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STUDY
OF PEDESTRIAN COMFORT OF RESIDENTIAL DEVELOPMENT ADJACENT TO OPEN SEA SPACE

ESTUDIO DEL CONFORT PEATONAL EN URBANIZACIONES RESIDENCIALES ADYACENTES AL ESPACIO MARÍTIMO ABIERTO

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ABSTRACT

Residential development located near the sea zone has a number of features that should be taken into account when designing a comfortable urban environment, such as wind regime. In this paper, the assessment of residential development in the city of Vladivostok, which has a special wind regime, was performed using SFD modeling, the obtained results were compared with the data of field observations, after which a number of measures were proposed to improve the pedestrian comfort of the development near the open sea area. Numerical modeling was performed in the ANSYS CFX software package, the parameters of the computational grid and boundary conditions are given. Assessment of pedestrian comfort is carried out. Further on the territory under consideration there are full-scale measurements of wind speed with anemometer, the results of full-scale measurements are comparable with the results of numerical modeling. To improve the pedestrian comfort in the residential complex, it is proposed to make changes in the geometry of the roof, after which numerical simulation of the modified model is performed. It is found that the improved pedestrian comfort indicators are significantly improved, which indicates the feasibility of making changes in the architectural and planning solution of the residential complex.

Keywords: Pedestrian comfort, Wind, CFD, Residential development, Sea space.

RESUMEN

El desarrollo residencial ubicado cerca de la zona marítima tiene una serie de características que deben tenerse en cuenta al diseñar un entorno urbano confortable, como el régimen de viento. En este documento, se realizó la evaluación del desarrollo residencial en la ciudad de Vladivostok, que tiene un régimen de viento especial, utilizando el modelado SFD, los resultados obtenidos se compararon con los datos de las observaciones de campo, después de lo cual se propusieron una serie de medidas para mejorar la comodidad de los peatones del desarrollo cerca del área de mar abierto. El modelado numérico se realizó en el paquete de software ANSYS CFX, se dan los parámetros de la cuadrícula computacional y las condiciones de contorno. Se lleva a cabo la evaluación de la comodidad de los peatones. Además, en el territorio en consideración hay mediciones a escala real de la velocidad del viento con un anemómetro, los resultados de las mediciones a escala real son comparables con los resultados del modelado numérico. Para mejorar la comodidad de los peatones en el complejo residencial, se propone realizar cambios en la geometría del techo, después de lo cual se realiza la simulación numérica del modelo modificado. Se ha constatado que los indicadores de confort peatonal mejorados han mejorado significativamente, lo que indica la viabilidad de realizar cambios en la solución arquitectónica y de planificación del conjunto residencial.

Palabras clave:

Confort peatonal, Viento, CFD, Desarrollo residencial, Espacio marino.

INTRODUCTION

The location of residential development near the seashore zone has its advantages: beautiful views, fresh air. However, the proximity of the sea entails a number of peculiarities that should be taken into account when designing a comfortable urban environment. One of such peculiarities is the wind regime. The open water surface creates specific conditions for the formation of wind flow, which can negatively affect the pedestrian comfort of coastal areas.

The main problem of building residential development near the shoreline in terms of pedestrian comfort is strong wind (Baş et al., 2023). The open space does not prevent the movement of air masses, which leads to an increase in wind speed, especially in cold seasons, and the associated discomfort of pedestrians. And if high-rise buildings are located on the embankment, a tunnel effect may occur, which can further increase wind speeds at ground level.

Several studies have noted that cold and temperate climates with strong winds that wind shelters are necessary to improve pedestrian comfort, and a poor microclimate leads to reduced attendance at public places (Bosselmann et al., 1995; Eliasson et al., 2007; Szűcs, 2013). And when the microclimate of residential development is unfavorable, people move from open street spaces to indoor spaces (Bosselmann et al., 1995; Johansson & Yahia, 2020; Westerberg, 2009).

