.

Then, integrating expression (1), we obtain:

$$\int_0^H dh = \frac{1}{\gamma}\int_0^T q_g dt, \qquad (6)$$

where $H = (\mu_m - \mu_0)S_n/\gamma$ is the change in snow cover height, T is the observed time period, and S_n is the characteristic value of snow on the ground at the relevant site.

Assuming q_g to be time-independent, (6) can be rewritten as:

$$\frac{(\mu_m - \mu_0)}{\gamma} = \frac{T}{\gamma} q_g$$

$$\mu_m = \mu_0 + \frac{T}{\gamma} q_g \qquad (7)$$

Separate *observing time periods* for snow deposition T_+ and for snow erosion T_-. are also introduced. Finally:

$$\mu_m = \mu_0 + \frac{q_+ T_+ - q_- T_-}{S_n} \qquad (8)$$

By varying the initial amount of snow μ_0, the observing time periods T_+ и T_-, and the wind speed at the inlet, different snow accumulation distributions and different contours of the modelled shape coefficient μ_m on the roof can be obtained to find the most unfavourable ones, which are determined from the mechanical safety considerations for the building.

It is important to note, with reference to the conclusions of the validation of the methodology for unsteady flow, that the obtained distributions of the modelled shape coefficient μ_m are used *qualitatively in conjunction with the building code recommendations*. Based on the synthesis of these approaches, the design shape coefficient μ is obtained.

For turbulence modelling, the Generalized *k-ω* model (see [5]) is used. Through adjustments of certain coefficients, it can be tuned for particular objects and can predict the boundary layer flow more accurately, which is crucial for determining the shear stress and, subsequently, the friction velocity. It comprises the capabilities of previously used *k-ε* and *k-ω* models, which at this point renders their further use redundant.

The flowchart of the methodology for steady flow can be represented as the following list:

1. *Analysis of the object*

Analysis of climatic characteristics at the location, identification of possible snow accumulation and snow drift zones.

2. *Problem statement*

Selection of blowing directions and velocities, specifying the flow characteristics (friction velocity, etc.).

3. *Computational model generation*

Creation of a geometric model of the computational domain and a computational mesh that takes into account the points of interest of the object.

4. *Tuning of the turbulence model*

Adjustment of the GEKO coefficients for proper simulation of the flow around the particular object.

5. *Definition of the calculation parameters*

Initial and boundary conditions, numerical schemes and solvers.

6. *Aerodynamic analysis*

Steady-state analysis which utilizes the modified erosion-deposition model, supplemented by hypotheses 1 and 2.

7. Engineering analysis of the calculation results
Derivation of the design shape coefficient μ through the synthesis of numerical modelling and building codes.

7. VERIFICATION OF THE METHODOLOGY FOR STEADY FLOW

Similar problems were considered for verification but the geometry of the dynamic contour of the CSTB wind tunnel (Fig. 4a) was used for the computational domain, as the data from [7] was utilized.

7.1 Solution of the model problem for steady flow: a one-phase flow around a cube

In a computational domain of 23×10×6 m, the one-phase flow around a 1×1×0.5 m cube with a logarithmic velocity profile at the inlet is simulated for 150 iterations. As with the previous simulations, an aerodynamic domain is formed from the finite-volume mesh (Fig. 4b & 4c).
The calculated snow accumulation (Fig. 4d & 4e) is consistent with both field observations, physical modelling in the wind tunnel and numerical modelling results for unsteady flow. The snow distribution on the top face of the cube is also observed, although not taken into account during the verification procedure. Similar to the unsteady flow case, two characteristic drifts on the windward and leeward sides and a horseshoe-shaped trace of the erosion flow are observed. The results allow to conclude that the modified erosion-deposition model can adequately simulate snow accumulation and snow transport for steady flow.

7.2 Solution of the building code problem for unsteady flow: a one-phase flow around a gable roof

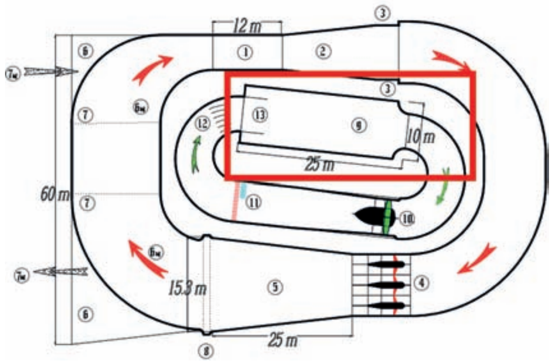
In the same computational domain from the paragraph 7.1, the one-phase flow around a 1×1×0.92 m building with a logarithmic velocity profile at the inlet is simulated for 150 iterations. An aerodynamic domain (Fig. 5a) is formed from the finite-volume mesh (Fig. 5b).
The calculated snow accumulation (Fig. 5d) suggests that *qualitatively* an uneven distribution of snow on the roof and a horseshoe-shaped trace around the building is obtained. *Quantitatively*, the result is close to the physical modelling (Fig. 5c), but not close enough to the building code distribution (see Table 2, total discrepancy ~22%).
In conclusion, the advantage of the steady-state approach over the transient approach is demonstrated, but the modelling results still *cannot be used directly* for the design shape coefficient. It should be also noted that the absolute height of the snow surface depends on the observing time periods T_+ and T_- and can be adjusted, but the pattern of the snow accumulation and snow transport itself remains unchanged and depends entirely on the shear stress pattern on the roof.

