WIND EFFECT ON WATER SURFACE OF WATER RESERVOIRS

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Abstract

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The primary research of wind-water interactions was focused on coastal areas along the shores of world oceans and seas because a basic understanding of coastal meteorology is an important component in coastal and offshore design and planning. Over time the research showed the most important meteorological consideration relates to the dominant role of winds in wave generation. The rapid growth of building-up of dams in 20th century caused spreading of the water wave mechanics research to the inland water bodies. The attention was paid to the influence of waterwork on its vicinity, wave regime respectively, due to the shoreline deterioration, predominantly caused by wind waves. Consequently the similar principles of water wave mechanics are considered in conditions of water reservoirs. The paper deals with the fundamental factors associated with initial wind-water interactions resulting in the wave origination and growth. The aim of the paper is thepresentation of utilization of piece of knowledge from a part of sea hydrodynamics and new approach in its application in the conditions of inland water bodies with respect to actual state of the art. The authors compared foreign and national approach to the solved problems and worked out graphical interpretation and overview of related wind-water interaction factors.

meteorology, water wave mechanics, wind-water interactions

The initial driving mechanisms for atmospheric motions are related either directly or indirectly to solar heating and the rotation of the earth. Vertical motions are typically driven by instabilities created by direct surface heating (e.g. air mass thunderstorms and land-sea breeze circulations), by advection of air into a region of different ambient air density, by topographic effects, or by compensatory motions related to mass conservation. Horizontal motions tend to be driven by gradients in near-surface air densities created by differential heating and by compensatory motions related to conservation of mass.

The waving on water reservoirs was investigated by many scientists since the dams have started to be built (e.g. Braslavskij, 1952; Saville, 1954; Kratochvil, 1970). They observed waves on inland water bodies during various conditions and they published the results which had the scientific impact into these days in the region of Czech Republic and Slovakia (Kálal, 1955; Kratochvil, 1970; Lukáč, 1972; Marhoun, 1988; Šlezingr, 2004).

MATERIALS AND METHODS

Due to the complexity of the physical phenomena, most methods for wave prediction are based on semi-empirical relations. The methods have been modified as wind and wave data were accumulated over time, resulting in better predictions.

The energy transferred to the water level by wind generates a range of wave heights and periods that increase as the waves travel across the available fetch length. Fetch means the area in which water level is affected by wind having a fairly constant direction and speed. The process of wave generation by wind can be explained by combining the resonance model developed by Phillips (1957) and the shear flow model developed by Miles (1957). Pressure fluctuations within the wind field disturb the still water and cause water surface undulations. These pressure fluctuations moving in the direction of the wind resonate with the free wave speed and amplify the undulations. As the size of these undulations increases, they begin to affect the pressure

distribution within the wind field, resulting in a pressure difference between two wave crests. The net force created by the higher pressure on the windward face of the wave results in wave growth.

The important relationships between basic magnitudes were analyzed in detail and their graphical representation through charts was carried out following the governing equations.

RESULTS AND DISCUSSION

Winds in coastal areas are influenced by a wide range of factors operating at different space and time scales. The important local effect in the coastal zone, caused by the presence of land, is orographic effect. Orographic effects are the deflection, channeling, or blocking of air flow by land forms such as mountains, cliffs, and high islands. A rule of thumb for blocking of low-level air flow perpendicular to a land barrier is given by the following ratio:

$$\frac{u}{h_m} \begin{cases} < 0.1 \rightarrow \text{blocked} \\ > 0.1 \rightarrow \text{no blocking} \end{cases} \text{ [-]}.$$

In the equation, u = wind speed and h_m = height of the land barrier in units consistent with u. Another orographic effect called katabatic wind is caused by gravitational flow of cold air off higher ground such as a mountain pass. Since katabatic winds require cold air they are more frequent and strongest in high latitudes.

The estimation of winds from nearby measurements has the appeal of simplicity and has been shown to work well for large water bodies (e.g. Great Lakes in USA). To use this method, it is often necessary to transfer the measurements to different locations (from overland to overwater) and different elevations (Ozeren, Wren, 2009). Such complications necessitate provide some corrections of wind speed.