The development of residential areas in coastal cities requires careful consideration from residential development design strategies to ensure that people can comfortably stay outdoors (Guo et al., 2011). In Zhang et al. (2022), conducted a large-scale study on "Influence of Tropical Cyclones on Outdoor Wind Environment in High-Rise Residential Areas", the authors analyzed the wind regime in 209 high-rise residential areas located in the coastal zone. It was concluded that courtyard style layout should be recommended for high-rise residential areas in coastal cities to minimize the negative impact of tropical cyclones. Thus, it was shown that the layout of a residential area in the coastal zone can both significantly improve and seriously worsen the comfort of people staying in the neighborhood. In particular, a certain type of layout resulted in large areas with high wind speeds.

In this paper, pedestrian comfort is assessed for a residential complex located near the coastline in the city of Vladivostok, a major port city in the Russian Far East, which is washed by the waters of the Sea of Japan. Vladivostok is characterized by a peculiar microclimate, an important component of which is wind (Kazantsev et al., 2019). Relief features, the proximity of the sea and seasonal changes in atmospheric processes determine the specificity of the wind regime of the city. Vladivostok is located in the monsoon zone - seasonal winds that change their direction twice a year. In winter, the cold and dry "northwest monsoon" prevails, bringing clear and frosty weather. In summer the humid and warm "southeast monsoon" prevails, causing rainy weather. The mountainous relief of Vladivostok has a significant influence on the wind direction and speed. In the valleys and on the coast the wind increases and, on the uplands, - weakens. In the warm season "day breezes" blowing from sea to land and "night breezes" directed from land to sea are characteristic. In autumn and winter Vladivostok is exposed to "typhoons", which bring strong storm winds, heavy precipitation and can cause significant damage to the city infrastructure. The highest wind speed recorded in Vladivostok is 40 m/s (during a typhoon).

Wind is an integral part of Vladivostok's climate (Kazantsev et al., 2019), which has a significant impact on the life of the city. Understanding the peculiarities of the wind regime allows us to adapt to it more effectively, ensuring the safety and comfort of the urban environment.

With the development of computational technologies, the use of CFD for pedestrian comfort assessment becomes an effective tool (Alekseev et al., 2015; Fernando et al., 2020; Klemm & Jabłoński, 2004).

MATERIALS AND METHODS

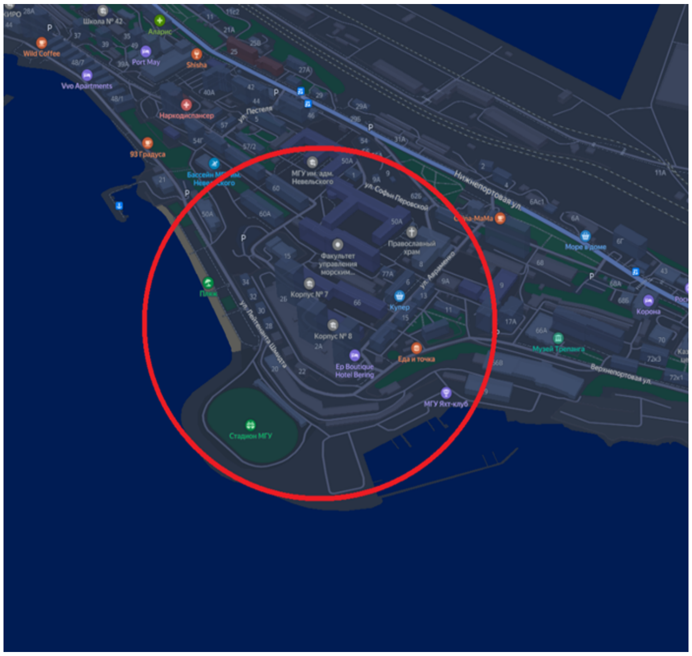
In this paper, a coastal district (Figure 1) in Vladivostok, Russia, which occupies an area of about 2,500 square meters, was selected as the object of the study. This area was chosen because it has a non-typical location for a residential neighborhood.

