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AN ANALYSIS OF INCOMING WIND PULSATION ON THE WIND EROSION PROCESSES ON A HILL

ANALIZA PODMUCHÓW WIATROWYCH W PROCESIE EROZJI GRUNTU NA POWIERZCHNI WZGÓRZA

Abstract

The present analysis undertakes the problem of surface wind over topography. The main focus is placed upon the effect of oncoming wind oscillations on the velocity field structure around a single sinusoidal shaped 2D hill. Additional effort has been undertaken to recognize the inflow gust influence on the surface shear stress related to the mechanism of wind induced erosion. Numerical simulations have been performed through the use of the phase-averaged form of RNG version of k-ε turbulence model. Experimental verification of numerical data has been done in wind tunnels equipped with devices generating unsteady wind boundary layers. The main findings of the simulations reveal: a strong dependence between the characteristics of inflow periodicity and the structure of vortices of the separation region; the mean position of the reattachment point; the phase averaged velocity field; skin friction variability downstream from the hill. The results have significant implications for the prediction of sand transport in unsteady winds.

Keywords: unsteady winds, surface friction over the bump, numerical modelling, wind erosion

Streszczenie

Niniejsza analiza podejmuje problem przepływu wiatru nad powierzchnią terenu o złożonej topografii. Główny nacisk położono na wpływ oscylacyjnych podmuchów wiatru na strukturę pola prędkości wokół pojedynczego sinusoidalnego 2D wzgórza. Dodatkowy wysiłek podjęto w celu rozpoznania wpływu podmuchów wiatru na powierzchniowe naprężenia ścinające związane z mechanizmem erozji wietrznej. Numeryczne symulacje przeprowadzano z zastosowaniem uśrednionego fazowo modelu turbulencji k-ε w wersji RNG. Weryfikacja danych numerycznych została wykonana w oparciu o wyniki badań eksperymentalnych zrealizowanych w tunelu aerodynamicznym wyposażonym w generator podmuchów wiatru w modelowej warstwie przyziemnej. Główne wnioski z przeprowadzonych symulacji wykazują silną zależność między okresowym charakterem napływu a strukturą wirów w obszarze separacji, średnim położeniem ponownego przylgnięcia; uśrednionym fazowo polem prędkości oraz zmiennością tarcia powierzchniowego za wzgórzem. Wyniki te mają istotne znaczenie dla prognozowania transportu piasku w nieustalonym polu wiatrowym.

Słowa kluczowe: niestacjonarne pole wiatrowe, tarcie powierzchniowe nad wzgórzem, modelowanie numeryczne, erozja wiatrowa

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1. Introduction

The experimental and numerical simulation of wind flow over hilly terrain has attracted considerable scientific interest during recent decades, [4, 5], because of the important implications of the problem in many fields (fire propagation, soil erosion, pollutant dispersion). Many factors have to be taken into account in order to accurately predict surface winds over complex terrain. In the predominant number of studies, the structure of the wind approaching the element of topography (hill or other object) is assumed to be steady and represented by a typical boundary layer profile (exponential or logarithmic) over the surface of different aerodynamic roughness. Considerably less effort has been made to take into account the unsteady features of incident wind associated with gust phenomena or large scale periodical pulsations generated in object environment. Wind gusts, which hardly affect the average wind speed and yet have a very strong effect on erosion are especially important in this context. Butterfield [1] indicated the role of sinusoidal velocity variations on sand transport. The present analysis undertakes the problem of the surface wind over topography. The main attention is placed on the effect of oncoming wind oscillations on wind erosion processes.

2. The methods of analysis

To recognize the effect of oscillating incident conditions on the wind flow around the hill, numerical as well as experimental simulations have been performed in the present study for different parameters of inflow periodicity. The hill considered was nominally 2D, symmetric with aspect ratio defined as slope of the hill $H/L = 0.6$ (Fig. 1a). The modelled hill has been placed in the boundary layer formed over the terrain of moderate roughness under the wind conditions characterised by oscillating component superimposed on mean velocity profile. The mean velocity profile can be described by the power law:

$$\bar{U}_0(z) = \bar{U}_\infty \cdot \left(\frac{z}{\delta}\right)^\alpha \tag{1}$$

where δ is the depth of boundary layer, and $\alpha = 0.16$ is the power law exponent, which corresponds to the velocity profile for open terrain with low vegetation (Fig. 1b).