The first correction refers to the measurement location. The wind record from an anemometer depends significantly on the physical conditions of the surrounding terrain. The surrounding terrain determines the boundary roughness and thus the rate at which wind speed increases with height above the ground. Consequently, physical conditions characterizing the surrounding fetches determine the wind environment at a site. At coastal sites, the fetch oriented from beach over water is generally characterized by relatively low roughness. The fetch oriented from water to land can vary significantly from site to site because it depends on the type of vegetation, terrain, etc. Differences exist between onshore and offshore wind speeds due to differences in friction conditions over the fetch (CERC, 1973). An empirical relationship between overland wind speed (u_{land}) and overwater wind speed (u_{water}) can be estimated from measured wind speeds at land and water sites by this formula (Hsu, 1981; Powell, 1982):

$$u_{water} = 1{,}62 + 1{,}17u_{land} \text{ [-]}.$$

The authors of equation recommend to use the formula when the air-water temperature difference does not exceed 5 °C. The Fig. 1 shows the ratio between overwater and overland wind speed as a function of overland wind speed.

The Czech standard specification ČSN 75 0255 (Calculation of wave effects on waterworks) deals with the estimation of overwater wind speed differently. The standard specification introduce the another term for fetch – effective length of wind run over water. This approach has been used for the determination of wave characteristics on valley dams in the Czech Republic and Slovakia (Kratochvil, 1970; Lukáč, 1980; Šlezingr, 2004, 2007, 2010). Fig. 2 shows the relationship between the fetch length and k-factor which is applied in the equation for estimation of overwater velocity (ČSN 75 0255):

$$u_{water} = k \times u_{land} \text{ [-]}.$$

The second correction refers to the elevation of wind speed. Often winds taken from observations do not coincide with the standard 10 m reference level. They must be converted to the 10 m reference level for predicting waves, currents, surges, and other wind generated phenomena. Failure to do so can produce extremely large errors. For the case of wind in near-neutral conditions at a level near the 10 m level (within the elevation range of about
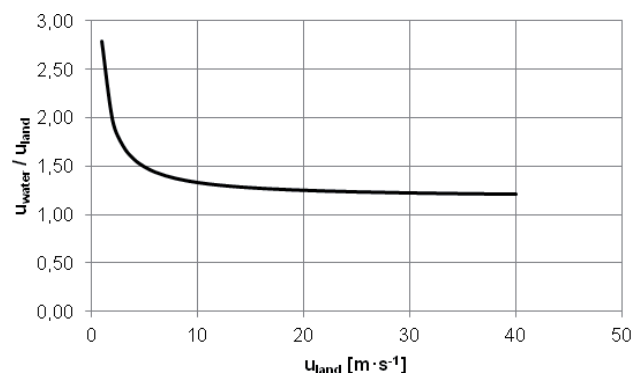
1: *Relationship between overwater and overland wind speed*

8–12 m), this simple approximation can be used (u_z = velocity at the desired elevation z, Fig. 3):

The net effect of wind speed variation with fetch is to provide a smooth transition from the (generally lower) wind speed over land to the (generally higher) wind speed over water (U.S. Army Corps of Engineers, 2002). The exact magnitude and characteristics of this transition depend on the roughness characteristics of the terrain and vegetation and on the stability of the air flow.

Elevation and stability corrections of wind speed provide a more comprehensive method to accomplish the above transformation, including both elevation and stability effects. The ratio of the wind speed at any height to the wind speed at the 10 m height is given as a function of measurement height for selected values of air-water temperature difference and wind speed. Air-water temperature difference (ΔT) is defined as:

$$\Delta T = T_a - T_w \ [^\circ C].$$

In the equation, T_a, T_w = air and water temperature in °C. For air-water temperature differences exceeding 5 °C, another correction can be applied. A temperature correction applied to wind speed as given by Resio and Vincent (1977) is:

$$u'_{10} = R_T \times u_{10} \ [m.s^{-1}].$$

In the equation, u'_{10} is the wind speed corrected for the air-water temperature difference and R_T is the correction factor applied to the overwater wind speed at the 10 m height (Fig. 4). The correction factor R_T is shown given by the equation:

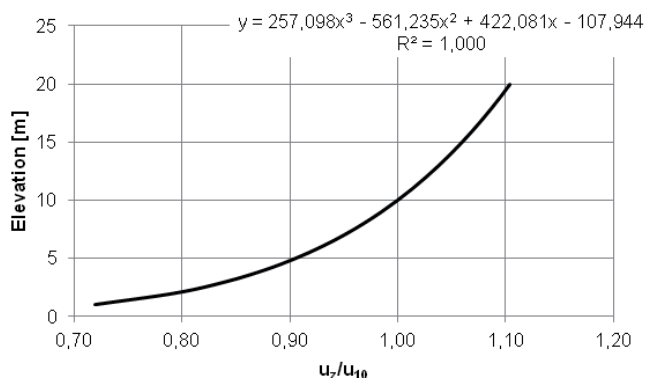$$R_T = 1 \pm 0{,}06878 \, |T_a - T_w|^{0,3811} \ [-].$$

The physical processes that determine the water surface wind field are contained in the basic equations of motion. But, these equations are mathematically very complex and can only be solved by using numerical methods on high-speed, large-scale computers. This approach is commonly referred to as weather prediction by numerical methods, pioneered originally by L. F. Richardson (1922).

If one does not have access to a large computer system with a real-time observational database, it will be necessary to perform a manual analysis of variables to construct the wind fields with the aid of some simple dynamical relationships. Although time consuming, manual analyses can produce more detailed wind fields than models.

The basic force that drives waves is the surface stress imparted by the wind however the parameter

$y = 0{,}0002x^3 - 0{,}0069x^2 + 0{,}0756x + 1{,}0269$
$R^2 = 0{,}9991$
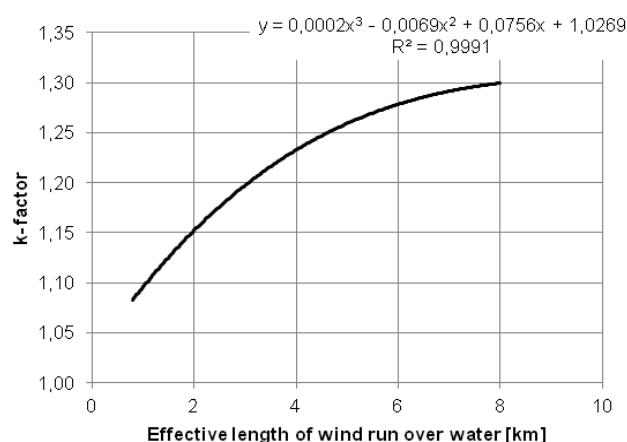
2: *K-factor for estimation of overwater velocity*

$y = 257{,}098x^3 - 561{,}235x^2 + 422{,}081x - 107{,}944$
$R^2 = 1{,}000$

3: *Wind speeds (u_z, u_{10}) ratio due to elevation*

is not measured directly. It is estimated by knowing the wind at a specified height (u_{10}) and applying an appropriate value for drag coefficient (C_d). Determining C_d has been the objective of many field research programmes over the years and there is one of the result formulas:

$$C_d = 0,001(1,1 + 0,035\,u_{10})\ [\text{-}].$$

The drag coefficient is dependent on elevation and stability (air minus water temperature difference) of the atmosphere above the water level. In unstable conditions the water is warmer than the overlying air and there is more turbulent mixing in the lower atmosphere. This increases the stress on the surface, so for the same wind speed at a given height, waves will become higher under unstable conditions than under stable conditions (WMO, 1998). Hence, characterizing friction and the stability in the lower boundary layer is an important step in deriving winds or surface stresses suitable for use in wave estimation.

The boundary layer itself can be separated into two regimes: the constant flux (or constant stress) layer (from the surface to about 50 m) and the Ekman layer (from about 50 m up to the free atmosphere, approximately 1 km). In the surface layer it can be assumed that the frictional forces contributing to turbulence are constant with height. The wind direction is consequently constant with

height. Using the mixing length theory developed by Prandtl, it can be shown that the flow in the constant flux layer (or Prandtl layer) depends only on the surface roughness length (WMO, 1998).

Under neutral conditions, Prandtl's solution shows that the horizontal flow over the water level follows the logarithmic profile in the vertical direction:

$$u_z = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)\ [\text{m.s}^{-1}].$$

In the equation, κ is the von Kármán constant, z_0 is the constant of integration, known as the roughness length, and u_* is the friction velocity:

$$u_* = \sqrt{C_d}\,u_{10}\ [\text{m.s}^{-1}].$$

For subsequent wave forecast models, it appears appropriate to express the input wind in terms of friction velocity because this is calculated taking stability into account. The wind is then expressed at some nominal height by applying the neutral logarithmic profile. This wind is then called the equivalent neutral wind at that height.