8. VALIDATION OF THE METHODOLOGY FOR STEADY FLOW

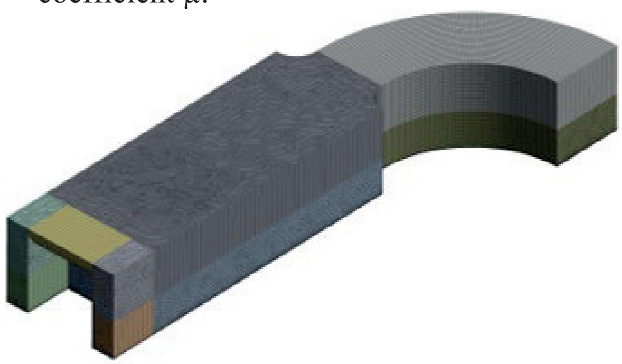
The methodology for steady flow has been validated on several real objects under construction, for which the synthesis of numerical modelling and building code recommendations has given the design shape coefficient μ. For all simulations, the following values of experimental constants were taken: $A\rho_a$ = 10^{-4} kg·s/m^4, w_f = 0.5 m/s, u_t = 0.25 m/s.

8.1 Community Centre

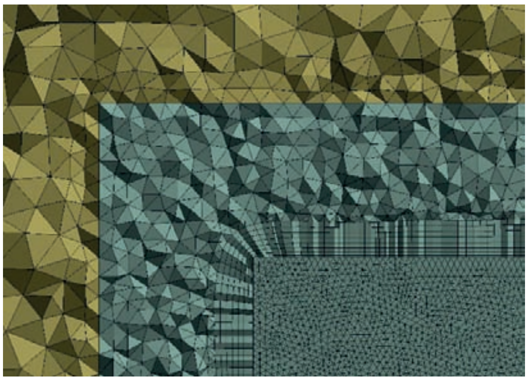
In a cylindrical computational domain of 600×100 m, the one-phase flow around a civil building (Fig. 6a) is simulated for 200 iterations. Ten simulations were carried out for the two wind directions due to the symmetry of the building (180° and 210°; 20 simulations total) using the numerical methodology for steady flow with varying wind speed without considering the surrounding buildings. According to Table 7.1 of SP 131.13330.2020 *Construction Climatology*, the average wind velocity at a height of 10 m during the winter period for the centre's location is 2.6 m/s. Simulations were carried out in the velocity range from 1 m/s to 10 m/s in steps of 1 m/s. The snow concentration *C* was assumed to be 5 g/m^3, which corresponds to a moderate snowfall. The contours of modelled shape coefficient μ_m obtained by numerical simulation for steady flow (Fig. 6c & 6e) were then analyzed to identify the most unfavourable cases from the mechanical safety point of view and summarized in the form of contours of the design shape coefficient μ.



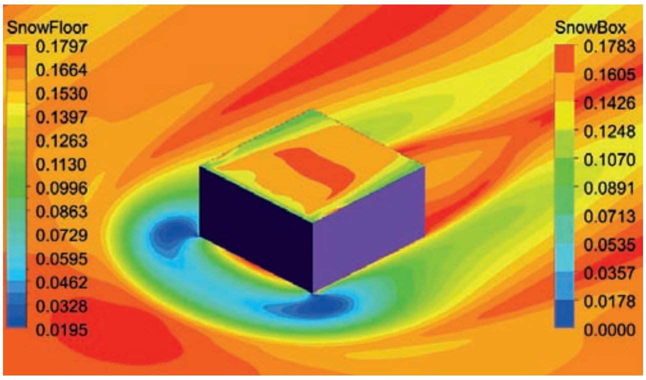
a) modelled part of the dynamic contour of the CSTB wind tunnel



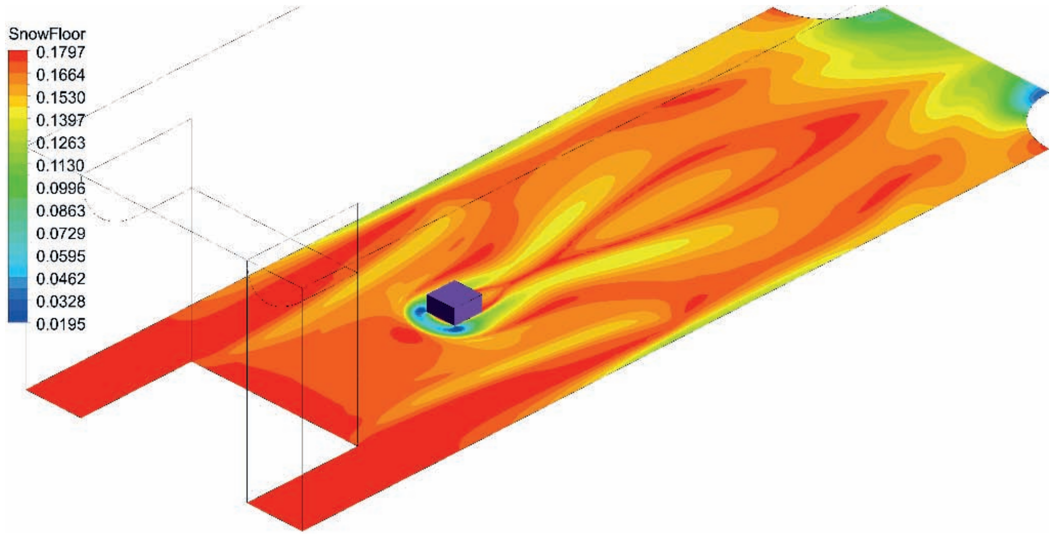
b) finite-volume mesh (~1.47m cells)



