Experimental Analysis of Waves in Environmental Flows

Theses of the PhD Dissertation

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von Kármán Laboratory
Budapest
2022

1 Introduction

The oceans represent the major components in the global climate model, where internal waves play a crucial role in the marine ecosystem by transferring heat, energy, and momentum. The effect of the density stratification is strongly recognized in the dynamics of environmental flows, of which rises an essential interest to the scientific enquiry. It is evident in the generation of the internal gravity waves. They are generated as a gravitational response to a disturbed stable system under the effect of buoyancy force.

In the two-layer stratified water, the barotropic or baroclinic current is usually interacted with a topography. That lead to the fluctuation of pycnocline in wave-like motion with a large amplitude, in which the main current is driven from surface waves such as tides and seiches.

Internal waves are also responsible for a substantial ocean mixing and energy dissipation, and significantly impact the water temperature in shallow and deep coral reefs by transporting cold and nutrient-rich water in nearshore regions, as well as aggregating phytoplankton near the water surface. Therefore, understanding the behavior of the waves in stratified systems and finding simplified mathematical theories to accurately describe their motion will lead to an increase in the accuracy of climatological models.

2 Scientific goals

Understanding the behavior of internal wave encounters difficulties due to the non-linear nature. Although the linear wave theory is the simplest way to describe the propagation of wave phenomena, there are limitations due to non-linearity, which is a topic of focus in numerous studies. One of the related questions is in what extend the linear wave theories can be applicable in understanding and predicting nonlinear surface and internal waves phenomena in quasi-two-layer stratified water.

One of the phenomena that exhibit a resonant amplification of the amplitudes is the dead water phenomenon, where important amount of the kinetic energy of the ship motion is converted to interfacial waves, mainly effected by the stratification profile. Despite this phenomenon was discovered over a century ago, the mechanism of wave-resonance still unclear. Besides, it is a suitable ground to test the applicability of linear theory.

Barotropic to baroclinic energy transfer in fjords system in the presence of the bottom sill is a cause of the fast damping of the surface seiche (standing wave). However, there was not any experimental study that investigated the effect of the sill and the stratification on the decaying rate of the seiche modes and the possible generated amplification of the baroclinic waves.

Our research mainly follows experimental based studies, to investigate wave phenomena in the marine environment which is characterized by quasi-two-layer stratified water in a simpler bathymetry (such properties are found in Scandinavian fjords, namely the Gullmar Fjord). We predominantly focused on the extent of the applicability of linear wave theories in understanding and predicting nonlinear waves phenomena (surface and internal), and the internal waves generation due to the vertical energy conversion in quasi-two-layer stratified water.

In an additional research, we focused on one of the challenges that is related to the reducing environmental impacts by shifting to the dependence on renewable energy resources. Studying the advantage of the spatial and temporal variability of climate variables and intermittency of renewable electricity sources have been presented in some places, Africa is somewhat underrepresented. The question is whether north-western Africa carry suitable geographical areas where the aggregation of solar and wind energy (hybrid) is optimal in an integrated renewable energy system. We have examined the complementarity of wind and solar in electricity production over north-western Africa, relying on analysing the ERA5 data bank (compiled and maintained by the European Centre for Medium Range Weather Forecast (ECMWF). One of the new products they provide is horizontal wind speed components at a height of 100 m).

3 Methods

Our work is an experimental research that was conducted in the von Kármán Laboratory of Environmental Flows.

In the laboratory modeling of the dead water phenomenon **#D** and seiche damping **#S**, we performed the experiments in two different rectangular narrow tanks filled up with quasi-two-layer stratified water. For the experiments **#D**, the ship model was pulled several times in each experiment letting the water layers to settle down before each run. The ship was pulled at a constant velocity in each experiment, which could be adjusted via DC power supply unit. For the seiche generation, each experiment **#S** consisted of five runs (to generate five seiche modes $m = 1$, 2, 3, 4, and 6) with and other five without the obstacle – An upside-down U-shaped small plastic obstacle was placed in the middle of the tank to the bottom – . We used an adjustable wave maker consisting of a metallic rod and six rectangular rubber foam 'bumpers' of equal size was placed above the water surface.

Data acquisition technique was based on the digital image processing of the painted density interface motion from the recorded videos.

In the additional project, We analysed the spatio-temporal dataset of the horizontal wind speed components at 10 m and 100 m and the surface solar irradiation was acquired from the ERA5 reanalysis data (the fifth generation ECMWF atmospheric reanalysis of the global climate) in the region of north-western Africa with spatial and temporal resolutions of $0.25° \times 0.25°$ and 3h (1h for In-Salah region) respectively. The evaluated period was nearly four decades until the end of the year 2019.

4 Theses

4.1 The study of the resonant feature of internal gravity waves of 'dead water' phenomenon

(1) We studied experimentally the resonance behavior that is featured in the dead water phenomenon associated with quasi-two-layer stratified water and the ship is moving in a constant velocity [1].