Different values of flow frequency f_0 and amplitude A have been introduced into the simulations, described in equation:

$$U_0(t) = \bar{U}_\infty \cdot (1 + A \cdot \sin(2 \cdot \pi \cdot f_0 \cdot t)) \tag{2}$$

The numerical modelling was performed using commercial CFD code ANSYS FLUENT with phase averaged form of RNG version of k-ε turbulence model. Pressure-velocity coupling was performed with the SIMPLEC algorithm. The time step was based on an experimental estimation of the period of flow oscillations. The time step in non-dimensional unit ($\Delta t \cdot U_0/H$)

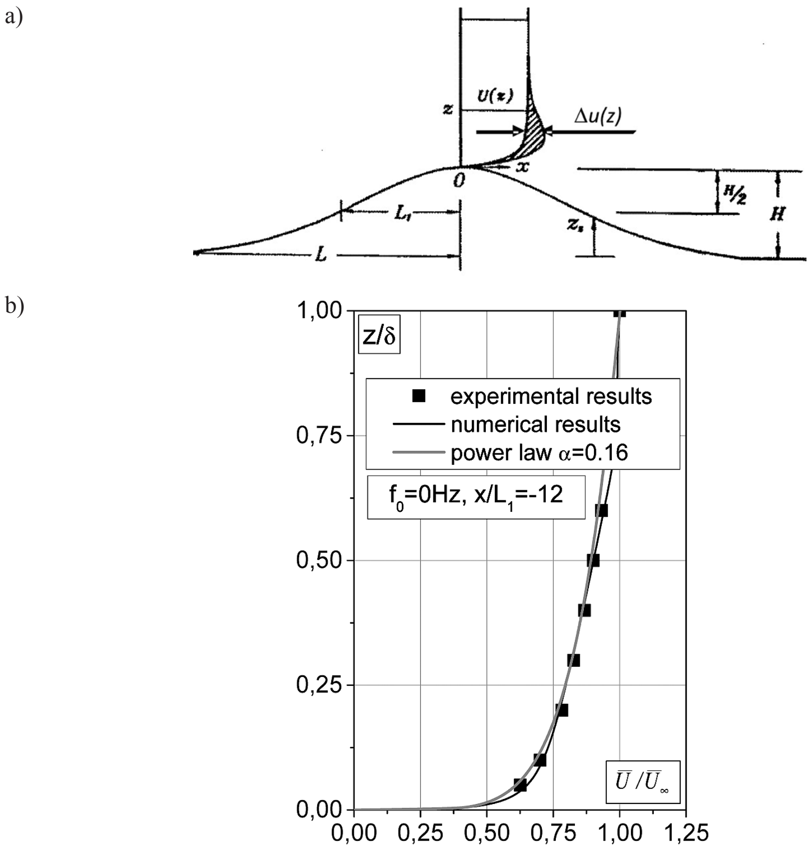

Fig. 1. Scheme of analysed hill (a) and mean velocity profile (b)

was about 0.14 in the present analysis. About 50 time steps per period were necessary to obtain converged pressure and velocity (both averaged) and rms values. A quadrilateral mesh with 15000 cells was generated in the computational domain according to [2, 3]. The hill was located 3 m from the entrance to the working section, perpendicular to the free-stream direction. Properly setting up the boundary conditions at the inlet and outlet of the model allowed for the achievement of an effect of real conditions. The following boundary conditions are used in calculations: at the inlet VELOCITY INLET; at the outlet PRESSURE OUTLET; for the upper and lower walls and the cylinder surface (WALL condition).