Residential development in the city of Vladivostok was assessed using CFD modeling, the results were compared with in-situ observations, and then a number of measures were proposed to improve the pedestrian comfort of development near open sea space.

Figure 2 shows a schematic diagram of the study area. CFD modeling creates a full-scale model of the urban area at a scale of 1:1. The main study areas have dimensions of 500 m x 500 m in the east-west (X) and north-south (Y) directions.

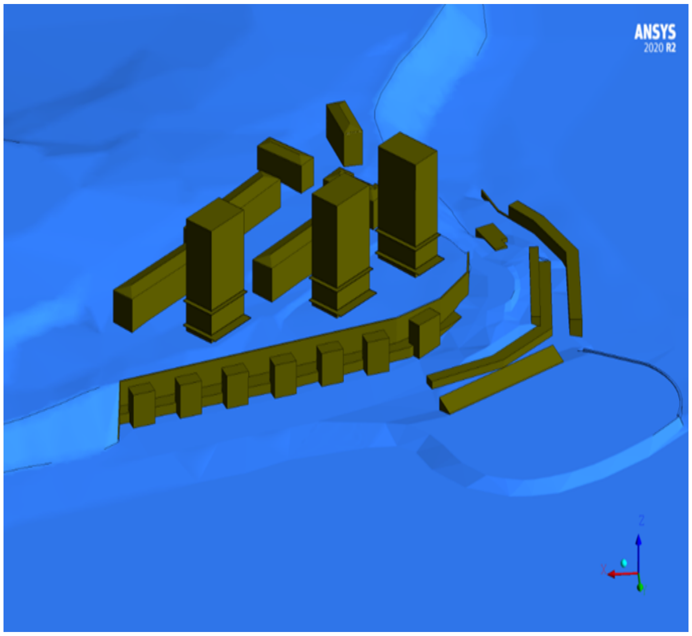
The solution of the task was realized using the ANSYS CFX computational software package based on the control volume method.

Fig 1. Research area.



Source: Own elaboration with the help of specialized software.

Fig 2. Geometric model.



Source: Own elaboration with the help of specialized software.

To determine the size of the computational domain, type and size of grid elements in the vicinity of the object under study, recommendations based on foreign experience of using computational aerodynamics (CFD) packages in building aerodynamics (Franke et al., 2004), experience accumulated by the researchers and ANSYS user manual were used. A 500 m high rectangular computational domain was created around the model at a naturalscale, having a square shape in plan with dimensions of 1500 x 1500 m (Figure 1).

A hybrid computational mesh is constructed, which includes tetrahedral and hexahedral elements, as well as prismatic elements forming the boundary layer.

A boundary layer is formed on the surface of the object when it is streamlined by wind flow, in which there is a significant flow velocity gradient in the direction normal to the object surface. The empirical relations of Cendel & Cimbala (2006), were used to determine the boundary layer thickness (F1):

$$\begin{aligned} \delta &= \frac{4.19L}{\sqrt{Re_L}}, Re_L < 5 \cdot 10^5 \\ \delta &= \frac{0.38L}{{Re_L}^{1/5}}, Re_L > 5 \cdot 10^5 \end{aligned} \qquad \text{(F1)}$$

To form the boundary layer in the ANSYS Meshing mesh generator, the boundary layer growth law with the following recommended parameters was used (F2).

