Internal waves: A potentially untapped marine energy resource

Kaustubha Raghukumar, Craig Jones, Grace Chang, Jesse Roberts

Abstract— **Internal waves are ubiquitous oceanographic features that occur in various forms across the world's oceans. Internal waves are characterized by isopycnal displacements that can exceed 30 m, and current velocities that approach 1 m/s. Internal wave energy converters, if developed, could have the advantage of no surface expression and provide for the availability of renewable ocean energy in regions of scant surface wave energy resources.**

Here, internal wave energies were computed at two locations: the New Jersey continental shelf and the coast of Central California. Results suggest that the internal wave energy flux is comparable to that of surface waves on the New Jersey continental shelf during the summer of 2006 but is two orders of magnitude lower than that of surface waves in Central California during the summer of 2017. When expressed in terms of forces on a cylindrical structure, internal wave forces are an order of magnitude lower than that of surface waves on identically sized cylinders. However, the forces of the two resources are comparable when the diameter of the cylinder is increased for the internal wave calculations. This suggests that while a larger energy converter would be required to harness internal wave energy, the larger size could be a reasonable tradeoff for advantages such as the lack of surface expression and the availability of energy in regions of limited surface wave energy resources.

Keywords—**resource characterization, internal waves, surface waves**

I. Introduction

Internal waves are ubiquitous oceanographic features that occur in various forms across the world's oceans. They manifest themselves as interface waves across ocean density layers (Fig. 1) that represent the interplay between buoyancy and gravitational forces.

Linear internal waves are notable in that their frequency spectrum is remarkably consistent across a wide range of bathymetric and geographic features [1], and represent an incoherent, random, diffuse field of density perturbations. While they are responsible for momentum transport between deep and shallow waters, due to their incoherent and diffuse nature, linear internal waves are not expected to advect significant energy from the point of view of a marine energy resource.

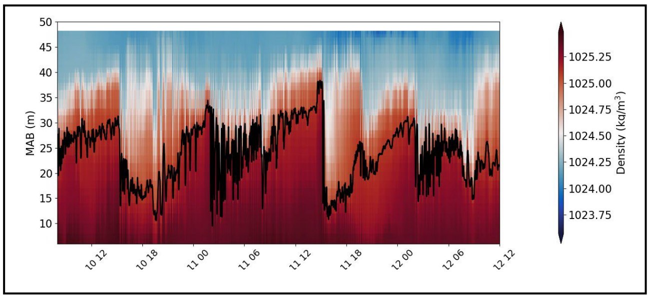

Fig. 1. Example of density perturbations driven by the propagation of nonlinear internal waves. The black line indicates the depth of the 1025 kg/m3 constant density layer (isopycnal). MAB = meters above bottom.

In contrast, nonlinear internal waves (NIWs) can exhibit density layer oscillations that can approach 30 m (Fig. 1), with horizontal velocities that can range from 0.25 to 1 m/s (0.5 knots to 2 knots). NIWs have been documented to occur globally, ranging from the New Jersey Shelf [2], Oregon [3], South China Sea [4], the Andaman Islands [4] and across the Gibraltar Strait [4]. Studies of NIWs that have examined their forces on offshore structures have indicated significant energy content [5].

Here, the NIW energy resource was characterized at two locations: the New Jersey continental shelf and the coast of Central California. The available energy resource calculated for NIWs was compared against surface gravity wave resources that were also characterized for each of these locations. The evaluation of this potentially new resource and comparisons against more widely characterized surface wave resources leveraged existing NIW and surface gravity wave data sets collected during previous experiments conducted along the New Jersey and California coasts. While no specific devices have yet been designed to capture this energy resource, it is hoped

"This work was supported in part by the Water Power Technologies office of the U.S. Department of Energy"

Kaustubha Raghukumar, Craig Jones and Grace Chang are at Integral Consulting Inc, 200 Washington Street, Suite 201, Santa Cruz, California, 95060, U.S.A (e-mails: kraghukumar@integral- corp.com, cjones@integral-corp.com, gchang@integral-corp.com).

