Challenge Journal of Structural Mechanics

Research Article

Influence of the distance between vertical cylinders positioned in a row on the wind load on them

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ABSTRACT

The silos and vertical cylindrical tanks of small volumes are often built in batteries, at short distances between them. As a result of their close location, the wind load on them increases. In the European standard EN 1991-1-4:2005+A1:2010 exists a methodology for determining this increase, which is dependent on the ratio a/d, where a is the distance between the facilities and d is their diameters. Unfortunately, this methodology is applicable for ratios $a/d > 2.5$. In cases where the values are smaller, the standard transfers to the national annexes. In the available to the author annexes, including the Bulgarian one, there is nothing on the subject. Moreover, the necessary information could not be found in the public scientific literature. Only in the Australian/New Zealand standard AS/NZS 1170.2:2011 are written some simple rules for closely spaced vessels. To fill this gap, multiple models of closely spaced cylindrical bodies has been created by the author. A computer fluid simulation (CFD) program is used for this purpose. In the present study, the bodies are arranged in one row and the wind blows them perpendicularly. Through these computer models is determined how the wind load changes due to their proximity. In contrast to what is stated in EN 1991-1-4:2005+A1:2010, the dependence is not linear, and the influence of the close arrangement of the bodies decays much faster. On the other hand, this influence should be considered at much greater distances between bodies than stated in AS/NZS 1170.2:2011.

ARTICLE INFO

Article history:
Received 3 June 2024
Revised 19 August 2024
Accepted 26 August 2024

Keywords:
Vertical cylinder
Wind
Distance
Load
CFD analysis

1. Introduction

Silos and vertical cylindrical tanks of small volumes are often built in batteries, at short distances between them. As a result of their close location, the wind load on them increases. Some standards specify how this should be accounted for. For example, standard AS/NZS 1170.2:2011 states that grouped circular bins, silos and tanks with spacing between walls greater than two diameters shall be treated as isolated silos. Closely spaced groups with spacing less than 0.1 diameters shall be treated as a single structure for wind actions. For intermediate spacings, linear interpolation shall be used.

The European standard about wind load from 2005, EN 1991-1-4:2005, states that for vertical cylinders arranged in a row, the force factor k depends on the wind direction relative to the axis of the row and on the ratio of between distance a and diameter d, as shown in Table 1.

In the latter edition of the standard, EN 1991-1-4:2005+A1:2010, there is a change in how to determine the factor k, as is shown in Table 2.

In the available to the author National Annexes is written:

a) In the Bulgarian National Annex, BDS EN 1991-1-4:2005/NA:2011 – there are no defined values for the factor k when $a/d < 2.5$;

b) In the Danish National Annex, DS/EN 1991-1-4 DK NA:2015, is written only “Table 7.14 may underestimate the wind force for $a/b < 2.5$”. I.e. the problem is here and it is clear, but there is no solution for it;

c) In the Singapore National Annex, NA to SS EN 1991-1-4:2009 – there are no additional information.

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ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2024.03.003

Table 1. Factor k for change of the wind load on vertical cylinders in a row arrangement according to EN 1991-1-4:2005, Table 7.14.

a/d	k
$a/d < 3.5$	1.15
$3.5 < a/d < 30$	$\frac{210 - \frac{a}{d}}{180}$
$a/d > 30$	1.00

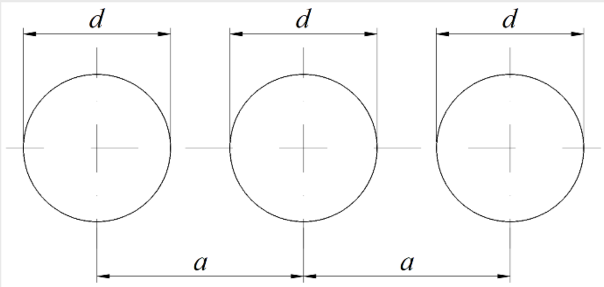
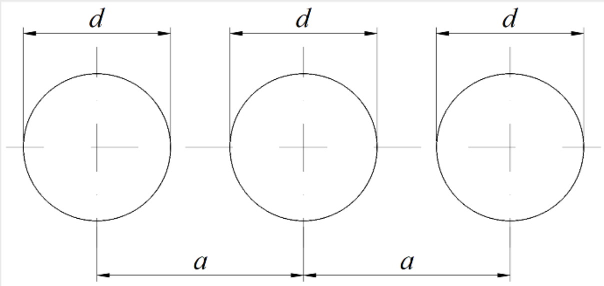


Table 2. Factor k for change of the wind load on vertical cylinders in a row arrangement according to EN 1991-1-4:2005+A1:2010, Table 7.14.

a/d	k
$2.5 < a/d < 3.5$	1.15
$3.5 < a/d < 30$	$\frac{210 - \frac{a}{d}}{180}$
$a/d > 30$	1.00



Note: for $a/d < 2.5$ the values of k may be given in the National Annex.