c) inflation in the boundary layer

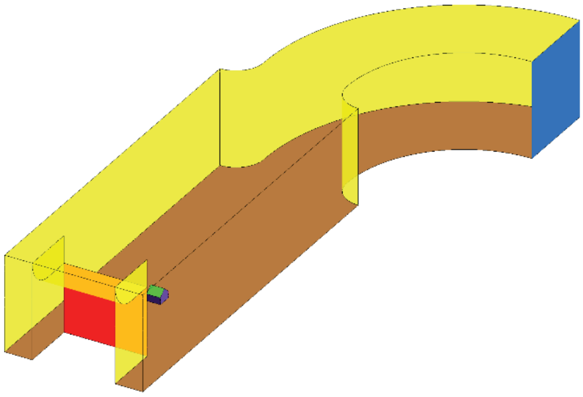


d) snow distribution on and around the cube at the end of the simulation (150 iterations, T_+=3600 s)

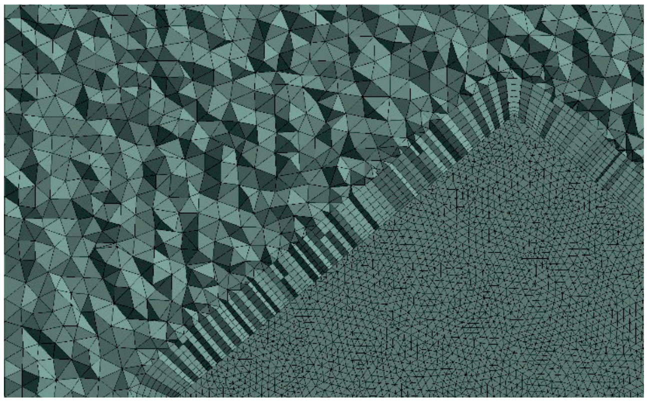


e) snow distribution in the whole aerodynamic domain

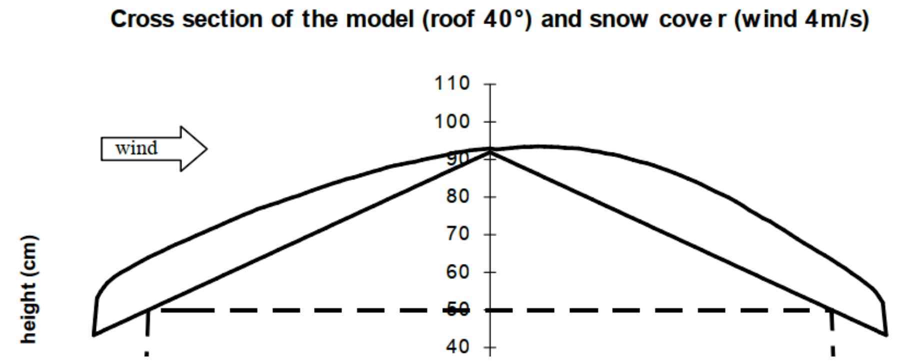
Figure 4. Steady numerical modelling of snow accumulation and snow transport around a cube



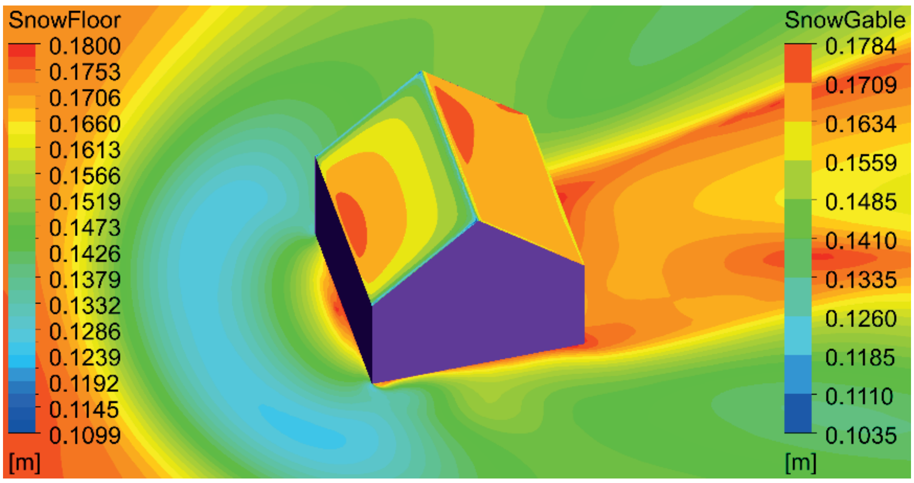
a) layout of the aerodynamic domain



b) inflation in the boundary layer of the finite-volume mesh (~1.65m cells total)



c) physical modelling of snow distribution on a gable roof (from [])



d) snow distribution on a gable roof at the end of the simulation (150 iterations, T_+=3600 s)