Jesse Roberts is at Sandia National Laboraties, Albuquerque, New Mexico, U.S.A (jdrober@sandia.gov)

Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-159

that this research will support the formulation of design criteria for internal wave energy devices.

II. WAVE DATA

The characterization of available NIW energy resources was conducted based on the analysis of two datasets gathered during two oceanographic experiments: Shallow Water 2006 (SW06) experiment off the New Jersey continental shelf (30 days of data) and the Inner Shelf Departmental Research Initiative (ISDRI) experiment off Vandenberg Space Force Base (VSFB) in Central California (60 days of data). During both experiments, extensive field data were gathered using water-column spanning thermistor chains and bottom-mounted Acoustic Doppler Current Profilers (ADCPs), which allowed for detailed measurements of internal wave displacements and velocities; wave buoys provided measurements of surface wave energy fluxes. These datasets were analysed to quantify NIW and surface wave energy fluxes. The feasibility of NIWs as an energy resource was then further investigated in terms of forces exerted on structures by surface waves and NIWs. The force of a wave on an object can yield insight into the dimensions of an energy converter needed for energy conversion.

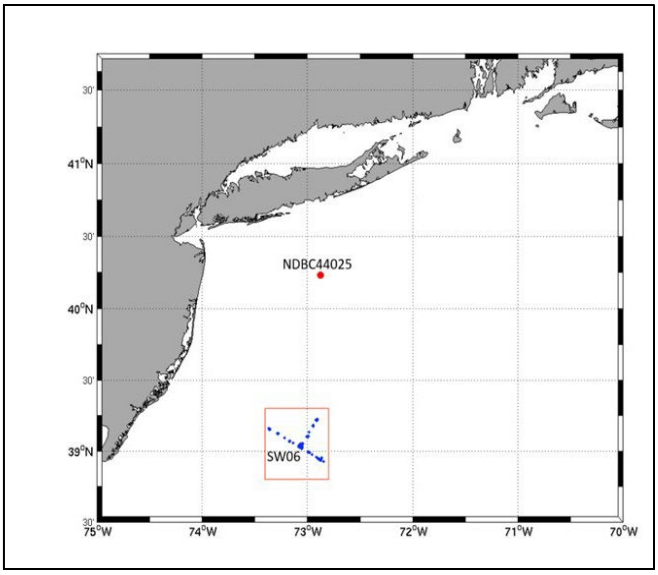

Fig. 2. Map of SW06 experiment deployment locations and the location of the NDBC buoy 44025.

A. Shallow Water 2006 (SW06) Experiment.

The SW06 experiment was conducted on the New Jersey continental shelf during August 2006, in water depths that ranged from 60 m to 500 m [6]. The goal of this experiment was to study the effect of oceanographic fluctuations on acoustic propagation; hence 62 acoustic and physical oceanographic moorings were deployed in a 'T-shaped' geometry centred on the 80 m isobath (Fig. 2). The center of this 'T' consisted of a dense array of acoustic and environmental moorings. This study analysed data from the SW30 mooring that was in 86 m deep water near the center of the 'T'. The mooring consisted of a 10-element conductivity-temperature chain (30 s sampling interval), and bottom-mounted ADCP (sampling interval 2 s, averaged into 30 s bins) that measured 3D currents in 4 m depth bins. Surface wave data were analysed from the National Data Buoy Center (NDBC) Buoy 44025.

B. Inner Shelf Direct Research Initiative Experiment (ISDRI)

The ISDRI experiment was conducted offshore VSFB in Central California (Fig. 3), between the months of September and October 2017, with the goal of understanding the physical oceanographic processes that link the surf zone to the outer continental shelf. A large set of environmental monitoring tools were deployed at a variety of water depths in this region that consisted of Acoustic Doppler Current Profilers (ADCPs), thermistor chains, wave buoys, high frequency radar, aerial observations and ship-based transects [7]. This study analysed data from the OC50 mooring that consisted of a 23-element thermistor string (30 s sampling interval) and a bottom-mounted ADCP (2 s sampling interval averaged into 30 s bins) that reported 3D velocities in 0.5 m depth bins. Additionally, Sofar Spotter wave buoy data were analysed from the SPOT-0028 mooring for the surface wave energy flux.