Macdonald et al. (1990) have studied in detail how the wind pressure changes over individual points in the central body of five closely spaced cylindrical bodies. Both the distance between the bodies and the angle of attack of the wind flow relative to the axis of the array of bodies were varied in their experimental models. Unfortunately, they did not look at how the summarized (total) wind load changes for the entire cylindrical body.

Except for the research above, no other useful information on the topic public scientific literature has been discovered by the author. To fill this gap, numerous models of closely spaced cylindrical bodies, where $a/d < 2.5$, see Tables 1 and 2, has been created. They are arranged in one row. A computer fluid simulation (CFD) program is used for this purpose. Through these numerical models is determined how the close position of the bodies changes the wind load on them.

2. Description of the Numerical Model

In the present study, the behaviour of the wind flow and the load generated by it was chosen to be analysed through computer simulation. Using the Workbench graphical interface of ANSYS (2024) and its Fluid Flow (CFX) module, multiple spatial models of site-built vertical cylinders were created. They are arranged in one row, perpendicularly to the wind flow. For bigger realism, their roofs are conical, with a height f = 50 mm, see Fig. 1.

The diameter of all cylindrical bodies is only one, d = 1,000 mm. In the models, the heights of the cylindrical bodies, their number, and the distance between them are changed. There are three heights of the cylindrical parts of the bodies – h = 2,500 mm, 5,000 mm and 7,500 mm. The other changes in the stacked cylindrical bodies are as follows:

a) Number of the cylinders – n = 1; 2; 3; 4 and 5, see Fig. 2;

b) The distance between their centres, see Tables 1 and 2, a = 1.1; 1.2; 1.5; 2; 3; 4; 5; 6; 7; 8, 9 and 10 m.

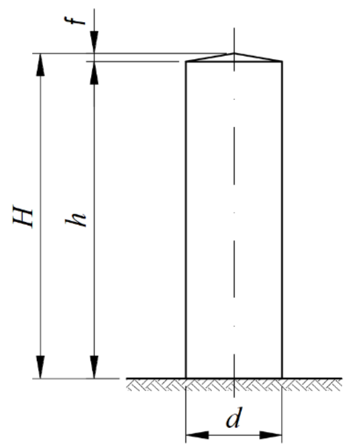


Fig. 1. Shape and dimensions of the examined bodies.

Spatial analysis was used in the present study. First, a cylindrical body is created, with the shape and dimensions shown in Fig. 1. Then it is multiplied. Parallelepiped-shaped wind tunnels have been created around the rows of cylinders, see Figs. 3 and 4. The boundaries of the wind tunnels are located at the following distances:

a) About the facilities with height h = 2,500 mm and 5,000 mm:

- Inlet of the fluid – at 30 m;
- Outlet of the fluid – at 60 m, i.e. the cylindrical bodies are located closer to the inlet of the wind tunnel than to the outlet, see Fig. 3;
- Vertical boundaries – at 30 m;
- "Roof" of the tunnel – at 30 m;
- "Bottom" of the tunnel – because the cylindrical bodies in the current simulations are placed on the ground, the distances between them and the "bottom" are equal to zero.

b) About the facilities with height h = 7,500 mm:

- Inlet of the fluid – at 45 m, see Fig. 4;
- Outlet of the fluid – at 90 m;
- Vertical boundaries – at 45 m;
- "Roof" of the tunnel – at 45 m;
- "Bottom" of the tunnel – the distances between the cylindrical bodies and the "bottom" are equal to zero.