Wind stress (τ) considered as the rate of momentum transfer into a water column (of unit surface area) from the atmosphere can be written in the parametric form, expressed as the relationship
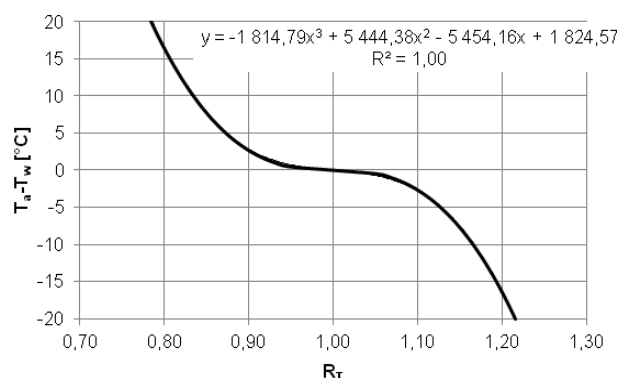
4: *Correction factor R_T expressed as function of air-water temperature difference*
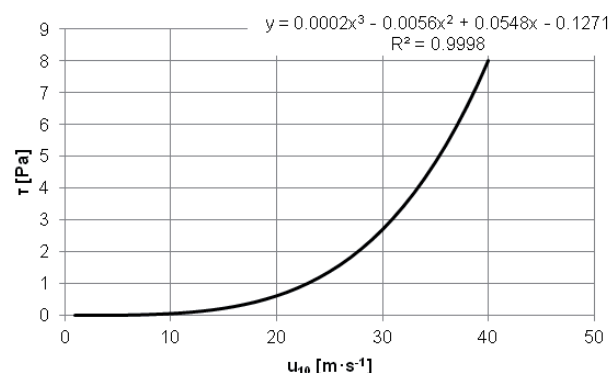
5: *Increasing of the rate of momentum transfer with the wind velocity*

between drag coefficient, wind speed and air density (ρ_a):

$$\tau = \rho_a \times C_d \times u^2 \, [Pa].$$

Fig. 5 illustrates the relationship between wind speed and wind stress.

CONCLUSION

Although wave generation by wind is complex, it is possible to predict wave properties from the wind data at a steady-state when speed and direction data are available. Even though these data may not be available at a given field site, long-term estimates of wave characteristics should be valid if theprediction is based on wind data from the same region, as long as the topography near the weather station is similar to that of the water reservoir.

Knowledge of the wind characteristics, waves and the forces they generate is essential for the design of coastal projects because they are the major factor that determines the geometry of beaches, the planning and design shore protection measures and hydraulic structures. Estimates of wave conditions form the basis of almost all coastal engineering studies.

SUMMARY

Aim of this work is the insight into fundamental wind-water interactions resulting in the wave origination and growth. Proper wind estimation should involve following procedures and corrections. When estimating wind characteristics from nearby measurements the correction of measurement location has to be involved due to the roughness difference between water surface and surrounding terrain. Since wind speed varies with the elevation this one has to be converted into the 10 m reference level. Further the air-water temperature difference influence the resulting wind velocity so the stability effects have to be taken into account. The magnitude called drag coefficient is dependent on elevation and stability. This coefficient is applied to determine implicitly the surface stress imparted by the wind. Thus, the input wind is expressed in terms of friction velocity because this is calculated with respect to the stability effects.

The paper presents the utilization of piece of knowledge from a part of sea hydrodynamics and new approach in its application in the conditions of inland water bodies with respect to actual state of the art. The authors compared foreign and national approach to the solved problems and worked out graphical interpretation and overview of related wind-water interaction factors.

The results contain graphical representation of some important relationships between discussed magnitudes. Further, the results are applicable for more accurately establishment of wave heights on water reservoirs due to wind with consequential better design of stabilization elements of dam and water body shorelines.

Presented relationships among some basic processes in the energy transfer between wind and water surface can facilitate insight into the wind-water interactions. Since the resulting wave prediction is as accurate as the wind estimation is correct.

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