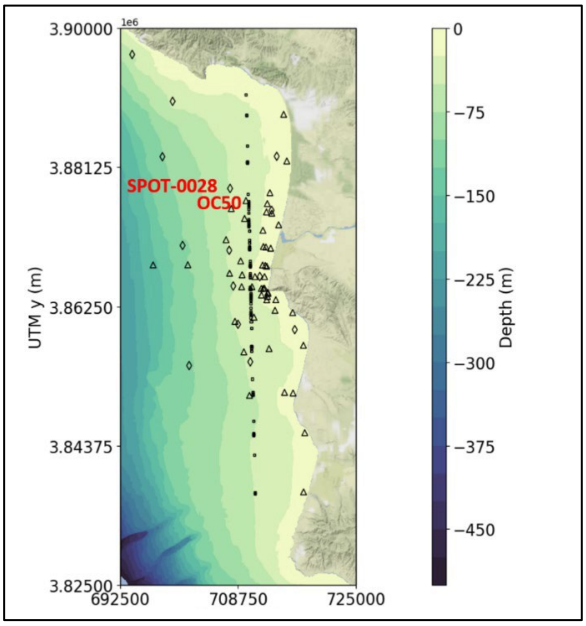

Fig. 3. Map of ISDRI Experiment deployment locations, with the locations of the SPOT-0028 wave buoy and OC50 mooring identified.

III. METHODOLOGY

The evaluation of energy resources for surface waves is typically conducted in terms of energy fluxes, which provide an estimate of the total available energy (potential plus kinetic) that a device can harness for conversion to electricity. Since the surface wave resource has now been identified as a viable energy resource [8], standardized wave resource calculations are available, such as those published by the International Electrotechnical Commission (IEC). However, no such standards are available for NIW energy resource assessment; therefore, a methodology was developed from available scientific literature [3,9,10].

While energy fluxes provide an estimate of available wave energy, the conversion to electricity is typically accomplished by transforming the force exerted on an object to electricity. Therefore, a comparison of the forces exerted by NIWs on an object is used to complement energy flux assessments for evaluation of the potential for NIWs as an energy resource.

A. *Surface Wave Energy Flux*

Standardized procedures [11] for wave resource assessment describe the computation of the surface wave energy flux based on either wave bulk statistics like significant wave height, peak period and mean direction, or using wave spectra when available. Here, wave spectra from NDBC buoy 44025 (east coast) and Spotter buoys (west coast) allow for the computation of the surface wave energy flux in Watts/meter as,

$$J_{SW} = \rho g \sum_{i} c_{g,i} S_i \Delta f_i \tag{1}$$

where ρ is the density of seawater, g the gravitational acceleration, $c_{g,i}$ is wave group speed for the ith frequency bin, S the omnidirectional variance density spectrum and Δf_i the spectral width of the ith frequency bin. Wave spectra are specified in units of m^2/Hz for frequency bins that span from 0.03 Hz to 0.4 Hz. Wave group speeds in (1) are computed as,

$$c_{g,i} = \frac{\pi}{k_i}\left(1 + \frac{2k_i h}{\sinh(2k_i h)}\right) \tag{2}$$

where k_i is the wavenumber and h the water depth. Wavenumbers are computed by solving to the dispersion relation,

$$(2\pi f_i)^{\,2} = g k_i \tanh(k_i h) \tag{3}$$

B. *Nonlinear Internal Wave Energy Flux*

Since internal waves have not yet been identified as a viable marine renewable energy resource, standardized energy flux calculations for NIWs are currently absent. However, energy fluxes for internal waves have previously been calculated [3,9] for the purpose of understanding momentum fluxes on the inner continental shelf. Using these methods [3,9], NIW energy fluxes were computed using a combination of water column temperature and velocity data collected during the SW06 and ISDRI experiments.