Figure 5. Steady numerical modelling of snow accumulation and snow transport on a gable roof

Table 2. Comparison of physical and numerical modelling of snow on a gable roof

Modelling approach	***Windward shape coefficient***	***Leeward shape coefficient***
Physical	0.88	1.13
Numerical	0.96	1.03
Discrepancy	9.1%	8.8%

The Community Centre simulations allowed thorough adjustments to the methodology. As such, they revealed that such a wide range of inlet velocities was excessive, and fewer velocities (as well as study cases) can be utilized in obtaining the contours of the modelled shape coefficient μ_m. It was also shown that an average value of 0.25 m/s for the threshold friction velocity is sufficient for achieving plausible snow distributions for real buildings.

8.2 Sports Centre

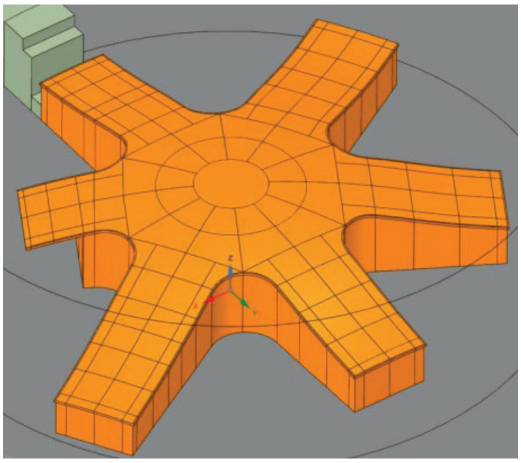
In a cylindrical computational domain of 1500×1200 m, the one-phase flow around a civil building (Fig. 7a) is simulated for 200 iterations. For this problem, two setups were considered: the one that includes the surrounding buildings and terrain around the Sports Centre (Fig. 7b) and the one that doesn't. This was made to both demonstrate the influence of the environment on the snow distribution and obtain more varied distributions in search of the most unfavourable ones.

In numerical modelling, three simulations were carried out for eight wind directions for the Sports Centre (0°, 36°, 90°, 144°, 180°, 213°, 270°, 327°; 24 simulations total) using the numerical methodology for steady flow with varying wind speed. With reference to the conclusions of the previous case, simulations were only made for wind speeds of 1 m/s, 3 m/s and 6 m/s. To simulate a longer snowfall, in which an uneven snow distribution can be obtained, the deposition time T_+ was assumed to be 6 h and the erosion time T_- to be 240 h.

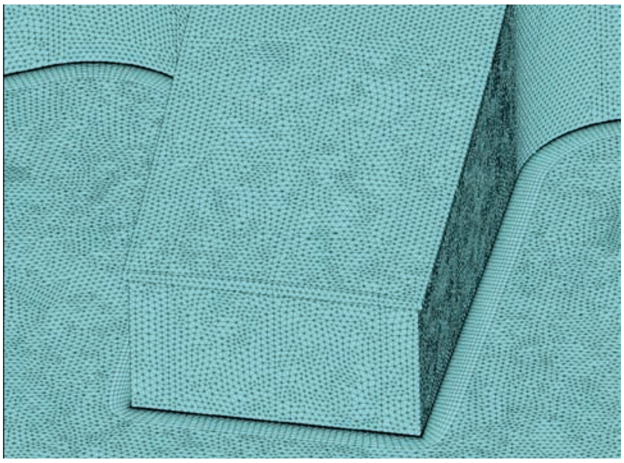
A more traditional physical modelling in the wind tunnel was also carried out for the Sports Centre, which allowed to both compare the results given by two approaches and validate one through the other. In physical modelling, the same wind directions were investigated as for the numerical, and the characteristic wind speeds at which snow transport was analyzed on the model ranged from 3.4 to 8 m/s. The modelling was performed at 3.5-4% humidity using wood flour with a particle size of 50÷250 μm as a snow-like material, which was shifted from a smooth painted surface at a wind speed of 3.4 m/s. As a result of prolonged exposure of the model covered with a thin layer of wood flour in the air flow at a speed of 6÷7 m/s, the patterns of snow transport were formed. Analysis of the obtained snow distributions was performed to zone the roof and obtain the *physically-modelled shape coefficient* μ_{mp} for the zones. As with the numerical modelling, the simulations were carried out with and without taking into account the surrounding buildings, albeit in a lesser radius due to the wind tunnel test chamber size.

