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Grouping effects on the pressure distribution of cylindrical silos in line

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SUMMARY:
This paper deals with the wind loads on thin-walled, circular cylindrical silos within a group. Pressure measurements were performed on three silo models with an aspect ratio H/D (height/diameter) of 2.0 arranged in line. The wind tunnel tests were carried out in a boundary layer wind profile at a Reynolds number Re of about 1.35×10^5. The effects of the gap between the cylinders and the inflow direction on the external pressure distribution were investigated on both the center cylinder and the one at the edge. To highlight the significant changes in the pressure coefficients, the results are presented together with the pressure distribution obtained on an isolated silo.

Keywords: circular cylindrical silo, grouping effects, pressure distribution

1. INTRODUCTION

For thin-walled, circular cylindrical silos, there is a risk of stability failure under asymmetrical wind loads, especially in the empty or partly filled state. In practice, it is common that silos are arranged in groups, so that the pressure distribution differs significantly from that of an isolated silo, especially in case of close spacing. In the literature, most of the studies conducted in this field either refer to groups of infinite circular cylinders in smooth flow or silos and tanks with a comparatively small aspect ratio H/D (e.g., Macdonald et al. (1990), Ruscheweyh and Windhövel (2019), Uematsu et al. (2015), and Zhao et al. (2014)). The number of studies on silo groups with larger H/D is quite limited (e.g., Uematsu (1986)). Within the scope of this research project, extensive investigations are carried out on various group arrangements of silos and tanks with different H/D. In this article, test results from pressure measurements on an in-line arrangement of three circular cylindrical silo models with $H/D = 2.0$ are presented.

2. EXPERIMENTAL SETUP

Wind tunnel tests were carried out in the boundary layer wind tunnel at the Institute of Steel Structures of TU Braunschweig with a cross section of 1.4 m × 1.2 m (width × height). An atmospheric boundary layer flow was simulated for the terrain category II according to the German National Annex DIN EN 1991-1-4/NA. The geometric scale is 1:200. The wind tunnel models were manufactured from transparent acrylic tubes with a diameter $D = 120$ mm. The maximum blockage of the wind tunnel cross section due to the installation of the models is about 5%. Pressure measurements are performed using an ESP-32HD scanner with 32 channels at a sampling rate of 650

Hz. The ring-shaped design of the model equipped with pressure taps (see Fig. 1 (a), center model) allows the pressure distribution to be determined at different heights. The tubing system (see Fig. 1 (b)) consists of PVC tubes with a length of 200 mm and an internal diameter of 1.0 mm and short brass tubes with an internal diameter of 0.6 mm, which end smoothly at the model surface. It is calibrated and its influence on the measured signal is eliminated by dividing the corresponding transfer function from the power spectra of the raw pressure. The test results presented here are mean values over a time interval of 30 seconds, obtained at 70% of the model height where the maximum pressure coefficients, both positive and negative, occur. All measurements were repeated several times to identify possible outliers. The pressure coefficients are defined as follows:


(a) (b)

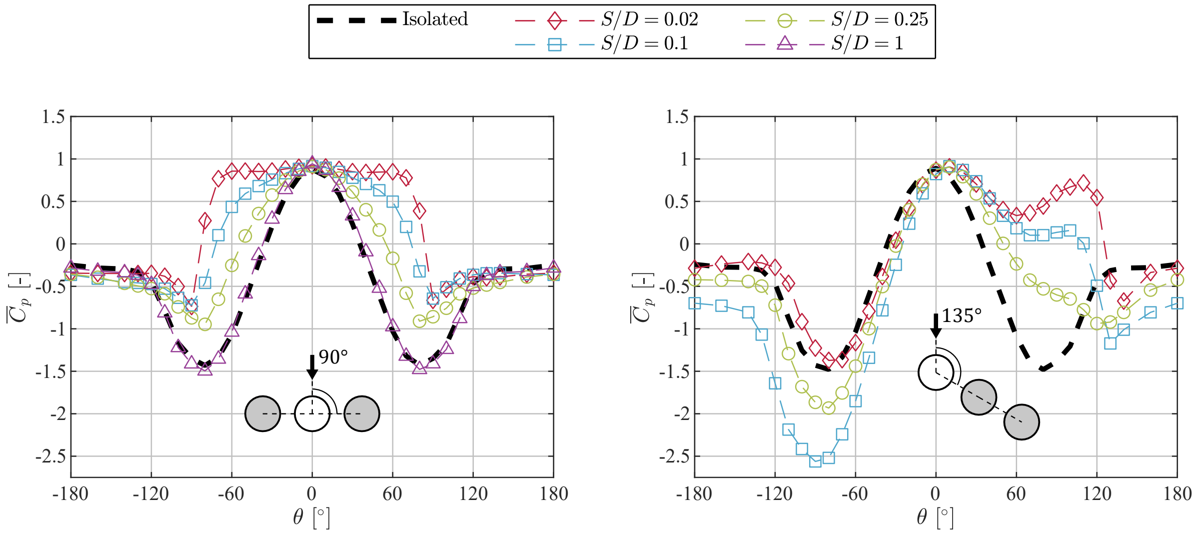
Figure 1. Silo models with $H/D = 2$. (a) Installation in the wind tunnel (here $S/D = 0.5$) and (b) tubing system