Experimental verification of numerical data was done in wind tunnels equipped with devices generating an unsteady wind boundary layer. Wind tunnel experiments comprised the modelling of unsteady wind conditions in the flow approaching the model of the hill, measurements of velocity distributions around the hill and surface wall shear stress. The velocity profiles around the model were measured by X hot wire anemometer. The wall shear stress was measured on the characteristic positions of the hill with the hot film sensor. Spectral analysis of the time records of velocity and wall shear stress were taken by means of a fast-scanning acquisition system.

3. The results

For the understanding of the shear flow in the region next to the ground surface, knowledge of characteristics of instantaneous velocity field is very important in the context of wind erosion processes. The following figures present the main findings of the numerical simulations, resulting on the basis of time sequences of velocity fields around the hill for different parameters of incident wind periodicity. Both frequency f_0 and amplitude A influence the extent of the recirculation zone as well as introduce some additional fluid flow actions in comparison to the steady case. The differences concerns mainly regular vortex street produced in the case of high frequency oscillations influx. The increase in the recirculation region is also observed, especially for higher values of amplitude.

Fig. 2 presents the experimental and numerical data performed for the velocity distributions at the top of the hill. Comparison between the mean velocity fields obtained through numerical methods and experimental methods shows strong correlation. A small disagreement has been noted for the vertical velocity component. Nevertheless, it should be emphasized here that the accuracy of the experimental determination of the cross velocity component by the use of an X hot-wire probe is about 15%. Phase averaging of the hot wire signal made it also possible to compare the experimental and numerical time records of the velocity at the points located at two distances above the hill top.

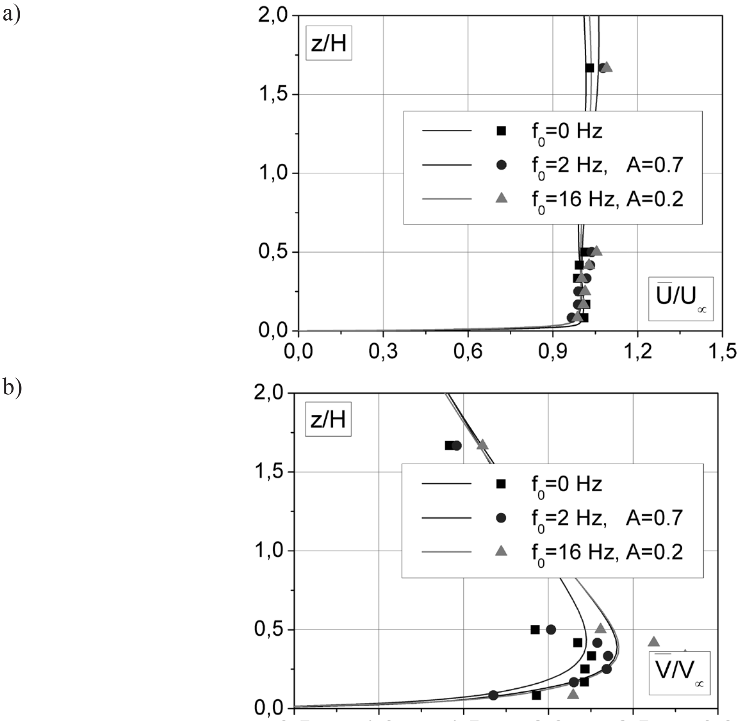

Fig. 2. Comparison of experimental (points) and numerical (curves) mean velocity profiles at the hill top for a) horizontal, and b) vertical component

The distribution of the averaged skin friction coefficient obtained as a result of numerical simulation and presented in Fig. 3 revealed a well-know behavior in the attached region. From the measurement of the skin friction, information about the position of separation points, recirculation zones or reattachment points can be derived. The skin friction starts from zero at the hill foot, peaks before the hill crest, drops from then on and achieves its negative values in the separation region. The separation is indicated by the vanishing of the skin friction. The influence of frequency of incident flow oscillation is strongly marked in the downwind area only for the case of higher value of amplitude of external gusts. Experimental verification of computational results has been done at the two points localized both on upwind (x/L_1 = -0.3) and downwind (x/L_1 = 0.3) sections of the hill surface.