The energy flux in Watts/meter for internal waves is expressed as,

$$J_{IW} = \frac{< E >}{T} \tag{4}$$

where T represents time and <*E*> is the energy per unit coastline (Joules/meter), and given by

$$< E > = \int_{0}^{h} dz \int_{-\infty}^{\infty} Ec\,dt \tag{5}$$

The energy density E (Joules/m3) is the sum of available potential energy (APE) and kinetic energy (KE), $E = APE + KE$, where the available potential energy,

$$APE = \rho_w g z \tag{6}$$

is computed using the density perturbation. The density perturbation ρ_w is computed as the difference between the water column density (ρ), and a background reference density (ρ_0) or $\rho_w = \rho - \rho_0$, where the background density refers to water column density prior to the perturbation of isopycnals by internal waves. Water column densities are computed from temperature data as measured by the thermistor chains, and salinity data. For the SW30 dataset, salinity data are available via the conductivity measurements. For the ISDRI dataset, density perturbations were found to be largely driven by temperature changes; therefore, a constant salinity of 33.43 g/kg could be assumed [10]. The calculation of the background density profile is computed by sorting measured densities by increasing density over successive 24.84-hour periods and scaling by water depth. This method has the advantage of removing internal wave signatures when a data set has persistent internal wave data [10].

The kinetic energy is expressed as,

$$J_{IW} = \frac{< E >}{T} \tag{7}$$

where u, v, and w are the three velocity components, available from the ADCP data at each site, and bandpass filtered between 3 minutes and 16 hours to focus on NIWs.

The final term in (5) is the NIW phase speed,

$$c = c_0 + \alpha \frac{\delta}{3} \tag{8}$$

where c_0 is the linear mode 1 wave speed. α in (8) is the quadratic nonlinear Korteweg-de Vries (KdV) coefficient The term δ in (8) represents the isopycnal displacements induced by the propagation of NIWs. Isopycnal displacements are computed using the measured density, $\rho(z, t)$ and background density $\rho_0(z, t)$.

C. Force Calculation

The energy flux calculations provide an estimate of the total available energy (potential plus kinetic) that a device can harness for conversion to electricity. However, the transformation of an available wave energy resource to electricity is typically accomplished via the force of the wave an object. This force of a wave on an object is typically calculated using the empirical Morison's equation [12] for forces on a submerged object, expressed as the sum of drag and lift forces,

$$F(z) = F_D + F_L = C_D\rho\frac{D}{2}u(z)|u(z)| + C_M\rho\frac{\pi}{4}D^2\frac{\partial u(z)}{\partial t} \quad (9)$$

where C_D and C_M are empirical coefficients for drag and inertia, specified for a 2D circular cylinder [12], and D is the diameter of the cylinder. Given the longer wavelengths and time periods of NIWs, it is reasonable to assume that internal wave energy converters (IWECs), if designed, would have a larger surface area than those for surface waves. Therefore, the cylinder diameters are assumed to be 5 m for surface waves (for e.g. a small bottom-referenced heaving buoy or a bottom-referenced submerged heave buoy [13]) and 20 m for NIWs. While the increased size lends itself to increased material costs for an IWEC, this would be offset by the relaxation of the stringent design criteria that WECs require to minimize fatigue and damage due to repeated exposure to extreme events; with significant opportunity to reduce overdesign costs.

IV. Results

An example of isopycnal displacements by NIWs during ISDRI are shown in Fig. 4. Displacements are seen to consist of both packets of solitons (such as those on 09/11/2017 02:09; Fig. 4, lower left) or triangular bores (such as that on 09/11/2017 15:09; Fig. 4, lower right).