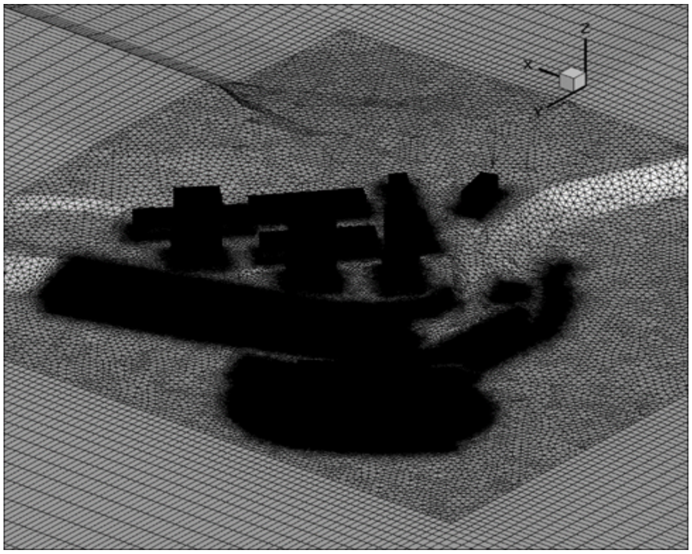
$$\begin{aligned} N &> 10, y^+ \sim 30; \\ N &> 25, y^+ \sim 1; \\ T &= 1\ [\text{м}], \end{aligned} \qquad \text{(F2)}$$

where N - number of layers in the boundary layer; y^+ - dimensionless distance from the wall to the first element; T - boundary layer thickness.

The important parameters of the grid are the rate of increase of cells along the normal to the surface and the size of the first cell in the corresponding direction. The growth rate of the constructed computational grid is 2.1. The appearance of the computational grid on the surface of the object under study is shown in the following figure (Figure 3).

The characteristic cell size on the surface of the investigated buildings is 0.5 m, on the relief surface - 1 m using the chopping function (curvature proximity) to 0.5 m. The thickness of the first cell is 1 mm. The minimum mesh quality (Element Quality criterion, ANSYS Meshing) is 0.282. The minimum angle (Element Angle criterion, ANSYS Meshing) is 29 degrees. The total dimensionality of the computational mesh was 20 million 865 thousand 297 elements.

Fig 3. Calculation grid.



Source: Own elaboration with the help of specialized software.

The input boundary specifies a profile of average wind speed obeying the steppe law of distribution by height. The velocity profile is normalized to a characteristic altitude, which corresponds to the data record at the weather station in a particular area (F3).

$$U_m(z) = U_0\left(\frac{z}{z_0}\right)^{\alpha} \qquad \text{(F3)}$$

were

– is the characteristic wind speed at the equivalent height;

– equivalent altitude;

– terrain type parameter.

For the outlet boundary, boundary conditions corresponding to the free outlet were used. The upper and two side surfaces were assigned flow symmetry conditions. At the ground surface and adjacent buildings, the air friction against the surface was set (U=V=W=0).

The solution of the task was realized using the ANSYS CFX computational software package based on the control volume method.

Mathematical (numerical) modeling of air mass movement on the territory of the research object was carried out in a stationary formulation using the RANS approach. The main feature of this approach is the necessity to close the main system of equations by additional relations called turbulence models. In practice, the k-omega SST turbulence model, which was used in this paper, has proved itself in such problems.

The criterion for computational completion is to achieve iterative convergence at 500 iterations or to achieve pressure and velocity component discrepancies of the order of 10^{-4}.

The wind regime of Vladivostok is determined by the monsoon circulation, expressed in the prevalence of northwestern wind in the cold half of the year and southeastern wind in the warm half of the year The mountainous relief and the character of Vladivostok's building have a great influence on the wind direction and speed During the transition to the summer circulation in spring, a gradual decrease in the frequency of occurrence of northerly winds and an increase in the frequency of occurrence of southerly winds are observed During the summer period, wind speeds decrease sharply

When determining the comfort of pedestrian zones, we consider the dimensionless wind amplification factor (Qxy), which is defined as the ratio of the calculated wind speed in the horizontal plane to the characteristic speed at a height of z = 1.5 m (F4).

$$Q_{xy} = \frac{\left(V_x^2 + V_y^2\right)^{0.5}}{V_{h=1.5\text{ м}}} \qquad \text{(F4)}$$

where is dimensionless wind amplification factor; is theoretical wind speed at a height of 1.5 meters; are wind speed projections on the horizontal plane.

