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Wind buckling of tanks with conical roof considering shielding by another tank

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ABSTRACT

Oil storage tanks are usually arranged in groups in tank farms, and this configuration may affect their buckling and postbuckling strength under wind loads. The assessment of wind action on tank structures is performed in this work by means of wind tunnel experiments to evaluate the pattern of pressure distribution for a tank which is shielded by another tank under various configurations and separation between them. The experimental results show significant changes in pressures due to shielding effects. In a second stage the structural response under the pressures previously evaluated is performed by finite element analysis using both linear bifurcation and geometrically nonlinear analysis. Results of two-tank interaction are compared with those of an isolated tank. Based on the results, it is concluded that the changes in wind pressures due to group effects induce changes in buckling loads and in the associated deflected patterns.

1. Introduction

Short steel tanks are usually employed in the oil industry to store large volumes of fluid, with aspect ratios between $0.2 < H/D < 1.0$ in which H is the height of the cylindrical part and D is the diameter; however, frequently employed dimensions have aspect ratios between 0.2 and 0.6. Tanks may have an internal floating roof and a fixed roof (either conical, flat, or dome roof). Some tanks do not have a fixed roof so that the floating roof is directly exposed to the environment.

Oil tanks are frequently constructed in groups in what are known as tank farms. Farms include between tens and hundreds of tanks, which may be the property of one or several oil companies. Under strong winds, the structural behavior of tanks depends on their location within the group, so that it may be possible to distinguish between tanks located in a front line from those placed in a second or third line with respect to the perimeter of the facility.

Because tank farms are so common in oil facilities, it is surprising to find that most available information on the wind response of tanks concentrates on isolated tanks in flat terrain. This is evidenced in the American [2] and European [5] recommendations for the design of aboveground tanks, in which only the behavior of isolated shells is considered in detail.

The first investigation on the interaction between neighboring cylinders with a roof was perhaps published by Esslinger et al. [4] in Germany, in which wind tunnel tests were reported on two small-scale silos with similar dimensions. The models were placed in a line with the wind direction, with dimensions which were representative of tall silos with $H/D > 2$. For even taller structures, with $H/D > 10$, Zdravkovich [28] and Tsutsui et al. [22] studied the interaction between two aligned cylinders. More recent studies concerning pressures in shells which are localized close to each other under wind were published by Gu and Sun [6] and Orlando [12]. However, such studies are not relevant to explain interaction effects between oil storage tanks, which are short cylinders with relative dimensions in the order of $0.25 < H/D < 0.5$.

A wind tunnel investigation on silos placed very close to each other in a line perpendicular to the direction of wind was carried out in Australia in the 1970s by Vickery and Ansourian [24]. The results have been reported in the form of an analytical expression for pressure coefficients around the circumference in the European recommendations [18], but without reference to the dimensions and separation between the shells.

Wind tunnel studies have been made of the external pressure distributions on multiple circular cylinders with conical or flat roofs. Regarding wind tunnel studies of tanks, MacDonald et al.

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[10] concluded that pressure distributions are independent of Reynolds number provided $Re > 1 \times 10^4$. Sabransky and Melbourne [19] studied silo structures with aspect ratios $H/D=0.66$ and conical roof inclination angle of 27°.

MacDonald et al. [11] performed wind tunnel testing of five tanks in a line in which the blocking and the target tank models had both a flat roof; however, only those in tandem configuration are reviewed here because they can be compared with present results. For point pressure measurements, a configuration with $S=0.125D$ was tested, where S is the wall-to-wall minimum distance between tanks. Mean value pressures showed two lobes of positive pressures centered with respect to the windward meridian, each with a central angle of approximately 50°. The positive pressures resulted in values significantly lower than in the isolated tank, with pressure coefficients $C_p < 0.5$. Peak suctions (located at 90° from the windward meridian) were also smaller, with $C_p < 1.0$. The single case investigated does not allow understanding effects due to tank separation. Panel measurements, on the other hand, were studied for configurations at $S=0.125D$, $0.25D$, and $0.5D$. The results for $S=0.5D$ are shown in the paper.

Tanks located in a second line with respect to the periphery of a tank farm, in which the blocking tank had a flat roof and the target tank had a conical roof, were studied by Portela and Godoy [13] based on wind tunnel tests. Six configurations were tested, with changes in the separation between tanks ($S=0.5D$ and $S=1.0D$) and in the relative height between blocking and target tank. Other cases reported include two tanks in the first line blocking the flow of a tank in a second line, with separations $S=0.5D$ and $S=1.0D$. Contours of pressure coefficient were presented and subsequently employed to carry out linear bifurcation analysis (LBA) and geometrically nonlinear analysis (GNA) on the tanks for which measurements were taken, always in the second line with respect to the periphery of the tank farm; results were compared with those obtained for an isolated tank [14]. Case studies concerning six tanks in a small plant were investigated in Ref. [15] in wind tunnel to obtain pressure coefficients for one target tank under various wind directions; LBA buckling and GNA post-buckling were next computed. Iamandi et al. [7] performed wind tunnel testing of a four-tank configuration due to an accident in a small chemical storage station in Romania but did not provide pressure coefficients.

