J. Wind Eng. Ind. Aerodyn. 138 (2015) 77–86

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Design wind loads for open-topped storage tanks in various arrangements

Yasushi Uematsu [a],*, Jumpei Yasunaga [b], Choongmo Koo [c]

[a] Department of Architecture and Building Science, Tohoku University, Sendai, Japan
[b] Steel Research Laboratory, JFE Steel Corporation, Kawasaki, Japan
[c] Intermediate Engineer, MIDAS IT Japan, Tokyo, Japan

ARTICLE INFO

Article history:
Received 14 July 2014
Received in revised form
11 December 2014
Accepted 31 December 2014
Available online 23 January 2015

Keywords:
Wind load
Storage tank
Open-top
Grouping effect
Wind tunnel experiment
Wind pressure distribution
Buckling
Finite element analysis

ABSTRACT

The present article proposes a model of wind force coefficient for designing open-topped storage tanks in various arrangements; main focus is on oil storage tanks. In our previous paper, we discussed the design wind force coefficients for isolated tanks, based on wind tunnel experiments of wind pressure distributions and buckling as well as on a finite element analysis of buckling under static wind loading. In practice, however, more than two tanks are constructed in various arrangements in a site. In such cases, the wind force distribution and the resultant buckling behavior of tanks may be affected by the arrangement significantly. Therefore, the present article focuses on the grouping effect on the wind force distribution and the buckling behavior. First, the wind pressures are measured simultaneously at many points both on the external and internal surfaces of a rigid model for various arrangements of two to four tanks in a turbulent boundary layer. The effects of arrangement pattern and gap spacing of tanks on the pressure distributions are discussed. Then, the buckling of tanks under static wind loading for various arrangements is analyzed by using a non-linear finite element method. The results indicate that the distribution of positive wind force coefficient in the windward area affects the buckling behavior significantly. Finally, based on the results obtained, we propose a model of wind force coefficient on tanks in various arrangements by modifying the model for isolated tanks that we proposed in our previous paper. For evaluating the design wind loads a gust effect factor approach is employed. The wind load evaluation is based on the quasi-steady principle and therefore the resonant effect is not taken into account.

1. Introduction

Open-topped storage tanks are usually composed of thin curved panels. Buckling may occur when they are subjected to wind loads in the empty or partially-filled state, because large suctions act on the internal surface, generating large net wind forces on the windward area. Even in the case of closed-topped tanks, a similar situation may occur when the tank is under construction and the roof has not been attached yet. Therefore, the wind-induced buckling is one of the most important considerations, when designing open-topped storage tanks.

Wind-induced buckling of closed-topped cylindrical structures were investigated by many researchers in the 1970s and 1980s (e.g., Wang and Billington, 1974; Kundrupi et al., 1975; Brendel et al., 1981; Resinger and Greiner, 1982; Jerath and Sadid, 1985; Uematsu and Uchiyama, 1985; Uematsu, 1986; Uchiyama et al., 1987). However, most of these studies were concerned with uniform smooth flow and the Reynolds number was in the subcritical regime. Recently, Portela and Godoy (2005a, b) investigated the buckling behavior of tanks with conical or spherical roofs using a finite element method, in which they used the distribution of wind pressure coefficients measured in a turbulent boundary layer.

Many researchers investigated the wind loads on closed-topped cylindrical structures in turbulent boundary layers (e.g., Sabransky and Melbourne, 1987; Macdonald et al., 1988; Macdonald et al., 1990a, b; Uematsu and Yamada, 1994). By comparison, the number of studies into wind loads on open-topped storage tanks is quite few. Holroyd (1983, 1985) investigated the wind loading and wind-induced vibrations of open-topped oil storage tanks in a turbulent boundary layer, focusing on the fluctuating wind pressures and the wind-induced vibrations of tanks. Uematsu et al. (2014) discussed the design wind force coefficients for isolated open-topped oil storage tanks, based on the wind tunnel experiments of wind pressure distributions and buckling as well as on a non-linear finite element analysis of the buckling of tanks under static wind loading. They found that the distribution of positive wind force (or pressure difference) coefficients in the windward area affected the buckling behavior significantly. Based on the results, they proposed models of

---

* Corresponding author. Tel./fax: +81 22 795 7875.
E-mail address: yu@archi.tohoku.ac.jp (Y. Uematsu).

http://dx.doi.org/10.1016/j.jweia.2014.12.013

external and internal wind pressure coefficients for designing open-topped oil storage tanks, focusing on the wind-induced buckling as the most important load effect. Recently, Yamaguchi et al. (2014) have investigated the effect of wind girder on the buckling behavior of open-topped oil storage tanks under static wind loading, based on a finite element analysis.

In practice, however, more than two tanks are constructed nearby in various arrangements in a site. It is likely that the wind pressure distributions and the resultant buckling behavior of tanks are affected by the arrangement significantly. Therefore, the design wind force coefficient should be specified by considering such a grouping effect of tanks. Wind loads on cylindrical structures arranged in an in-line group were investigated by several researchers. For example, Sabransky and Merbourne (1987) measured the wind pressure distributions on three circular silos with conical roofs in a turbulent boundary layer. They found that large negative pressures (suctions) were induced on the central silo by accelerated gap flow between silos when the spacing was relatively narrow and the wind direction was normal to the line of arrangement. Similar measurements were made by Macdonald et al. (1990a) for five cylindrical structures with flat roofs. They showed that the range of positive pressure area became wider as the spacing between silos was decreased. Iamandi et al. (2003) carried out a CFD simulation of the flow around four tanks with conical roofs in a square arrangement. They investigated the effect of spacing on the mean wind pressure distribution on tanks, and indicated that the magnitude of wind pressures on the leeward tanks was reduced significantly due to a ‘shielding effect’ of the windward tanks.