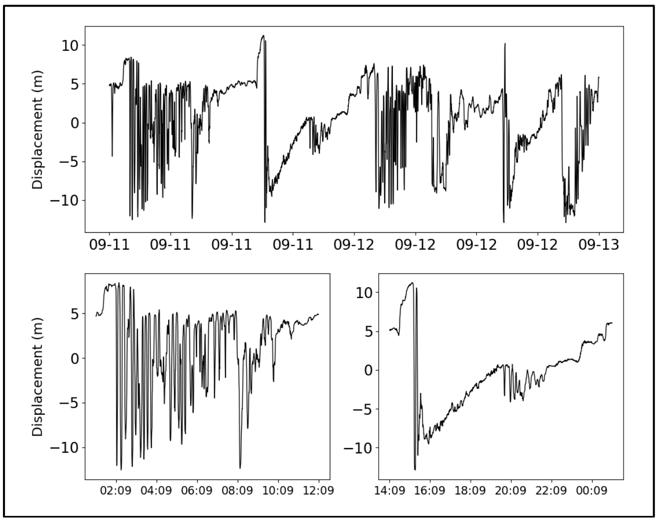

Fig. 4. Isopycnal displacements as measured during ISDRI.

While both solitons and bores are seen to exhibit similar displacements, the time scales of each is vastly different, ranging from about 10 minutes per soliton to about the length of a tidal period for a bore.

A comparison of energy fluxes of surface waves (1) and NIWs (4) is shown in Fig. 5. While the various datasets do not always overlap in time, they nevertheless yield insight into relative energy fluxes. During the summer months shown in the plot, surface wave energy fluxes are comparable across both experiment sites, although surface wave fluxes on the west coast can be expected to be significantly larger during the fall and winter. However, during this summer period, NIW energy fluxes are considerably higher on the east coast, and comparable to that of surface waves. This finding holds promise that NIWs can be a source of energy on coastlines with relatively low surface wave energy fluxes.

Since NIW wavelengths and timescales are considerably longer than those for surface waves (kilometers and minutes versus hundreds of meters and seconds, respectively), it is recognized that a larger device would be needed for conversion of NIW forces to electrical energy. Therefore, forces were calculated on a 20 m diameter cylinder for NIWs, and a 5 m diameter cylinder for surface waves (Fig. 5).

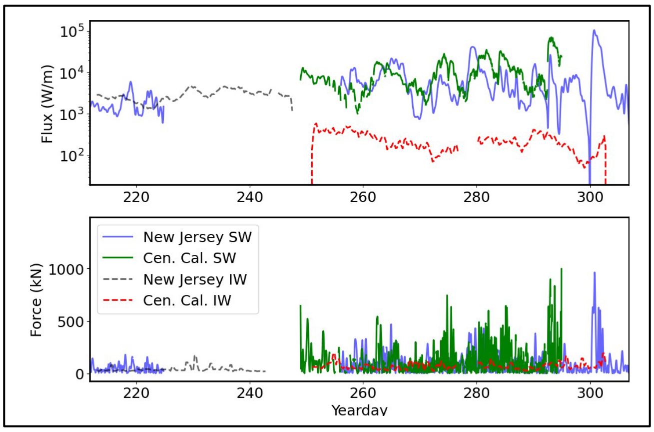

Fig. 5. Comparison of (Top) internal wave (IW) energy fluxes with that of surface waves (SW), and (bottom) forces on a 5 m diameter cylinder (SWs) and 20 m diameter cylinder (IWs).

It is found that the forces on the two sizes of cylinders are comparable for both surface waves and NIWs, indicating that an IWEC with a 20 m diameter could potentially harvest the same energy as a 5 m surface wave energy converter, thereby providing a considerable augmentation of the wave resource. Conversely a smaller device, producing less power, could be useful to PBE applications that require a lack of surface expression and/or operation in regions of limited surface wave resources.