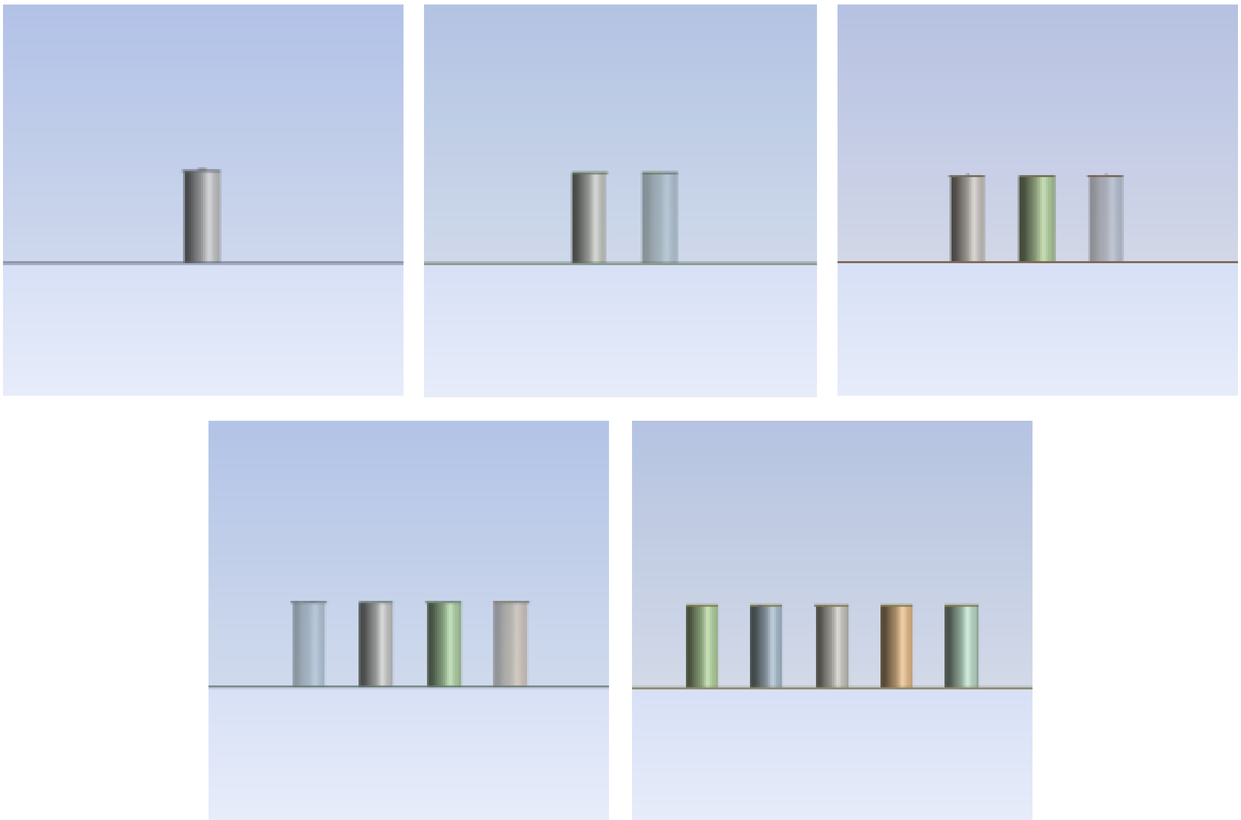


Fig. 2. Number and position of the examined bodies.

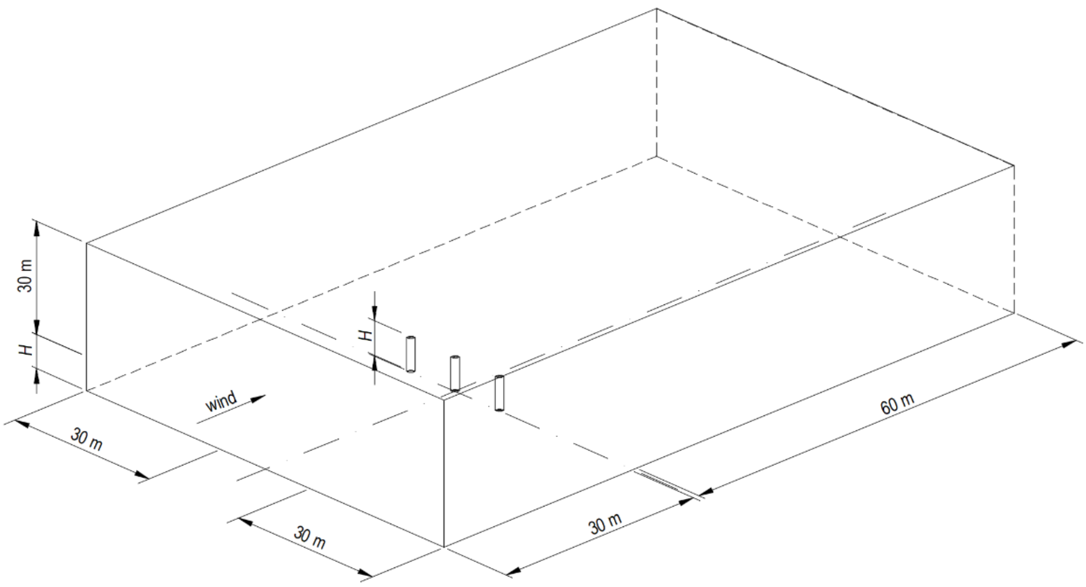


Fig. 3. Shape and dimensions of the wind tunnels
when heights of the cylindrical bodies are h = 2,500 mm and 5,000 mm.