According to this methodology, when conducting design studies, it is necessary to identify zones of increased air flow velocity in the vicinity of the object under study compared to the velocity of the overlying wind at a height corresponding to the level of z=1.5 m (for natural scales) in the absence of buildings. This makes it possible to judge the location of zones of relative comfort or not.

Values of the wind speed at the height z=1.5 m:

- average value (corresponding to the maximum of the average wind speed in the rhumba - 6 m/s) - 4.5 m/s;

- value of wind speed in the gust (corresponding to the wind speed of 14 m/s) - 10.5 m/s.

According to the data of Primorsky hydrometeorological department, on the number of cases of various combinations of maximum speed (at a height of 10 m) and wind direction for the period 2012-2021, the number of cases with a maximum wind speed of 10 m/s and more is 44% of the total number of cases with wind. The wind speed of 14 m/s is chosen as a reference value, the probability of exceeding this wind speed in a gust is 35%.

In order to assess pedestrian comfort, the distribution of flow velocity modulus over the flow field is analyzed in practice. Lawson & Penwarden (1975), evaluated the effect on pedestrians of winds of different velocities. The results are summarized in Table 1.

Table 1. Beaufort scale and the effect of wind force on pedestrians.

Beaufort scale	Wind force	Wind speed at a height of 1.5 m, m/s	Effect on pedestrians
0	Doldrums	0-0.1	The wind is not perceptible
1	Quiet breeze	0.2-1.0	The wind is not perceptible
2	Light breeze	1.1-2.3	You can feel the wind on your face
3	Weak breeze	2.4-3.8	Swaying of clothes, hair; difficulty in reading newspapers
4	Moderate breeze	3.9-5.5	Raising dust, scattering papers, mussing hair
5	Fresh breeze	5.6-7.5	The strength of the wind can be felt by the body and there is a possibility of tripping when entering the wind zone
6	Strong breeze	7.6-9.7	Difficulty using umbrellas, difficulty keeping walking direction, unpleasant wind noise in the ears
7	Strong wind	9.8-12.0	It’s extremely uncomfortable to walk
8	Storm wind	12.1-14.5	It’s difficult to move around and keep your balance
9	Heavy storm	14.6-17.1	The fall, the loss of balance

Source: own elaboration.

When assessing pedestrian comfort in the vicinity of real facilities, it is important to consider the wind patterns characteristic of the area where the facilities are located. For example, it may be that the most frequent wind directions correspond to the most unfavorable flow patterns (with the highest local flow acceleration). In such cases, there will be areas in the vicinity of the facility where pedestrians would assess it to be “constantly windy”. Conversely, even if there is significant flow acceleration near the facility for some wind directions, but these unfavorable wind directions have a relatively low frequency of occurrence, it will be comfortable from a pedestrian perspective to be near the facility. In any case, an assessment of pedestrian comfort using spatial patterns of object flow and data on the frequency of occurrence of strong winds depending on their direction will identify the most favorable and unfavorable areas of space.