$$\overline{C}_p(\theta) = \frac{p - p_\infty}{\rho \cdot v_\infty^2/2} \tag{1}$$

where p is the total pressure measured at the model surface, p_∞ the static pressure, ρ the air density and v_∞ the velocity of the undisturbed incoming flow at the top of the model height. It is well known that the flow around a circular cylinder is influenced by many factors, such as the Reynolds number Re. Macdonald et al. (1988) investigated the Reynolds number dependence in turbulent flow and found that full scale conditions can be modeled if $Re > 1.0 \times 10^5$. In the present studies Re is about 1.35×10^5, defined with v_∞ and D.

3. TEST RESULTS

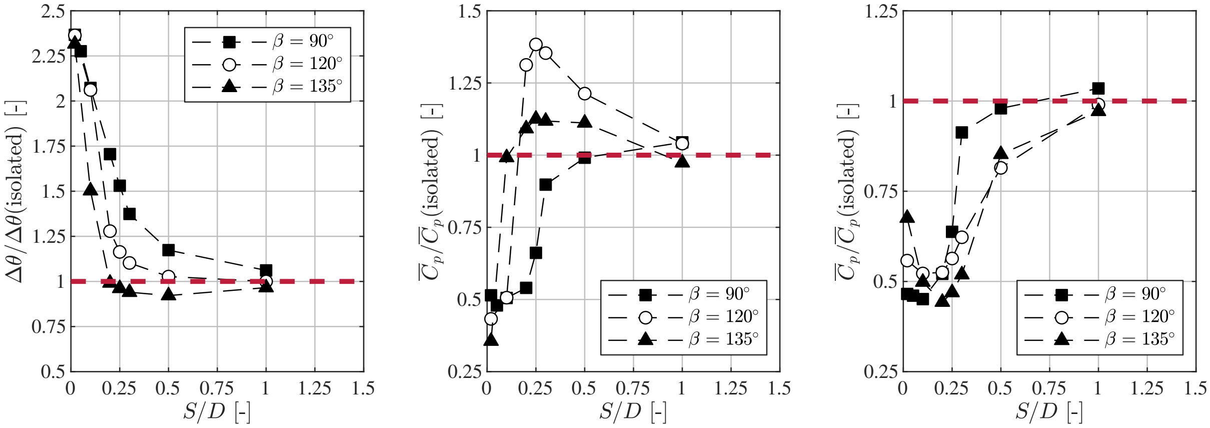
Pressure measurements were performed on both the center model and the one at the edge. The wind direction β was varied from 0° to 180°. For each wind direction different spacings $S/D = 0.02 - 1.0$ were investigated, where S is the gap width. The most significant deviations from the pressure distribution on an isolated silo were found for wind directions between $\beta = 90^\circ$ (normal to the line of silos) and 135°. Fig. 2 shows the pressure distributions measured on the center model for $\beta = 90^\circ$ and on the edge model for $\beta = 135^\circ$ at different S/D. The black dashed line represents the results obtained on the isolated cylinder. For $\beta = 90^\circ$ and $S/D = 0.02$ the range of positive $\overline{C}_p$ on the windward side of the center model increases significantly (see Fig. 2 (a)). In this case, $\overline{C}_p$ values comparable to that at the stagnation point extend over a range of about 140°. For $\beta > 90°$, a significant increase in the magnitude of the minimum pressure coefficient $\overline{C}_{pm}$ was observed on the side opposite the leeward gap, presumably due to the blockage of the flow through the adjacent lee-side cylinders. The maximum increase was measured on the edge model for $\beta = 135°$ and $S/D = 0.1$ (see Fig. 2 (b)), where the mean suction reaches a value of -2.6, equivalent to an amplification of $1.73 \times \overline{C}_{pm}$ on the isolated cylinder. Fig. 3 and Fig. 4 plot the range of positive $\overline{C}_p$ values and the minimum pressure coefficients $\overline{C}_{pm}$ on both sides of the cylinder as a function of S/D for the center model (see Fig. 3) and the edge model (see Fig. 4), respectively. For experimental reasons, the measured model has to be installed in the center of the wind tunnel test section. Therefore, the maximum possible gap for the measurements on the edge