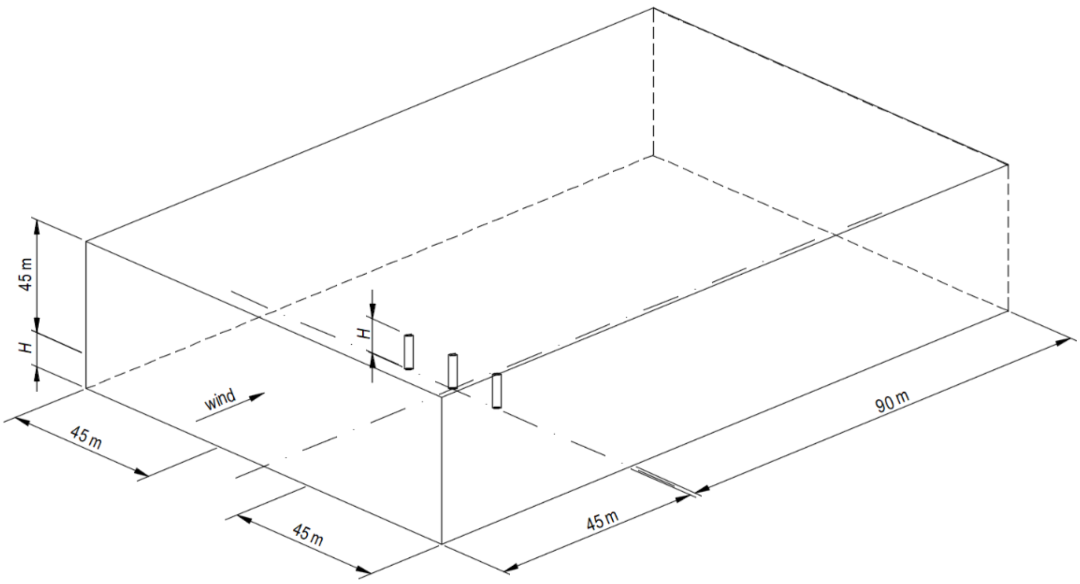


Fig. 4. Shape and dimensions of the wind tunnels when heights of the cylindrical bodies are h = 7,500 mm.

The determining of the above-written distances between the boundaries of the virtual wind tunnel and the facilities is based on the principle that airflow adjacent to the bodies should not be affected, see Rusev et al. (2012a) and Pantusheva et al. (2022). Accepted distances are bigger than the requirements of Tominaga et al. (2008), as follows:

- The top/side boundary should be set 5H or more away from the obstacle, where H is the whole height of the bodies in the current research ($H = h+f$, see Fig. 1);

- The outlet boundary should be set at least 10H behind the obstacle.

For facilities where h = 5,000 mm and 7,500 mm their total height is H = 5,050 mm and 7,550 mm respectively. In other words, the accepted distances are almost 6H and 12H, like the simulations of Hillawaere et al. (2013, 2015).

At the same time, to avoid heavy computer solutions and save computational time, the maximum number of finite elements is maintained within reasonable limits. To optimize their mesh, it is significantly refined in the area around the facilities, see Fig. 5, and is coarse to the periphery, as is done in Rusev et al. (2012b). The maximum size of the finite elements of the air is limited to:

a) Elements in direct contact with the cylindrical bodies – 100 mm;

b) Elements in direct contact with the “bottom” of the wind tunnel – 500 mm;

c) All other elements – 1,000 mm.

The "Linear" option was used when creating the mesh finite elements, as a result of which nodes in the middle of their edges are not preserved. This approach reduces the required computational time. The finite elements are "Tetrahedrons", with four nodes each. The algorithm for creating the mesh is "patch conforming", i.e. it starts from the edges and surfaces of bodies. This approach guarantees a "clean" mesh and high accuracy of the solution.

