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Prediction of mean wind velocity in port areas for wind load provisions: simulated *versus* analytical profiles

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SUMMARY:
Ports are important nodes and facilitate a large portion of the worldwide trade volume via sea. Here, accidents caused by storm winds do not only imply considerable economic losses but also high risks for the workers. Despite many efforts towards the safety management of ports and waterways, the characterization of local wind conditions in such environments is still challenging. In this paper, 3D steady-state Reynolds-averaged Navier-Stokes (RANS) simulations validated with on-site measurements (OsM) were used to characterize the mean velocity profiles approaching the commercial terminal of one of the largest European ports, the Port of Rotterdam, in the Netherlands. The RANS mean velocity profiles were compared to the corresponding profile calculated with the Eurocode (EN-1991-1-4) and the profile obtained by coupling the EN-1991-1-4 with an urban canopy layer (UCL) velocity profile available in the literature. Similarities between the RANS and Eurocode profile were observed in absence of UCL (i.e. open areas) with the latter more conservative for wind load provisions.

Keywords: 3D RANS simulations; on-site measurements; urban canopy layer; mean wind velocity; wind loads provisions.

1. INTROCUTION

The Maritime Safety is one of the key areas identified by EU Commission where further work is needed to strengthen the competitiveness of the sector while enhancing its environmental performance. Besides the unquestionable and positive impact of port areas on the global economy, the increasing ship size can also cause larger wind forces which renders the maneuvering and cargo operations more difficult in case of stormy weather. Many activities usually carried out in these areas also imply high risks for human beings and the consequences of accidents may be not only economic losses but also human losses (Solari et al., 2012). On this subject, these areas are considered among the most vulnerable and risky in the world. In the last decade, many studies were carried out on the prediction of mesoscale and microscale wind conditions over coastal and port areas by means of experimental and numerical techniques. However, it is still challenging to accurately characterize the wind velocity profile through/over complex environments (as port areas) for wind load provisions. The presence of obstacles (as containerships, container stakes, cranes, cruise ships, etc.) and large open areas (as waterways and empty terminals) can lead to significant changes of the UCL height (H_{UCL}) and associated mean velocity profiles. This is the scope of the present study, for which 3D steady RANS simulations were carried out on one of the largest European ports (the Port of Rotterdam) and validated with OsM. The paper is structured as follows: Section 2 describes the methodology used in this study; Section 3 shows the main results and Section 4 closes the paper with conclusions and perspectives.

2. METHODOLOGY

3D steady RANS simulations were performed on the commercial terminal of the Port of Rotterdam, in the Netherlands, for 12 reference wind directions with an interval of 30° (Figure 1a). In order to properly develop an approaching neutral atmospheric boundary layer (ABL) wind throughout the whole domain an extensive area with dimensions of 18 km (length) *x* 18 km (width) *x* 0.5 km (height) was considered. A high-resolutions computational grid of 167 million cells was constructed in accordance with the best practice guidelines (BPGs) for CFD applications in wind engineering (e.g. Tominaga et al. 2008; Franke et al., 2007). Geometries of cranes were simplified by omitting small-scale mechanical details like wheels and rails (mounted on the ground), while container stacks were approximated to parallelepipeds. Buildings were modeled based on their real ground plans and heights, but pitched roofs were represented by flat roofs (Figure 1c-e). The results were analyzed in three *stages*:

1) RANS results were validated with OsM carried out by means of 9 ultrasonic anemometers (mp1 – mp9) installed at about 15 m a.s.l. (Figures 1b). In particular, simulated and measured data were compared in terms of the mean wind speed ratio ($\gamma = U_i / U_{ref}$), with U_i and U_{ref} indicating the mean wind velocity at the *i-th* position (with *i* = *mp2*, … *mp9*) and the mean wind velocity at the reference position (*mp1*), respectively.

2) RANS contours of normalized wind velocity (*K*) were plotted at different horizonal and vertical planes throughout the whole computational domain, in order to investigate the UCL development.

3) Three types of vertical mean velocity profiles were compared at 72 target positions (from 0 to 250 m a.s.l.): (*i*) vertical mean velocity profiles from RANS (U_{RANS}); (*ii*) vertical mean velocity profiles calculated with the Eurocode (U_m); (*iii*) vertical mean velocity profiles (U_d) obtained by coupling the mean velocity profile "in" the UCL (U_c) – calculated with the formulation of Bentham and Britter (2003) – and the U_m with a zero-plane displacement (H = $2/3h_o$, with h_o the crane height equal to 80 m) "above" the UCL. More details about the parameters used to calculate U_m and U_c will be provided in the full paper. The results of the three stages are presented in Section 3.