(a) Center model: $\beta = 90°$

(b) Edge model: $\beta = 135°$

Figure 2. Mean pressure distributions on (a) the center model and (b) the edge model



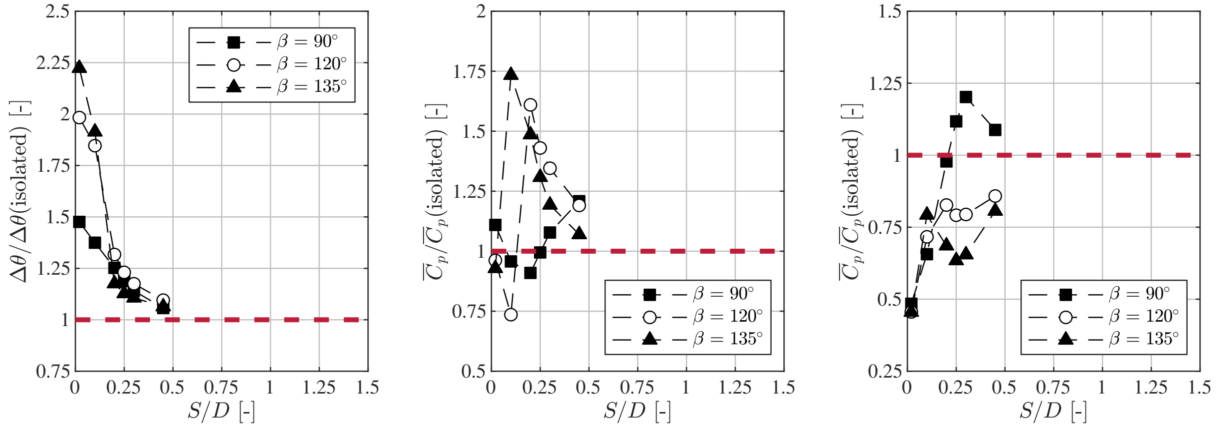
(a) Range of positive $\overline{C}_p$

(b) $\overline{C}_{pm}$ on windward gap side

(c) $\overline{C}_{pm}$ on leeward gap side

Figure 3. Center model: variation of the range of positive $\overline{C}_p$ values and minimum pressure coefficients $\overline{C}_{pm}$

wind tunnel test section. Therefore, the maximum possible gap for the measurements on the edge cylinder is $S/D = 0.45$. The pressure coefficients become similar to the values obtained on the isolated silo for $S/D > 1.0$. It is worth noting that on the center model for $\beta = 90°$, no increase in suction was measured for all investigated S/D (see Fig. 3 (b) and (c)).



(a) Range of positive $\overline{C}_p$ (b) $\overline{C}_{pm}$ opposite the gap (c) $\overline{C}_{pm}$ on the gap side

Figure 4. Edge model: variation of the range of positive $\overline{C}_p$ values and minimum pressure coefficients $\overline{C}_{pm}$

4. CONCLUSIONS

The presented test results on three in-line cylinders with $H/D = 2.0$ demonstrate that small gap spacings S/D can lead to significant changes in the pressure coefficients compared to an isolated silo. The extended range of positive $\overline{C}_p$ as well as the significant increase in the magnitude of $\overline{C}_{pm}$ are supposed to bring non-negligible impacts on the stability of a thin-walled silo. In the next phase, other H/D will be investigated and tests on multi-row silo groups will be performed.

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