Tall cylinders ($H/D=2.56$) with flat roof in tandem arrays were studied by Said et al. [20] by means of wind tunnel tests and finite volume simulations. The flow pattern was found to be highly dependent on the separation S between both cylinders: for the short separation $S=1.28D$, the flow accelerates on the roof of the first cylinder and impacts on the top part of the second cylinder, while increasing the pressure. The wake of the first cylinder modifies the pressure field on the target tank and reduces the pressures on the windward region. This effect decreases as the distance increases to $S=5.12D$, with the consequence that the target tank becomes subjected to a flow pattern that is similar to that in the isolated tank.

Uematsu and coworkers [23,25] reported wind tunnel results on open top tanks to investigate group effects in arrangements of two, three and four tanks. The tanks had the same geometry with aspect ratios of $H/D=0.25D$, $0.5D$, and $1.0D$ and spacings of $0.125D < S < 1.0D$. Zhao et al. [27] were also interested in large open-topped tanks with low aspect ratio ($H/D=0.275$), and performed a comprehensive wind tunnel study considering two, three, and four interacting tanks, all of which were instrumented. Two tanks of identical geometry in tandem configuration were tested at $S=0.5D$, $1.0D$, and $1.5D$. Pressures on the external wall of the second tank showed large changes, with peak positive pressures in the windward region for $S=0.5D$ being reduced to 0.24 of their values in the isolated tank; whereas less significant reductions were obtained for larger values of S. Changes were found not only in pressure values but also in pressure distributions. Reductions in pressures on the internal walls were also reported in the windward region. The results highlight the expected changes in pressures for open tanks, but the results cannot be directly employed for tanks having a fixed roof.

The diversity of configurations which may be found in tank farms, even for tanks having similar dimensions and spaced in a regular pattern, points to the need to have more information on pressure coefficients and on the structural response to such wind. This work addresses the problem of a tank with conical roof which is obstructed by another one having the same geometry, in which the angle of wind incidence is taken as a variable to investigate several group configurations. Wind tunnel studies are performed to obtain pressure coefficients, which are subsequently employed in a finite element analysis of shell buckling. Two approaches of shell buckling are investigated, namely linear bifurcation analysis (LBA) and geometrically nonlinear analysis with imperfections (GNIA).

2. Wind tunnel experiments

2.1. Main features of the wind tunnel facility

The wind tunnel facility at the National University of La Plata, which is the largest facility in its kind in Argentina, has been used in this research. The tunnel is capable of reproducing an atmospheric boundary layer, in which high turbulence may be generated together with a non-uniform wind velocity in elevation.

Fig. 1 shows the main components of this close-circuit wind tunnel, with a cross section having 1.40 m (width), 1.0 m (height), and 7.5 m in length. The fan has six blades and is moved by a 50 HP engine. The engine has a system of velocity control which allows changing the flow velocity up to a maximum of 20 m/s measured at the center of the cross section. The access door with glass panels to visualize the development of the test is shown in Fig. 1a, whereas the section where testing is done is shown in Fig. 1b.

Air flows through a honeycomb to enforce axial symmetry and through a set of horizontal obstacles (shown in Fig. 1b) which can rotate on their axes to generate turbulence. Changes in turbulence are obtained by means of variations of the relative location of the obstacles with respect to the wind direction. Once the desired turbulence has been obtained, roughness is modeled by small parallelepiped blocks attached to the floor.

The mechanism employed can represent mean velocities in elevation that follow power or logarithmic laws, depending on the needs of the study; in our case the applied power law was adopted with an exponent $P=0.32$. Different types of turbulence may be implemented in the lower atmospheric boundary layer. During testing, the turbulence intensity was 0.15.

The tunnel is equipped with a system of NetScanner electronic pressure sensors with 128 channels, in which pressures are recorded. A computer is connected for the acquisition and processing of experimental data. A hot wire anemometer with telescopic arm is employed to record reference velocity and temperature of flowing air.

2.2. Prototype tanks considered

A specific geometry was chosen as a case study in this research, having $H/D=0.52$; in the prototype, the dimensions are $D=30.48$ m and $H=15.75$ m.

The separation S between tanks in a tank farm is an important parameter in the present study. Because of limitations in available space in an oil facility, there is a trend to locate them as close as