3. RESULTS

Figure 2 recaps the results obtained in the three stages introduced above.

For *stage 1*, Figure 2a shows the comparison between simulated (γ_{CFD}) and measured (γ_{exp}) data, for 12 reference wind directions. A good agreement is generally found with approximately 89% of γ_{CFD} samples within a deviation of ± 25% from γ_{exp} data. A comparison was also performed in terms of local wind directions, however, for sake of brevity this comparison was not reported here.

For *stage 2*, as an example Figure 2b shows two contours of normalized wind velocity ($K = U/U_{ref}$, with U_{ref} taken at 250 m a.s.l.) crossing the APM and ECT terminals, for the prevailing wind direction 210°. In general, a deep UCL is observed at both terminals in between the container stacks and cranes, with a larger variation of the H_{UCL} observed at the APM terminal due to the presence of the vertical axis wind turbine.

For *stage 3*, as an example Figure 2c shows the comparison of U_{RANS}, U_m and U_d at one target position T_P (see Figure 1b). For the RANS profiles a distinction is made between profiles approaching from an open area/sea (blue lines) and profiles approaching from a densely built-up area (orange lines). The following observations are made:

- While for the U_{RANS} a large variability in terms of magnitude and H_{UCL} can be observed for the 12 wind directions as function of the upstream surface roughness exposure, for the U_m (and U_d) only one characteristic profile can be defined.
- The U_m values "in" the UCL are larger than U_{RANS} values even in case of profiles developing from an open area/sea. Conversely, the U_m values "above" the UCL are slightly smaller than U_{RANS} ones for only one wind direction.
- Deviations in terms of H_{UCL} are found between the U_{RANS} (orange) and U_d profile. Indeed, while for the case U_d the H_{UCL} is assumed "locally" equal to $2/3h_o = \sim 53$ m, for the U_{RANS} the H_{UCL} is function of the wind flow development upstream of the monitored T_P.
- The U_c value calculated with the formulation of Bentham and Britter (2003) - by using the roughness class (z_0) of the Eurocode and H = $2/3h_o$ - falls into the variability range of the U_{RANS} values found "in" the UCL.