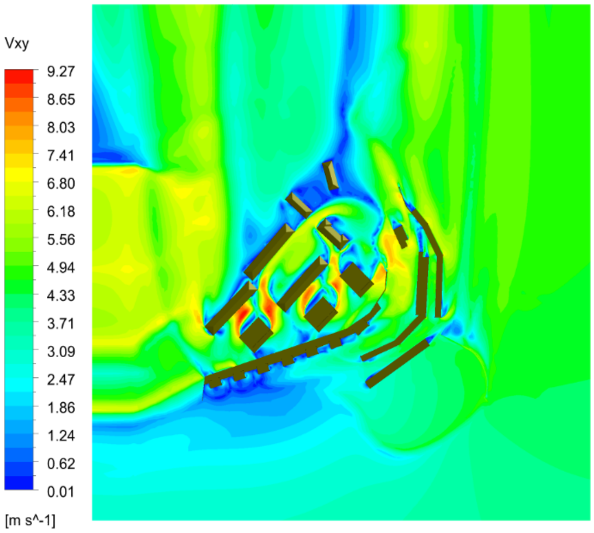
In this paper we consider the distribution of velocities because of wind action, corresponding to the data of the meteorological station in Vladivostok. When determining the unfavorable wind direction, the weather report on the number of days and wind strength was used, which corresponds to the northern wind direction with an average speed of 6-9 m/s at a height of 10 m. The northern direction should be understood as the movement of air masses along the -Y direction.

RESULTS AND DISCUSSION

Data from the Primorsky hydrometeorological department on the number of days and wind strength on days with winds above 10 m/s show that Vladivostok is significantly dominated by winds mainly from the N and S directions. Thus, to assess pedestrian comfort, it is necessary to pay special attention to the flow velocity distributions in the vicinity of the object at given angles of attack.

It is necessary to consider that local values of the flow velocity depend on the velocity of the oncoming flow, so it is reasonable to consider the distributions of the parameter Qcrit, which characterizes the ratio of the maximum (in time) local flow velocity to the air velocity measured at a large distance from the building complex under consideration (relative wind velocity). Measurement of this parameter and visualization of its distributions were performed on a specially selected surface located parallel to the ground surface at a height of 1.5m. This distribution is shown in Figure 4.

Fig 4. Distribution of wind speeds in the residential area.



Source: Own elaboration with the help of specialized software.

According to the obtained result, it can be stated that in general, the area under consideration will be quite comfortable for pedestrians, taking into account the value of the average annual wind speed, according to the SP "Construction Climatology". The value of dimensionless parameter Q, characterizing the degree of deviation of local wind speed in most of the considered territory at a height of z=1.5 does not exceed 1.4 (6.3 m/s). Zones exceeding the local wind speed by 60-80% are mainly located on the territory of the residential complex.

It should be considered that the background value of the overlaying wind speed is quite high (in gusts reaches 12 m/s and higher at a height of 1.5 m above ground level), respectively, under unfavorable climatic conditions, even in the shaded areas on the territory of the investigated object, wind flow speeds higher than 5 m/s can be observed. This is primarily due to the climatic conditions of the site under consideration.

To confirm the obtained results of numerical modeling, field measurements were carried out in the area under consideration using an anemometer. The results of field measurements are presented in Figure 5. The red arrows show the zones of wind direction with the speed of 6-12 m/s, the blue circle marks the windless zones.

Fig 5. Distribution of wind speeds in the residential area.

Source: Own elaboration with the help of specialized software.

One of the options for assessing the comfort of pedestrian zones is the calculation in accordance with the Russian requirements of MDS 20-1.2006 "Temporary recommendations for the assignment of loads and impacts acting on multifunctional high-rise buildings and complexes in Moscow". It should be noted that the speed thresholds specified in this document are relevant for the territory of Moscow. Taking into account that the gust wind speed in Vladivostok is about 10.5 m/s, the comfort level No. 1 according to MDS 20-1.2006 will not be observed on the whole territory, regardless of its location. Only zones of significant shading of wind flow will be an exception. The condition of their comfort is in the form:

$Tc(Vcr) < Tlim$ if $V < Vcr$

where ***V*** is the wind speed in the gust at the level of 1.5 m; ***Tc*** is duration of occurrence of wind speed ***V***, greater than some critical value ***Vcr***; ***Tlim*** is limit value of Tc.

The values of ***Vcr*** and ***Tlim*** for three established comfort levels are given in Table 2.

Table 2. Critical wind speeds and the ultimate duration of their occurrence.