V. Conclusions

This initial, exploratory study evaluated the potential for internal waves as a marine renewable energy resource. The evaluation of this energy resource was conducted using a methodology like standardized methods that are now available to evaluate surface wave energy resources. Physical oceanographic data spanning approximately two months that were available during two field experiments on the east coast and west coast of the U.S.A were analysed. Thermistor chain and current profiler data were analysed to evaluate NIW energy fluxes, while wave buoy data were analysed to compute the surface wave energy flux.

An analysis of temperature and current velocity data gathered on the east and west coasts of the U.S.A. shows that NIWs can be a source of marine energy to support both continental grid and PBE markets, with particular value to coastlines with low surface wave energy fluxes.

It was found that internal wave forces on a 20 m cylinder can be comparable to surface wave forces on a 5 m cylinder. This indicates a potentially larger IWEC scale relative to a WEC but may not necessarily increase overall costs due to much reduced impact of extreme events. Further, IWECs, if built, can provide a considerable augmentation to the surface wave resource. Conversely, a smaller sized IWEC could be a useful resource for PBE applications that require lower power, no surface expression and/or operation in regions of limited surface wave resources.

REFERENCES

[1] C. Garrett and W. Munk. "Internal waves in the ocean," Ann. Rev. Fluid Mech., vol. 11, pp. 339-69, 1979.

[2] D. Tang, J. Moum, J. F. Lynch, et al. "Shallow Water '06: A joint acoustic propagation/nonlinear internal wave physics experiment," Oceanography, vol. 20(4), pp. 156-167, 2007.

[3] J. Moum, J. Klymak, J. Nash, A. Perlin, and W. Smyth, "Energy Transport by Nonlinear Internal Waves," J. Phys. Oceanogr., vol. 37, pp 1968–1988, 2007.

[4] J. Apel. An atlas of oceanic solitary internal waves. Global Ocean Associates. Prepared for Office of Naval Research Code 322 PO.

[5] Z. Song, B. Teng, Y. Gou, L. Lu, Z. Shi, Y. Xiao and Y. Qu. "Comparisons of internal solitary wave and surface wave actions on marine structures and their responses,"Applied Ocean Research, vol. 33, pp. 120-129, 2011.

[6] J. Lynch, and D. Tang, "Overview of shallow water 2006 JASA EL special issue papers," J. Acoust. Soc. Am., vol. 124, pp.EL63-EL65, 2008.

[7] J. Lerczak, J., et al. "Untangling a web of interactions where surf meets coastal ocean", Eos, vol. 100, https://doi.org/10.1029/2019EO122141. Published on 02 May 2019.

[8] D. Bull and A. Dallman, "Wave Energy Prize experimental sea state selection". ASME 2017 36th International conference on ocean, offshore and arctic engineering, vol. 10: Ocean Renewable Energy, 2017.

[9] J. Colosi, N. Kumar, S. Suanda, T. Freismuth, and J. MacMahan, "Statistics of Internal Tide Bores and Internal Solitary Waves Observed on the Inner Continental Shelf off Point Sal, California," J. Phys. Oceanogr., vol. 48, pp. 123–143, 2018.

[10] J. McSweeney, J. Lerczak, J. Barth, J. Becherer, J., Colosi, J. MacKinnon, J. MacMahan, J. Moum, S. Pierce and A. Waterhouse, "Observations of shoaling nonlinear internal bores across the central California inner shelf," J. Phys. Ocean, vol. 50, pp.111-132, 2018.

[11] IEC, "Marine energy – Wave, tidal and other water current converters – Part 101: Wave energy resource assessment and characterization," IEC TS 62600, vol. 101. IEC, Geneva, Switzerland. 2015.

[12] F. El-Hawary, H. Maeda and M. Rahman, "The Ocean Engineering Handbook-CH 1.- Marine Hydro Dynamics and Vehicles Control," Boca Raton, FL: CRC P LLC, 2001.

[13] A. Babarit, J. Hals, M.J. Muliawan,, A. Kurniawan, T. Moan and J. Krokstad. "Numerical benchmarking study of a selection of wave energy converters," Ren. Energy, vol. 41, pp. 44-63, 2012.