- We found that the generated interfacial waves resonate at a critical velocity $U^* \approx 0.8c_0^{(2)}$, and critical flow velocity under the ship bow in the upper layer was found to be $U_f^* \approx c_0^{(2)}$.
- These waves exhibit different behaviors, for sub- and supercritical wavelengths, which depend on the vertical density profile of the stratification.

(2) We discussed the linear dispersion relations that may describe the relationship between the velocity of the generated interfacial waves of large amplitudes and their wavenumbers [1].

- After testing the linear two-layer and three-layer approximations of the dispersion relation of a freely propagating internal wave on our observations (in the quasi-two-layer stratification), we found that the linear three-layer approximation predicted the phase velocity of the wave that is characterized by subcritical wavenumber.
- The supercritical wavenumber is set by a fixed effective buoyancy frequency linearly related to the buoyancy frequency of the pycnocline with a lee wave-like dynamics.
- We demonstrated that the coalescence of these two fundamental wave motions (the freely propagatinf internal wave and the lee wave) indicates the maximum

amplification of interfacial internal waves in the dead water phenomenon at a critical value.

(3) We checked the effect of the ship length on the critical wavelength. It was found that the critical wavelength tends to increase with the ship length, implying that the ship configuration also plays a role in the wave number selection [1].

4.2 The study of the influence of stratification and a bottom sill on seiche damping

(4) We proved the agreement of the theoretical linear dispersion relation of homogeneous surface gravity wave with the observed surface seiche for the five modes in density profile configurations [2].

(5) The literature show that the energy dissipation of surface seiche is dominated by the barotropic-to-baroclinic energy conversion. However in our research we studied how this energy is converted, in which two pathways were uncovered [2].

- Short wave with period of surface seiche is excited by the horizontal flow above the obstacle, and its amplitude is at maximum when the seiche node is exactly above the sill.
- Large period internal seiche resonates with a long wavelength fit integer number to the wavetank length which exists either in the presence or absence of the bottom obstacle.

(6) The influence of the bottom sill on the seiche damping was manifested throughout the comparison of the dominant seiche decay rates in the presence of the sill with those from control runs without bottom topography [2].

- We demonstrated that in almost all cases internal wave activity yields a detectable increase of the damping at the presence of the sill. A pronounced rates associated with odd modes in which the short internal waves are generated.
- Decay coefficient was obtained from the decaying sinusoidal oscillations formula.

(7) The linear internal wave dispersion relation indeed describes the pattern that the observed interfacial internal waves follow (generated through the energy conversion from the aforementioned modes). It describes baroclinic waves generated in the real quasi-two-layer sill fjords quite well in cases where the surface forcing frequencies are large. While the three-layer correction for such system within the range of large wavenumbers is negligible [2].

4.3 The study of the combined wind-solar electricity production potential over north-western Africa

(8) Via the ERA5 reanalysis data, we estimated the wind potential at altitude of 100 m for electricity production [3].

- The comparison of wind speeds at 10 m and 100 m altitudes indicates steep vertical wind profiles over the Sahara (gradients of 1.5–1.6).
- We didn't find any utilisable spatial anti-correlation of wind speed in the studied region.
- The relatively large hub-height mean wind speeds at 100 m over the Saharan region suggest that the capacity factors of wind electricity generation (larger than 40–45%) should be comparable with off-shore wind farms.

(9) For a smooth output of electricity production of the combined wind and solar resources, we utilised the linear combination with a total output integrated over a longer period as a function of the resource fraction c [3].

- We found the existence of utilisable daily anti-correlations between local wind speeds at altitude of 100m and solar radiations over the Sahara.
- The linear model of electricity output aggregation from the wind and solar resources suggests that the optimal resource combinations in this region for smooth electricity output is between 60-40 % and 70-30% (wind-solar).
- Low capacity factor loss to the maximum electricity output (pure wind $c_{max} = 1$ or pure solar $c_{max} = 0$) between 0% and 5% in a large area in either wind dominated or solar dominated resources.

5 Conclusions

We conduct that our research projects contribute in enhancing the quantitative and quantitative knowledge for better understanding the waves behavior in the stratified media. And the additional project suggests that the combination of wind and solar resources for a dramatically improved quality of electricity production output over Sahara is possible. Our results have been published in Peer-reviewed scientific journals.

References

[1] K. Medjdoub, I. M. Jánosi, and M. Vincze, “Laboratory investigations on the resonant feature of ‘dead water’phenomenon,” *Experiments in Fluids*, vol. 61, no. 1, pp. 1–12, 2020.

[2] K. Medjdoub, I. M. Jánosi, and M. Vincze, “Laboratory experiments on the influence of stratification and a bottom sill on seiche damping,” *Ocean Science*, vol. 17, no. 4, pp. 997–1009, 2021.

[3] I. M. Jánosi, K. Medjdoub, and M. Vincze, “Combined wind-solar electricity production potential over north-western Africa,” *Renewable and Sustainable Energy Reviews*, vol. 151, p. 111558, 2021.