Through the comparison of the results, it was clearly observed that both the physical and the numerical modelling provide mostly similar snow distributions. The overall distribution pattern, as well as some local snow drifts, were in agreement with each other (compare Fig. 7c vs. 7e & Fig. 7d vs. 7f and Fig. 8a vs. 8c & Fig. 8b vs. 8d). A similar influence of the surrounding buildings on the obtained contours was also noted. As per the methodology, the results given by the two approaches were summarized and used qualitatively in the engineering analysis in conjunction with the building code recommendations, which provided the final contours of design shape coefficient μ (Fig. 7e; note a small μ = 2.7÷0.6 zone on the right side of the picture, which was specified by the code).

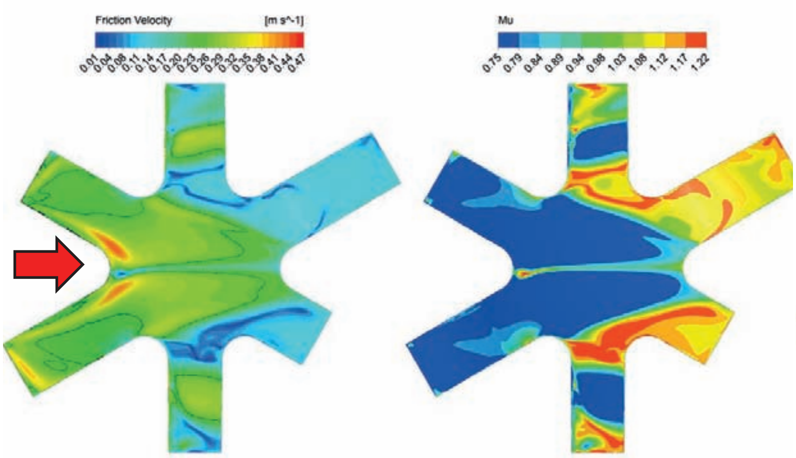
In conclusion, the use of numerical modelling for both validation cases made it possible to provide the design shape coefficient μ, as well as identify some non-obvious and hazardous distributions of said coefficient, which could not be obtained solely by following the recommendations of the Russian building code or any other building codes. The physical modelling carried out for the Sports Centre also evidently showed that numerical modelling is capable of providing similar and thus plausible results, which are true to the nature of the snow accumulation and snow transport processes.



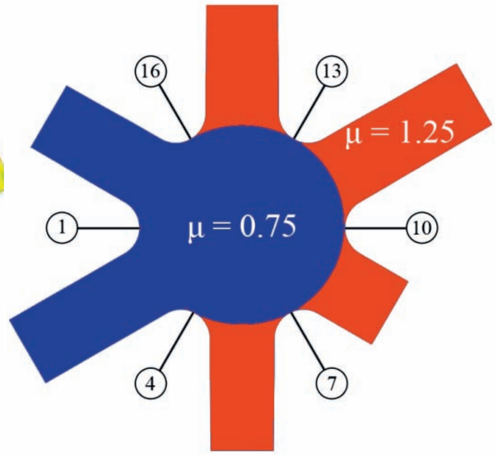
a) geometry of the Community Centre



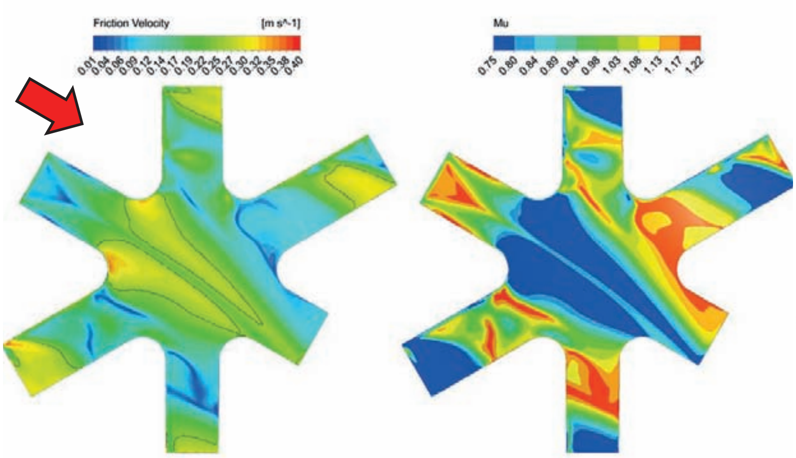
b) inflation in the boundary layer of the finite-volume mesh (~5m cells total)