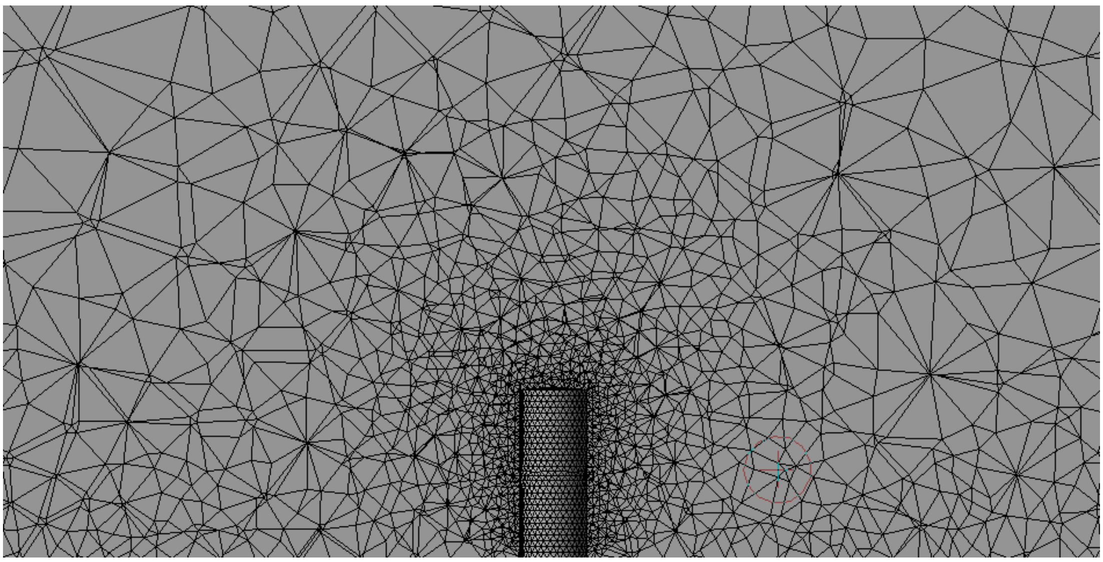


Fig. 5. Refinement of the mesh around the circular bodies.

Steady-state analysis type is used in a Fluid Flow (CFX) module. k-ε model, part of the Reynolds-averaged Navier Stokes (RANS) family, is used to simulate the turbulent flow of the fluid around the bridges. According to Agyropulos and Markatos (2015), they look like as:

$$\frac{\partial \overline{u_i}}{\partial t}+\frac{\partial(\overline{u_i}\,\overline{u_j})}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i}+\nu\frac{\partial^2\overline{u_i}}{\partial^2 x_j}-\frac{\partial\left(\overline{u_i'}\,\overline{u_j'}\right)}{\partial x_j} \quad (1)$$

where u_i is the mean speed of the fluid; $\overline{u_i'}$ is the change of the speed; ρ is the density of the fluid; ν is the kinematic viscosity; t is the time; $\bar{p}$ is the pressure of the fluid; and $\overline{u_i'\,u_j'}=\tau_{ij}$ is the tensor of the stresses of Reynolds.

In analogy to molecular viscous stresses, Reynolds stresses can be represented by Markatos (1986) as:

$$\tau_{ij}=\overline{u_i'}\,\overline{u_j'}=\frac{2}{3}k\delta_{ij}-\nu_t\left(\frac{\partial\overline{u_i}}{\partial x_j}+\frac{\partial\overline{u_j}}{\partial x_i}\right) \quad (2)$$

where k is the kinetic turbulence energy; and $\nu_t = \mu_t/\rho$ is the turbulence or eddy (kinematic) viscosity.

In the models with one equation, according to Launder and Sharma (1974), ν_t is accounted by the expression:

$$\nu_t = C_{\nu1}\sqrt{kL} \quad (3)$$

in which $C_{\nu1}$ is a dimensionless parameter.

A two-equation model, such as the used here standard k–ε model, uses differential equations to calculate the characteristic velocity, on the length scale L, and then evaluates the value of ν_t by the following equation, see Markatos (1986):

$$\nu_t = C_\mu\frac{k^2}{\varepsilon} \quad (4)$$

where C_μ = 0.09; and ε is the turbulence dissipation rate.