These studies focused on cylindrical structures with roofs (closed top). By comparison, few studies have been made on open-topped storage tanks in various arrangements. In the case of open-topped storage tanks, the wind pressure acting on the internal surface (called ‘internal pressure’ hereafter) is strongly affected by the separated flow at the top of tank. Consequently, the net wind force, given by the difference between the external and internal pressures, seems different both in magnitude and distribution from that on closed-topped tanks. Furthermore, the wind pressure distribution may be affected by the arrangement significantly. To the authors’ best knowledge, no study has been made of the grouping effect on the wind loads and wind-induced buckling of open-topped storage tanks.

In the present study, therefore, a wind tunnel experiment was carried out with two to four tank models in order to investigate the effects of arrangement on the external and internal pressure coefficients; main focus is on open-topped oil storage tanks. Note that focus is on the mean (time-averaged) wind pressure distributions, based on the results of our previous study (Uematsu et al., 2014), in which the instantaneous distribution of wind force coefficients at an instant when the external wind pressure coefficient at the stagnation point became the maximum peak value was found to be similar to that of the mean wind force coefficients. It is thought that the design wind load can be evaluated based on the quasi-steady principle.

Then, a buckling analysis of tanks under static wind loading is made by using a non-linear finite element method. A discussion is made of the effect of wind force distribution on the buckling behavior. Finally, we propose models of external and internal pressure coefficients on tanks in various arrangements by modifying the models for isolated tanks that we proposed in our previous paper (Uematsu et al., 2014).

2. Wind tunnel experiment of wind pressure distributions on tanks

2.1. Experimental apparatus and procedure

The experiment was carried out in a closed-circuit-type wind tunnel at Kajima Technical Research Institute, which has a working section 18.1 m long, 2.5 m wide and 2.0 m high. A turbulent boundary layer with a power law exponent of 0.15 for the mean wind velocity profile was generated on the wind tunnel floor. The intensity I_u and integral scale L_x of turbulence at a height of $z = 125$ mm were approximately 0.16 and 0.6 m, respectively. Three models (named ‘A’, ‘B’ and ‘C’) with different aspect (height/diameter) ratios of $H/D = 1.0$, 0.5 and 0.25 were used; the external diameter D and wall thickness of the models were 250 mm and 6 mm, respectively. Although the wall thickness is much thicker than that of practical tanks, its effects on the external and internal pressures seem minimal. The geometric scale of the models is assumed 1/400, which is nearly equal to that of the wind-tunnel flow.

The notation and coordinate system used in the present article are shown in Fig. 1. Note that the origin of coordinate θ depends on the arrangement and wind direction. Fig. 2 shows the arrangements of models tested in the present study, in which the shaded circles represent ‘dummy’ models with the same shape as that of the instrumented model (white circle) and no pressure taps. A picture of models mounted on the wind tunnel floor is shown in Fig. 3. The arrangement of models is represented by wind direction (β or β^*) and gap spacing (S) between models. The non-dimensional gap spacing S/D ranged from 0.125 to 1.0. The pressure taps of 0.5 mm diameter were installed at a step of 15° on the external surface and at a step of 30° on the internal surface along the circumferences at several heights (see Uematsu et al. 2014). The pressure taps were connected to pressure transducers in parallel through 80 cm lengths of flexible vinyl tubing of 1 mm inside diameter. The wind pressures at all taps were sampled simultaneously at a rate of 1 kHz for approximately 33 s. The compensation for the frequency response of the pneumatic tubing system was carried out by using a digital filter to obtain a flat response up to approximately 500 Hz.

The wind velocity U_H at the model height ($z = H$) was approximately 10 m/s in any model case; the corresponding Reynolds number Re ($= U_H D/\nu$, with ν being the kinematic viscosity of the air) is approximately 1.6×10^5. It is well accepted that the flow around circular cylinders is affected by many factors, e.g., the Reynolds number Re, the aspect ratio and surface roughness of the cylinder and the turbulence intensity of the flow. According to Macdonald et al. (1988), who investigated the Reynolds number effect on the external pressure distributions on smooth circular cylinders with aspect ratios of $H/D = 0.5$–2.0 in a turbulent boundary layer and compared their results on the mean pressure coefficient distributions with those obtained from a full-scale measurements by Cook and Redfearn (1980), the wall pressure distributions are almost independent of Re, provided that the value of Re is greater than 1×10^5. The Reynolds number in the present experiment is approximately 1.6×10^5, and the turbulence intensity of the flow is almost the same as that Macdonald et al. (1988) used in their experiment. Therefore, it is thought that our measurements were carried out in the so-called ‘transcritical’ regime and the results can be used for practical applications.

The external and internal pressure coefficients, C_{pe} and C_{pi}, are defined in terms of the velocity pressure q_H ($= 1/2 \rho U_H^2$ with ρ being the air density) of the approach flow at the model height ($z = H$).

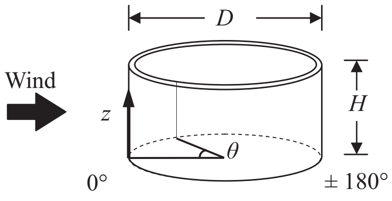

Fig. 1. Notation and coordinate system.