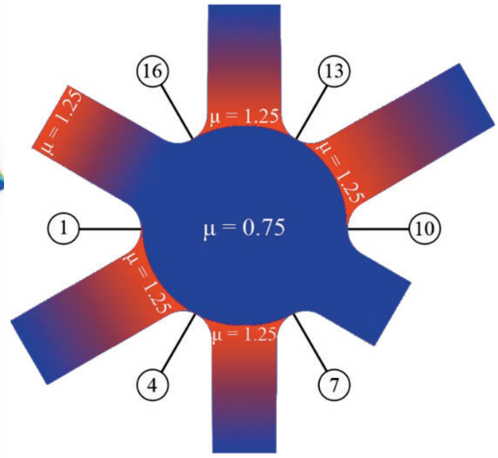
c) contours of friction velocity and modelled shape coefficient for wind direction 180° at 7 m/s



d) design shape coefficient for wind direction 180°

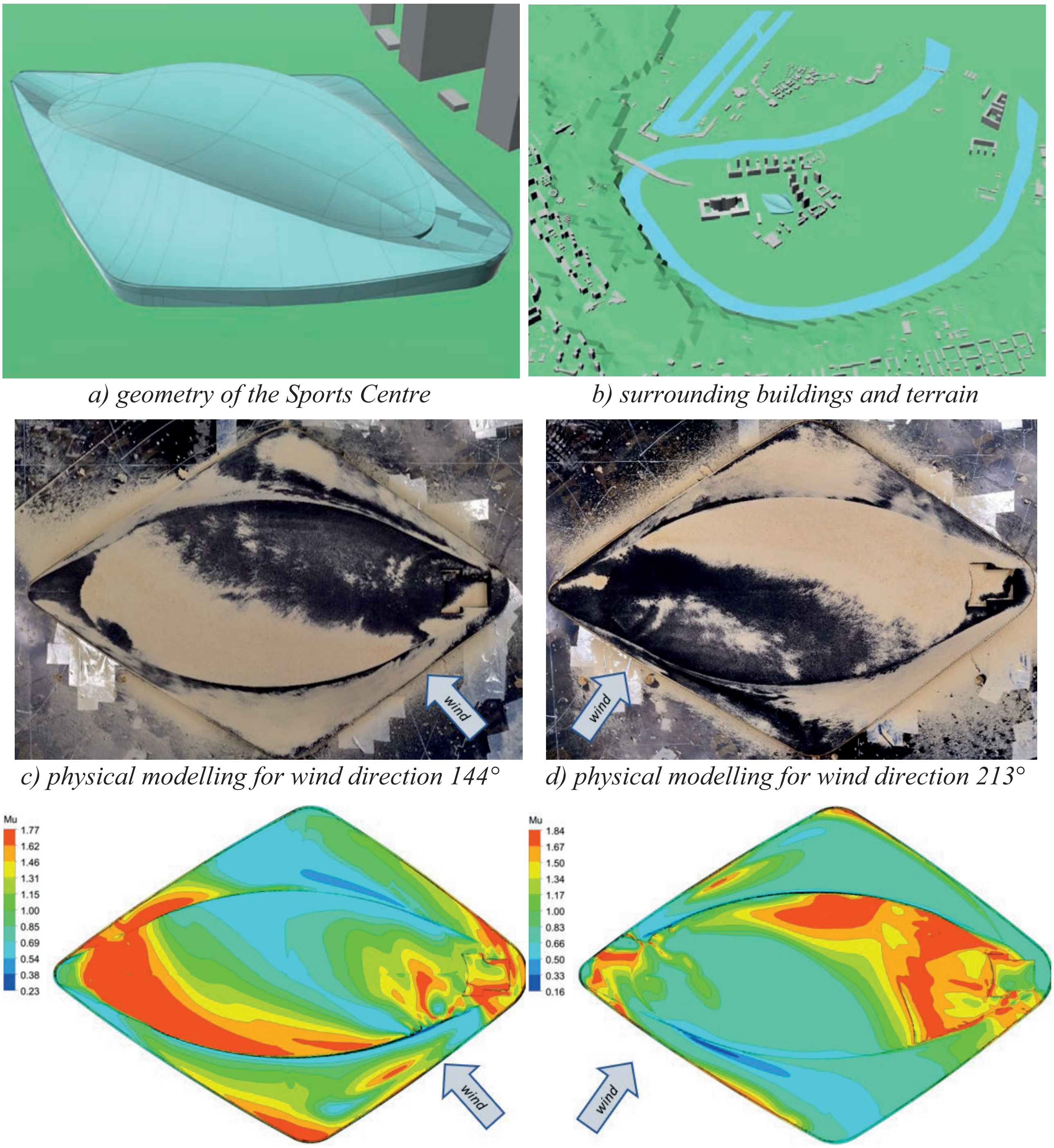


e) contours of friction velocity and modelled shape coefficient for wind direction 210° at 7 m/s



f) design shape coefficient for wind direction 210°

Figure 6. Steady numerical modelling of snow accumulation and snow transport for the Community Centre



a) geometry of the Sports Centre *b) surrounding buildings and terrain*

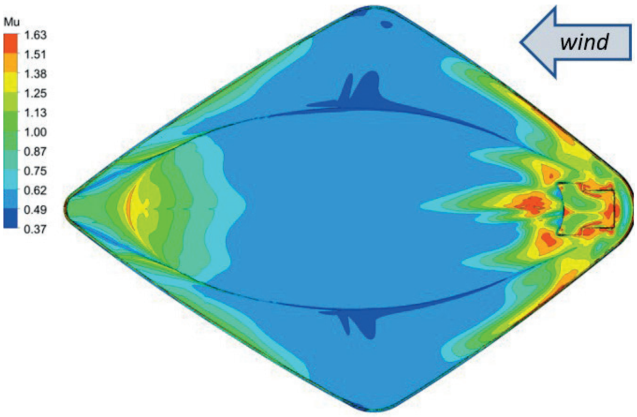
c) physical modelling for wind direction 144° *d) physical modelling for wind direction 213°*

e) numerical modelling for wind direction 144° *f) numerical modelling for wind direction 213°*