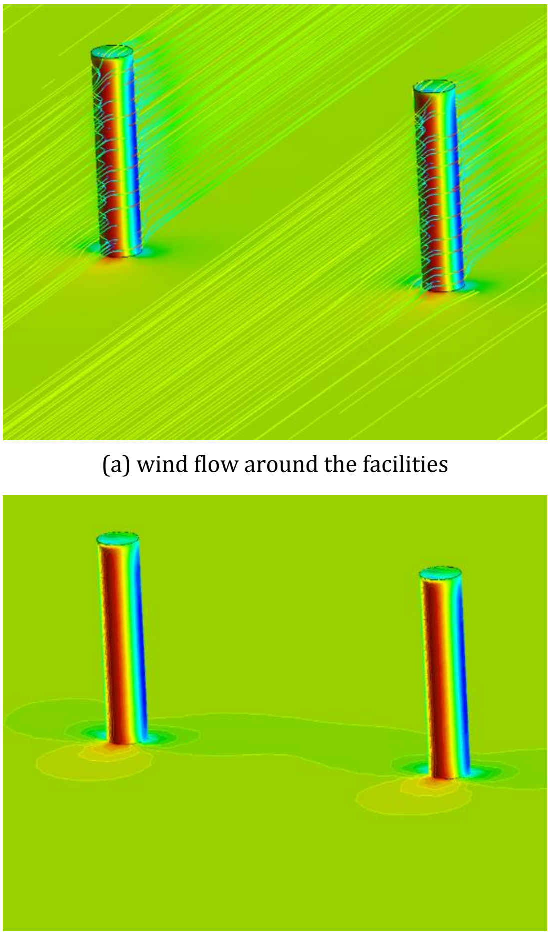
These RANS equations are an adequate representation of the wind tunnel's reality, Baklanov et al. (2007). Accepted turbulence has a medium (5%) intensity. No combustion and thermal radiation. The used fluid is an air-ideal gas with a temperature of 25 °C. Its speed at the inlet domain of the tunnel is constant in height and has a value of v = 25 m/s. Flow regimes in the outlet and opening domains are subsonic, with a relative pressure of 0 Pa. Flow direction is normal to boundary conditions for the domain opening. The domain of cylindrical bodies is a no-slip smooth wall. The surface of the terrain under the bridge is perfectly smooth, too (Zdravkov 2022).

Unlike the research of Yu et al. (2011), main wind flow is horizontal there, i.e. the angle of attack is 0°. The direction of the approaching wind is perpendicular to the axes of the row of cylinders.

During its movement, the wind flows around the facilities, see Fig. 6a, which leads to the occurrence of pressure on their surfaces, see Fig. 6b. As a result, horizontal forces are generated at the base of the cylindrical bodies and they can be accounted. Considering the force at the base of an isolated (independent) cylinder and comparing it with the forces at the bases of multiple bodies united in a group, can determine the influence of the distance between the bodies, using Eq. (5):

$$k=\frac{F_{h,i}}{F_{h,1}} \quad (5)$$

where $F_{h,i}$ is the horizontal force at the base of the i-th cylindrical body of the group, accounted in the direction of the wind flow; and $F_{h,1}$ is the accounted in the direction of the wind flow horizontal force at the base of the isolated (independent) cylinder.



(a) wind flow around the facilities

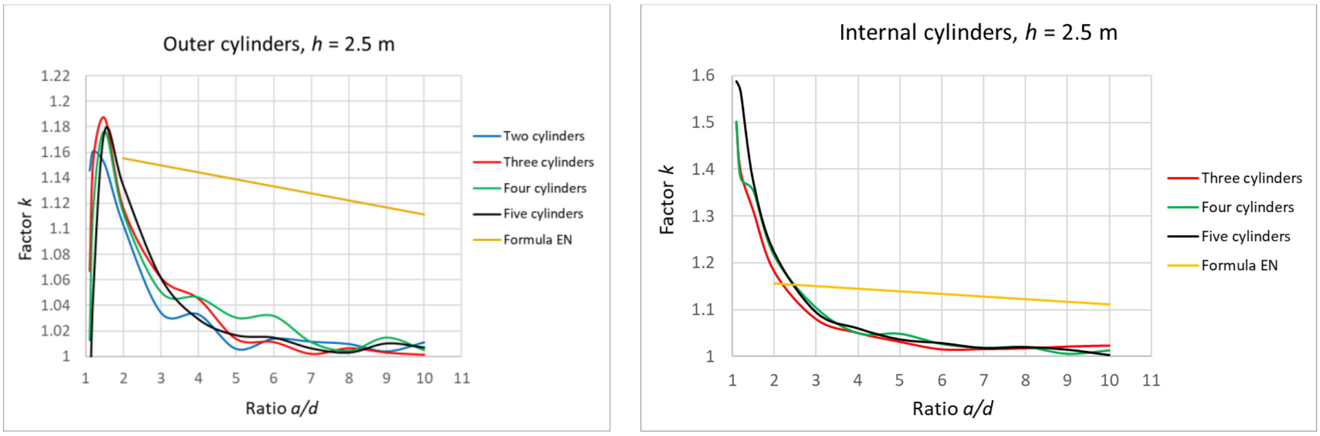
(b) pressure on surfaces of the bodies

Fig. 6. Wind flow around the cylindrical bodies and the resulting pressure on their surfaces.