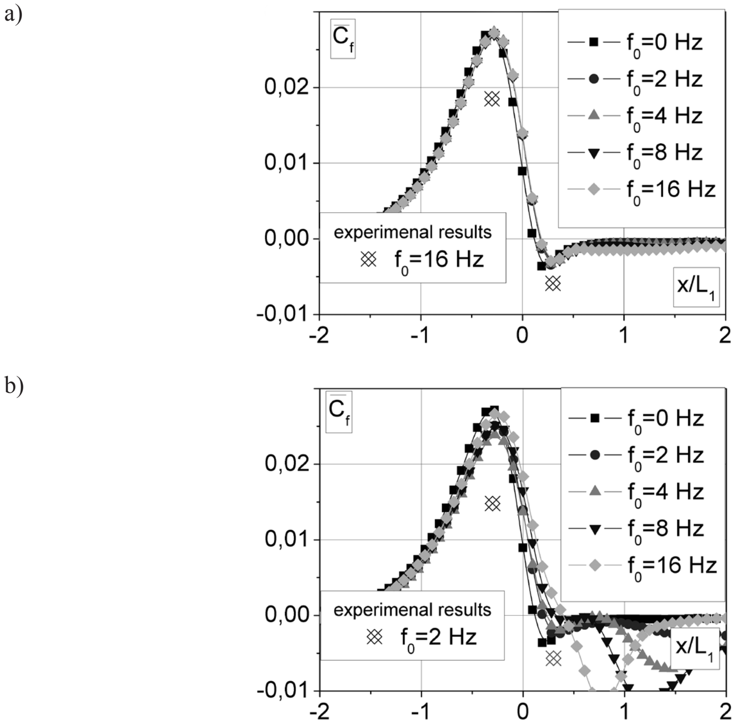

Fig. 3. Distribution of mean wall shear stress coefficient around the hill surface for a) low (A = 0.2) and b) high (A = 0.7) amplitude of inflow oscillations

Fig. 4 shows the time dependence of instantaneous values of friction coefficient $c_f(t) = \overline{c}_f + \tilde{c}_f(t)$, obtained on the basis of numerical simulations for sample inflow frequencies and amplitudes A = 0.2 and 0.7. The periodicity of the friction coefficient traces is clearly visible. At the point before the hill top (x/L_1 = -0.3), the influence of external gusts amplitude A dominates over effect of inflow frequency level. The time distributions recorded in the vicinity of boundary layer separation on downwind slope (x/L_1 = 0.3) are strongly related to frequency f_0, especially for A = 0.7 case. The periodicity of surface friction distribution loses its mono-harmonic character in this region.

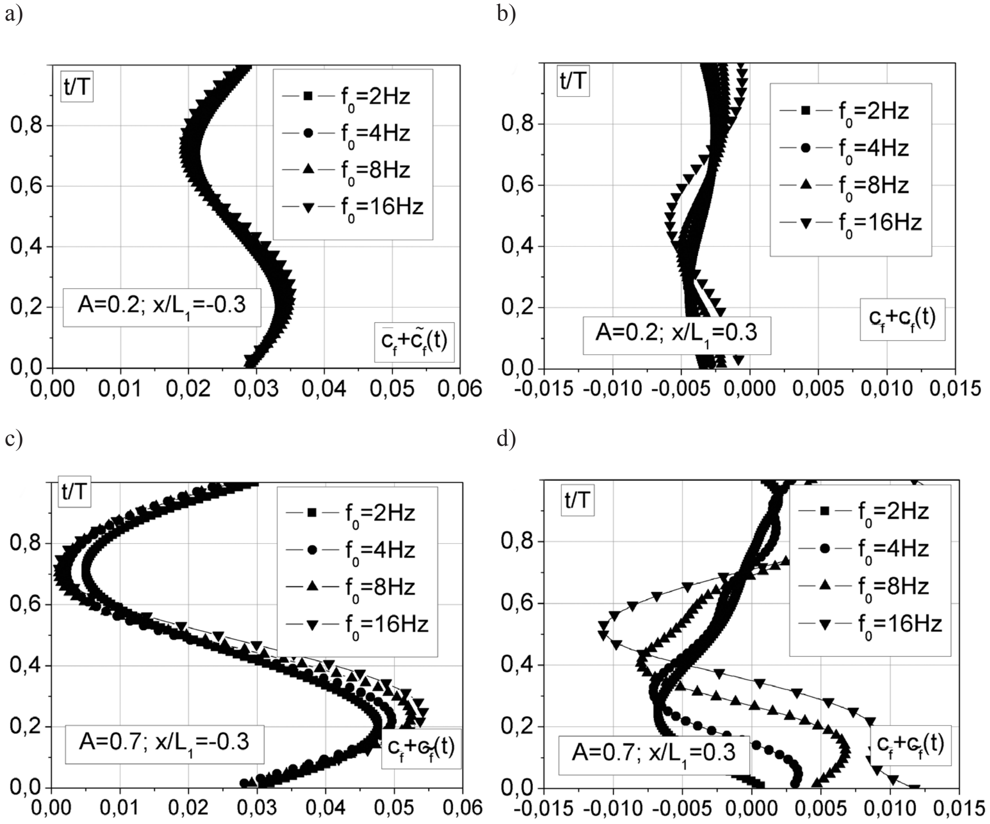
a)
b)
c)
d)