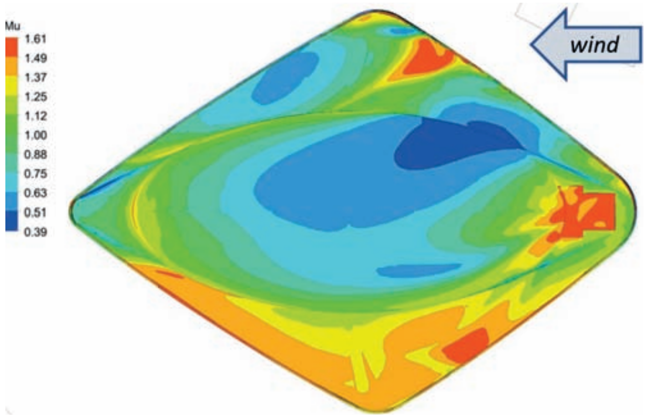
Figure 7. Steady numerical modelling of snow accumulation and snow transport for the Sports Centre (provided design shape coefficient contours for these wind directions are not given in this paper)

a) physical modelling for wind direction 90°
(surrounding buildings ignored)

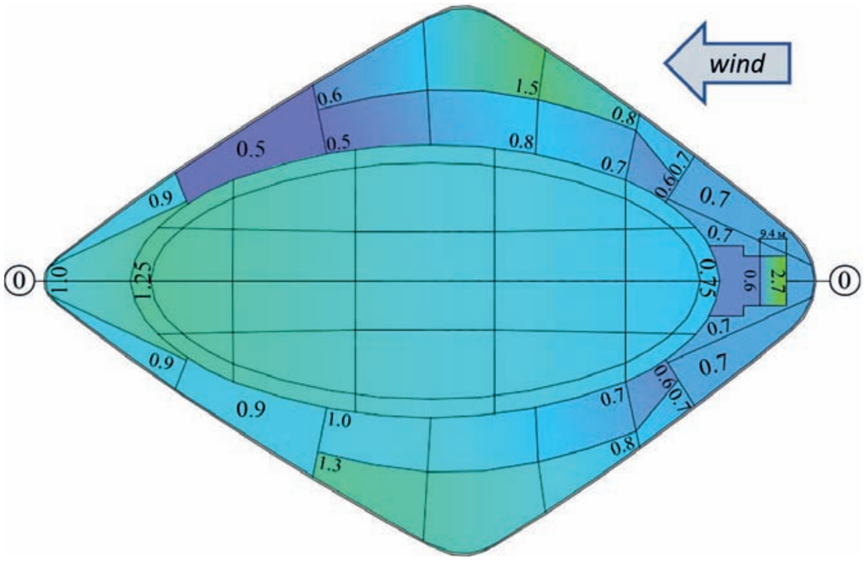
b) physical modelling for wind direction 90°
(surrounding buildings considered)



c) numerical modelling for wind direction 90°
(surrounding buildings and terrain ignored)



d) numerical modelling for wind direction 90°
(surrounding buildings and terrain considered)



e) design shape coefficient based on the results of physical and numerical modelling
and the building code recommendations for wind direction 90°

Figure 8. Steady numerical modelling of snow accumulation and snow transport
for the Sports Centre

9. CONCLUSION

The methodologies of numerical modelling of snow loads for unsteady and steady flows have been developed, verified, and validated. The specifics of the erosion-deposition model used at their basis have been studied, the limits of the applicability have been determined.

The methodology for unsteady flow has proven to be capable of producing plausible results that agree with field experiment. The validation process also revealed its high sensitivity to initial conditions and ability to provide a wide variety of snow distributions for the same geometry under different flow regimes. With that said, this methodology is unlikely to become practically applicable in the nearest future. High resource intensity and computational time demands all make it difficult to apply the methodology to everyday engineering problems, especially when multiple study cases need to be examined and multiple simulations are required. Its ability to produce special cases of snow accumulation and snow transport also appears to be its disadvantage in this sense, as producing a more general snow distribution on the roof requires varying the initial conditions and summarizing the results.

The methodology for steady flow, on the other hand, successfully combines the strengths of its unsteady counterpart and benefit of being time-independent without losing too much in accuracy. For a wide range of long-span roof geometries, the steady-state approach appeared to be sufficient in producing plausible results. Comparisons with field experiments and physical modelling make it clear that numerical modelling is in no way less efficient in simulating snow accumulation and snow transport and may be used for obtaining the design shape coefficient μ if applied reasonably. In the case of the methodology for steady flow, the results of the numerical modelling are considered qualitatively to gain insight into the snow behaviour and used in conjunction with the building code recommendations to assign the coefficient values for the roof. With this approach, the methodology for steady flow can be applied in engineering practice due to its lower resource intensity and efficiency and a more generalized nature of the snow distributions it provides.