3. Results and Discussion

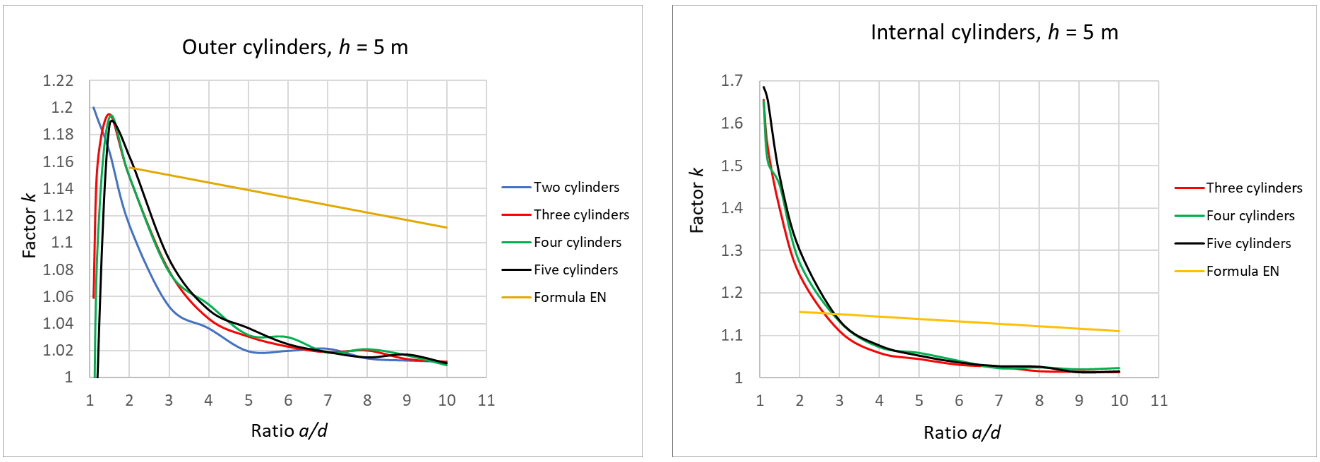
The shearing force $F_{h,i}$ in the base of every one cylindrical body in the group is obtained during the research. Analogical data $F_{h,1}$ is accounted for the isolated (independent) cylinders. The values of factor k are calculated, using Eq. (5). They are shown graphically in Figs. 7–9, where: a is the axial distance between the cylindrical bodies, see Table 1 and 2; and d = 1,000 mm is the diameter of the bodies in the research.

The numerically obtained values for the factor k are compared with those, determined analytically, according to the methodology of EN 1991-1-4:2005+A1:2010, see yellow line in Figs. 7–9.



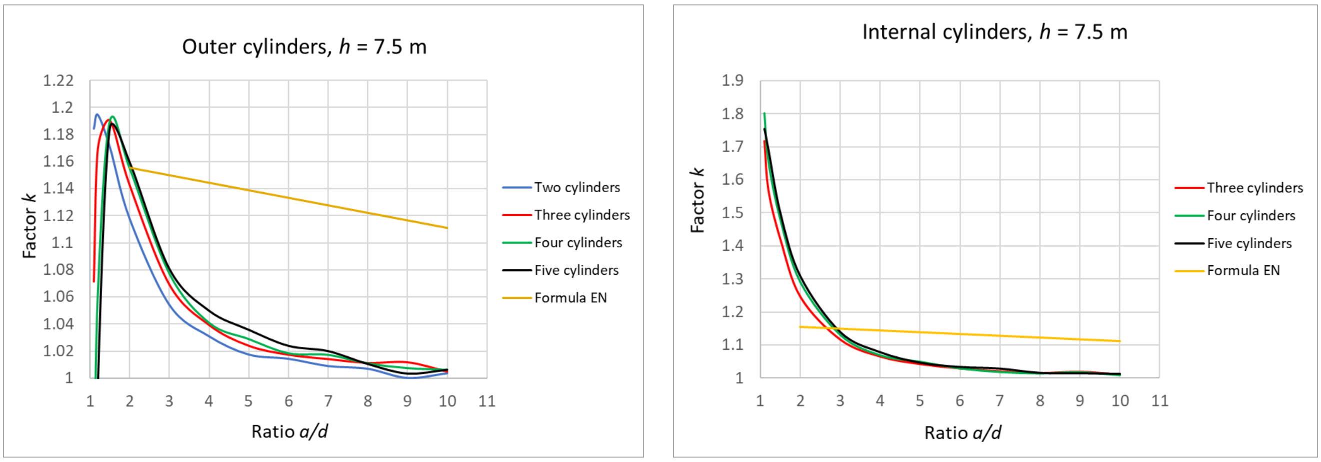
(a) at outer cylinders (b) at internal cylinders

Fig. 7. Influence of the distance between cylindrical bodies with a high *h* = 2.5 m on the total wind load on them.