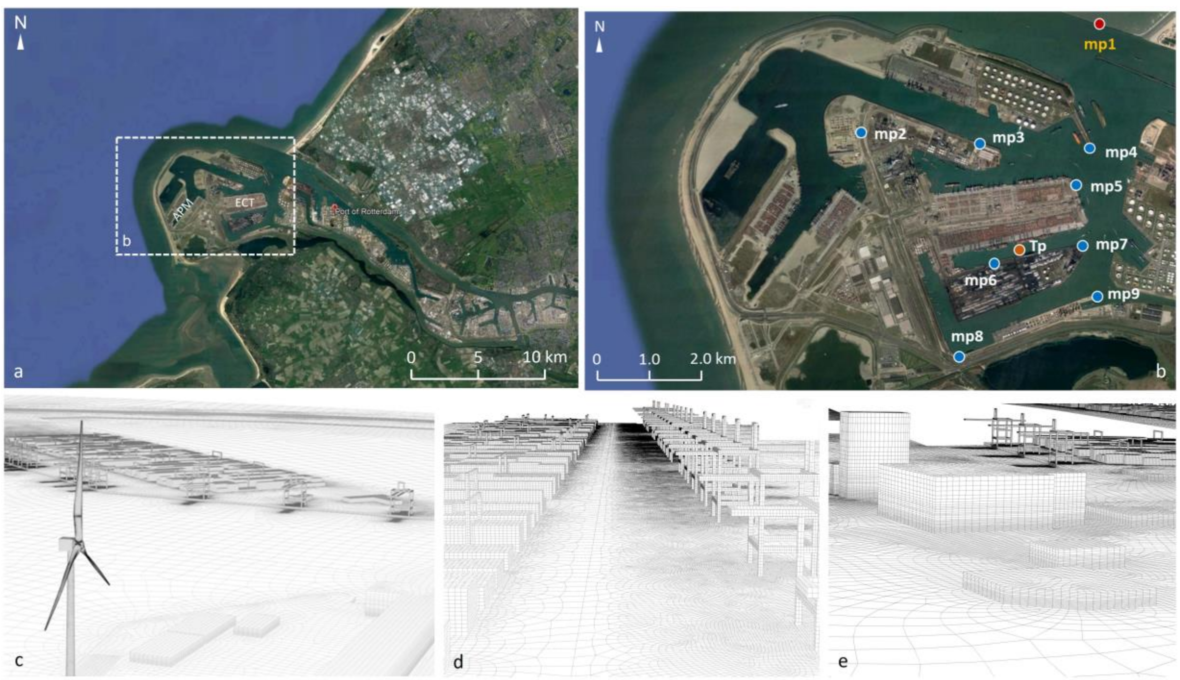

Figure 1. (a,b) Geographical location of the Port of Rotterdam with the indication of the anemometer stations (*mp1* - *mp9*) and the target position (T_P) at the ECT terminal where the approaching vertical profile is monitored for all wind directions. (c-e) Pictures of the high-resolution computational grid with detailed views on the ECT terminal and port infrastructures.

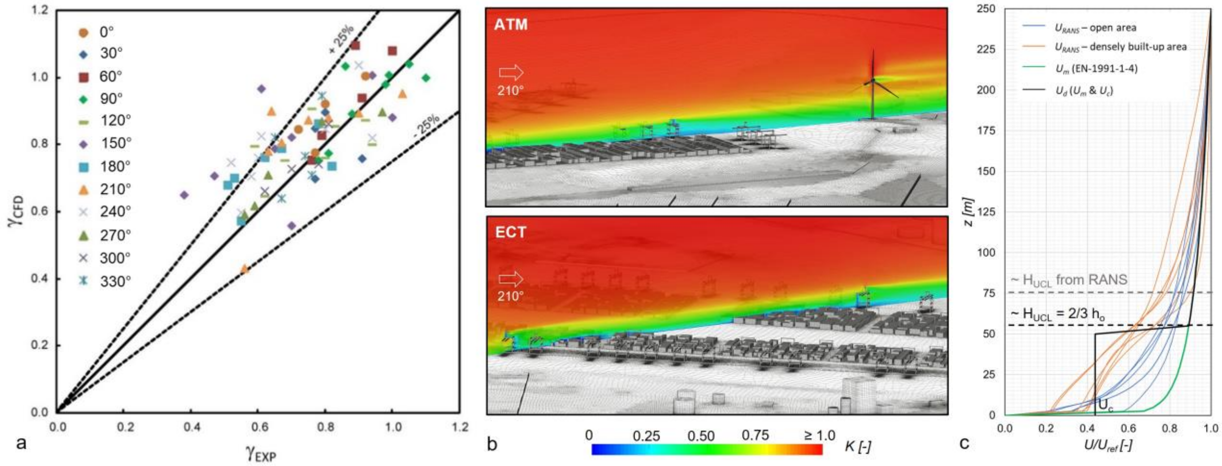

Figure 2. (a) Comparison of simulated (γ_{CFD}) and measured (γ_{EXP}) wind velocity ratios at the positions *mp2 – mp9*. (b) Contours of normalized wind velocity (*K*) made through a vertical plane crossing the APM and ECT terminals, for the wind direction 210°. (c) Comparison of vertical mean velocity profiles among RANS (U_{RANS}) from open and densely built-up areas, Eurocode (U_m) and the profile with zero-plane displacement (U_d).

4. CONCLUSIONS AND PERSPECTIVES

The present study presented experimental, numerical and analytical analyses on the wind flow development throughout a port area. The comparison between RANS and OsM data confirmed that this numerical approach is sufficiently reliable to predict the UCL development and associated mean wind velocity profiles throughout large-scale domains. The profiles of U_{RANS}, U_m and U_d were compared at 72 target positions, but only one reported here as an example. Overall, the U_m profile showed to be more conservative for wind load provisions with respect to U_{RANS} profiles, especially "in" the UCL, while it could slightly underestimate the velocity "above" the UCL for some wind directions. Deviations in terms of H_{UCL} were also found between RANS and analytical function. However, it is worth to stress that the arbitrary definition of some parameters in U_m and U_c (as z_0 and H) and the omission of the "transition layer" in the U_c formulation can play an important role. More detailed results will be presented in the full paper to provide a more comprehensive overview about the research study.

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