Unsolved problems remain that the methodologies do not consider. For example, at current time they don't account for snowmelt, the impact of which may be detrimental for many roofs and buildings, specifically for translucent constructions. We believe that the methodology may and will be expanded to take other snow accumulation phenomena into consideration and thus allow to obtain higher-quality results and further secure the mechanical safety of buildings.

REFERENCES

1. **Belostotsky, A. M., Britikov, N. A., & Goryachevsky, O. S.** (2021). Comparison of determination of snow loads for roofs in building codes of various countries. International Journal for Computational Civil and Structural Engineering, 17(3), 39-47.
2. **Belostotsky, A. M., Britikov, N. A., & Goryachevsky, O. S.** (2021). Critical review of modern numerical modelling of snow accumulation on roofs with arbitrary geometry. International Journal for Computational Civil and Structural Engineering, 17(4), 40-59.
3. **Belostotsky, A. M., Goryachevsky, O. S., & Britikov, N. A.** (2021). Critical review of physical modelling of snow accumulation on roofs with arbitrary geometry. International Journal for Computational Civil and Structural Engineering, 17(4), 22-39.
4. **Gromke, C., Horender, S., Walter, B., & Lehning, M.** (2014). Snow particle characteristics in the saltation layer. Journal of Glaciology, 60(221), 431-439.
5. **Menter, F. R., Matyushenko, A., & Lechner, R.** (2018, November). Development of a generalized k-ω two-equation turbulence model. In Symposium der Deutsche

Gesellschaft für Luft-und Raumfahrt (pp. 101-109). Springer, Cham.
6. **Naaim, M., Naaim-Bouvet, F., & Martinez, H.** (1998). Numerical simulation of drifting snow: erosion and deposition models. Annals of Glaciology, 26, 191-196.
7. **Sanpaolesi, L., Currie, D., Sims, P., Sacré, C., Stiefel, U., Lozza, S., ... & Formichi, P.** (1998). Scientific support activity in the field of structural stability of civil engineering works: Snow loads. Final Report Phase II. Report, Commission of the European Communities. DGIII-D3, 2.
8. **Thiis, T. K.** (2003). Large scale studies of development of snowdrifts around buildings. Journal of Wind Engineering and Industrial Aerodynamics, 91(6), 829-839.
9. **Thiis, T. K., & O'Rourke, M.** (2015). Model for snow loading on gable roofs. Journal of Structural Engineering, 141(12), 04015051.

СПИСОК ЛИТЕРАТУРЫ

1. **Белостоцкий А., Бритиков Н., Горячевский О.** Comparison of determination of snow loads for roofs in building codes of various countries //International Journal for Computational Civil and Structural Engineering. – 2021. – Т. 17. – №. 3. – С. 39-47.
2. **Белостоцкий А., Бритиков Н., Горячевский О.** Critical review of modern numerical modelling of snow accumulation on roofs with arbitrary geometry //International Journal for Computational Civil and Structural Engineering. – 2021. – Т. 17. – №. 4. – С. 40-59.
3. **Белостоцкий А., Горячевский О., Бритиков Н.** Critical review of physical modelling of snow accumulation on roofs with arbitrary geometry //International Journal for Computational Civil and Structural Engineering. – 2021. – Т. 17. – №. 4. – С. 22-39.
4. **Gromke C. et al.** Snow particle characteristics in the saltation layer //Journal of Glaciology. – 2014. – Т. 60. – №. 221. – С. 431-439.
5. **Menter F. R., Matyushenko A., Lechner R.** Development of a generalized k-ω two-equation turbulence model //Symposium der Deutsche Gesellschaft für Luft-und Raumfahrt. – Springer, Cham, 2018. – С. 101-109.
6. **Naaim M., Naaim-Bouvet F., Martinez H.** Numerical simulation of drifting snow: erosion and deposition models //Annals of glaciology. – 1998. – Т. 26. – С. 191-196.
7. **Sanpaolesi L. et al.** Scientific support activity in the field of structural stability of civil engineering works: Snow loads //Final report phase I. Report, Commission of the European Communities. DGIII-D3. – 1998. – С. 2.
8. **Thiis T. K.** Large scale studies of development of snowdrifts around buildings //Journal of Wind Engineering and Industrial Aerodynamics. – 2003. – Т. 91. – №. 6. – С. 829-839.
9. **Thiis T. K., O'Rourke M.** Model for snow loading on gable roofs //Journal of Structural Engineering. – 2015. – Т. 141. – №. 12. – С. 04015051.

Britikov Nikita Aleksandrovich, engineer of the A.B. Zolotov NICCM of the National Research Moscow State University of Civil Engineering; postgraduate student of the Russian University of Transport (MIIT); 129337, Russia, Moscow, Yaroslavskoe shosse, 26. E-mail: n.a.britikov@gmail.com

Бритиков Никита Александрович, инженер НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; аспирант Российского университета транспорта (МИИТ); 129337, Россия, г. Москва, Ярославское шоссе, д. 26. E-mail: n.a.britikov@gmail.com