(a) at outer cylinders (b) at internal cylinders

Fig. 8. Influence of the distance between cylindrical bodies with a high *h* = 5 m on the total wind load on them.



(a) at outer cylinders (b) at internal cylinders

Fig. 9. Influence of the distance between cylindrical bodies with a high *h* = 7.5 m on the total wind load on them.

Analyzing the graphs above within the framework of the present study, where the maximum number of cylindrical bodies in a row is five and the axial distance between them is in the interval $a = (1.1 \div 10) \cdot d$, the following impression is made:

a) When wind blows perpendicularly to the axis of the row, there is a difference in the wind load on the outer and internal bodies. The shearing forces in the bases are smaller at the outer bodies and bigger at the internal ones;

b) The amplification of the wind load is more significant for bodies with larger values of the height-to-diameter ratio (h/d);
c) The wind load on the cylindrical bodies decreases as the distance between them increases. The dependence here is non-linear, in contrast to the linear expression, specified in standard EN 1991-1-4:2005+A1:2010;
d) For outer cylindrical bodies, the coefficient $k < 1.2$, regardless of how close they are to each other. I.e., for them can be assumed factor $k = 1.2$ within the limits $1.1 \le a/d < 2.5$;
e) For internal bodies, the factor k can be taken as follows:
- $k = 1.8$ within the limits $1.1 \le a/d < 1.5$;
- $k = 1.55$ within the limits $1.5 \le a/d < 2.0$;
- $k = 1.35$ in the limits $2.0 \le a/d < 2.5$;

f) The maximum value of the factor $k \approx 1.027$ at a ratio $a/d = 8$, i.e. the overload is only 2.7% compared to an isolated cylinder. The coefficient k is even smaller for values of $a/d > 8$. It is therefore very likely the specified in the standard EN 1991-1-4:2005+A1:2010 requirement to consider the influence of closely spaced cylindrical bodies at $a/d < 30$, is too strict. On the other hand, it is quite possible that the statement in the Australian and New Zealand standard AS/NZS 1170.2:2011, that at distances greater than twice their diameter they should be considered as isolated (separate) facilities, is overly optimistic.
g) At the current stage of the research it appears that when the ratio $a/d > 8$, the increase in the wind load is negligibly small and does not necessary to be considered.

4. Conclusions

The European standard EN 1991-1-4:2005+A1:2010 does not specify a methodology for determining the increase in wind load at ratio $a/d < 2.5$, see Tables 1 and 2. In the available to the author national annexes, including the Bulgarian one, BDS EN 1991-1-4:2005/NA:2011, recommendations on the subject do not exist, too. In an attempt to find the information he needed, the author first surveyed the available scientific literature on the topic. After failing to find the necessary data, a parametric computer study was conducted. Many numerical models of closely spaced cylindrical bodies, has been created, using the ANSYS Workbench graphical interface and its Fluid Flow (CFX) computer simulation module. The following conclusions can be drawn from the research:

- The reduction of the effect of the mutual influence of closely located bodies is non-linear, in contrast to the linear dependence specified in the standard EN 1991-1-4:2005+A1:2010. This requires the written in the standard methodology to be refined;
- The mutual influence of the bodies due to wind load on them decreases much faster, compared to what is indicated in EN 1991-1-4:2005+A1:2010. On the other hand, this influence should be considered at much greater distances between bodies than stated in AS/NZS 1170.2:2011. I.e. here both standards should be refined;
- The following values could be assumed for the factor k, until more research is done on the subject:
  - For outer bodies – $k = 1.2$ within the limits $1.1 \le a/d < 2.5$;
  - For internal bodies:
    $k = 1.8$ within the limits $1.1 \le a/d < 1.5$;
    $k = 1.55$ within the limits $1.5 \le a/d < 2.0$;
    $k = 1.35$ in the limits $2.0 \le a/d < 2.5$;

Acknowledgements
None declared.

Funding
The author received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest
The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability
The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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