Comfort level	**I**	**II**	**III**
Vcr, m/s	6	12	20
Tlim, hour/ year	1000	50	5

Source: own elaboration.

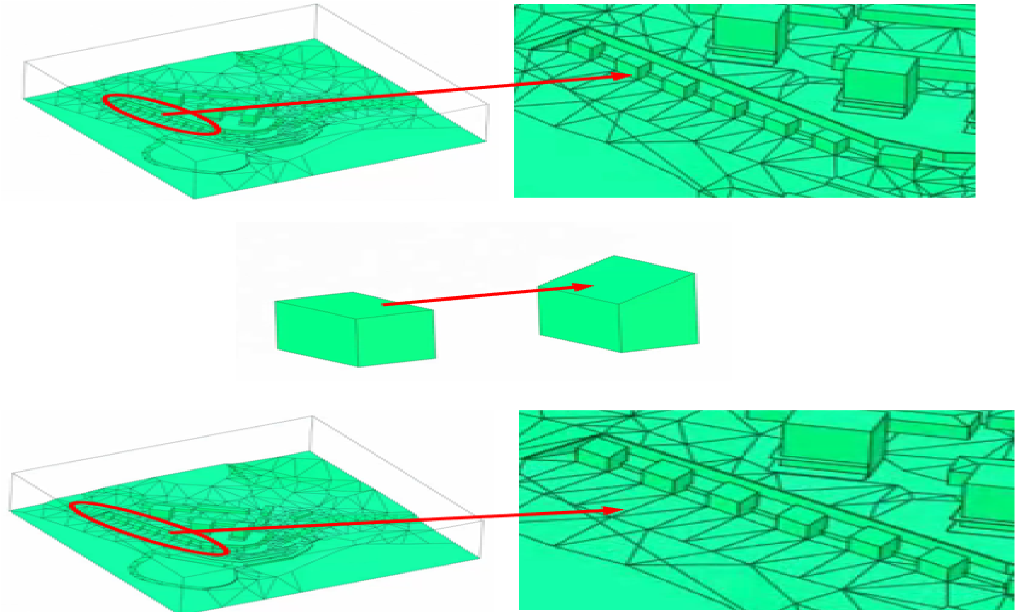
On the basis of these requirements the zones in the considered territory at wind gusts (9.6 m/s at height z = 1.5 m) are obtained (Figure 6).

Fig 6. Cumulative discomfort zones.

Source: Own elaboration with the help of specialized software.

In order to improve the wind regime in the projected residential complex it is proposed to make changes in architectural and planning solutions: the geometry of the roof is changed. The roofing was changed to a single slope roof at an angle of 30 degrees (Figure 7).

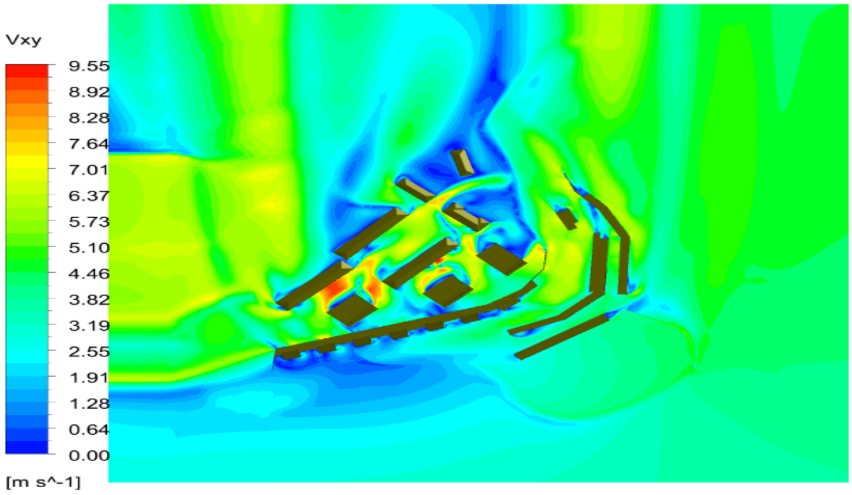
Fig 7. Changing the roof covering.