Fig. 4. Time dependent distributions of the wall shear stress coefficient obtained from numerical simulation for inflow amplitude $A = 0.2$ (a, b) and $A = 0.7$ (c, d) at upwind $x/L_1 = -0.3$ (a, c) and downwind $x/L_1 = 0.3$ (b, d) positions

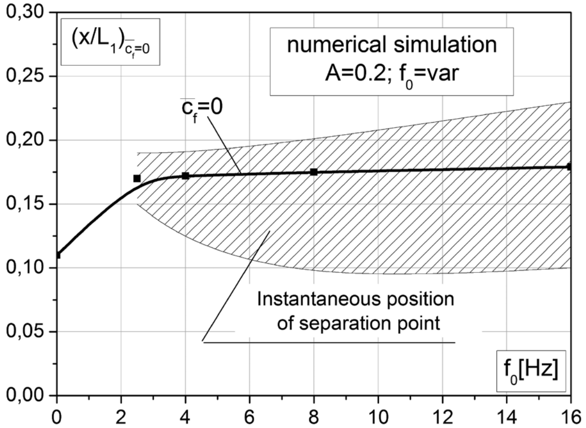

Fig. 5. The position of the separation point for low amplitude inflow conditions

The pictures observed as the results of numerical simulation of the instantaneous skin friction distributions over the hill surface given in the form of time-space distribution made it possible to analyse that problem for the modelling of the erosion process, [6]. One may see that the location of separation is changeable in time and space, undergoing oscillations around the position indicated by the zero value of mean skin friction coefficient. The results presented in Fig. 5 obtained on the basis of time-space distributions of the wall shear stress coefficient, indicate the band of possible instantaneous positions for which a zero value of skin friction may occur.

4. Concluding remarks

The conducted analysis of the experimental/numerical pattern allows the presentation of the influence of oscillating winds with changing frequency and amplitude on the shaping of the flow around a singular, waving hill. Analysis includes the wind surrounding a streamlined object, therein apex and recirculation zone in the track behind the hill. The main attention was focused on areas that were characterized by increased ground erosion during flow around the hill, localized in the section of oscillating wind field.

The instantaneous pictures of the flow field around the hill revealed the different features resulting from the inflow frequency and amplitude change. One can note the significant importance of large scale periodical pulsations of incident wind on the dynamics of separation zone behind the hill. Both frequency f0 and amplitude A influence the extent of the recirculation zone as well as introduce some additional fluid flow events in comparison with the steady inflow case.

The differences deal mainly with the regular vortex street generated in the case of high frequency inflow oscillations. Amplification of the downwind recirculation is also observed especially for the higher values of amplitude A. Periodic inflow disturbances bring about intensive oscillations of the wall shear stress. the location of separation is changeable in time and space, undergoing oscillations around the position indicated by the zero value of the mean skin friction coefficient.

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