Source: Own elaboration with the help of specialized software.

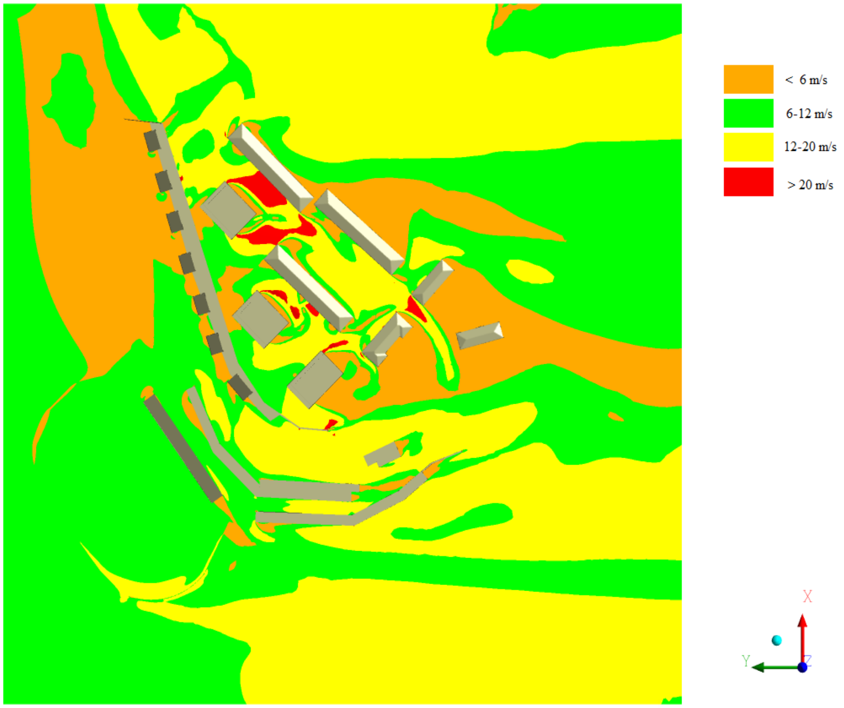
The shape changes results in a distribution pattern of the dimensionless Q coefficient (Figure 8) and the corresponding estimate at gust wind speed (Figure 9).

Fig 8. Relative velocity distributions at a height of 1.5 m in the North wind direction with modified roofing.



Source: Own elaboration with the help of specialized software.

Fig 9. Cumulative discomfort zones.



Source: Own elaboration with the help of specialized software.

As can be seen from Figure 6, the pedestrian amenity indicators have been significantly improved in the area of the proposed residential complex, which is located close to the sea area. Qualitatively, the size of the zones corresponding to I, II and III comfort levels decrease, but doesn't disappear altogether. One of the options for solving this problem is to locate trees in the zones of significant excess of wind regime

CONCLUSIONS

This study examined the impact of coastal wind patterns on pedestrian comfort in residential areas near the sea. Through computational simulations and field observations, it identified the challenges posed by strong winds in Vladivostok, where the open sea and high-rise structures contributed to increased wind speeds, affecting outdoor walkability.

To address these issues, modifications to architectural design were implemented, particularly changes in roof geometry. These adjustments significantly reduced wind intensity in critical areas, leading to improved pedestrian comfort. The findings demonstrated that integrating wind-sensitive architectural solutions into urban planning could effectively enhance the livability of coastal residential developments.

The work was carried out using the equipment of the Main Regional Center for Collective Use and the unique scientific installation Large Research Gradient Wind Tunnel of the National Research University Moscow State University of Civil Engineering. The research was conducted as part of the development program for 2021-2030 of Moscow State University of Civil Engineering under the framework of strategic academic leadership program "Priority 2030".

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