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Review of Recent Studies in Ocean Waves

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REVIEW OF RECENT STUDIES IN OCEAN WAVES

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Introduction

A review of recent studies in wave problems of the ocean was undertaken for the following reasons:

(a) to become familiar with modern research in wave problems of the oceans,

(b) to summarize the results of researches to date, as a necessary background for future efforts in this field, and

(c) to formulate recommendations on what might be attempted in Canadian Atlantic waters.

Sources of Literature

A familiarity with the problems of physical oceanography with emphasis on wave phenomena was sought through reading and study in -

(a) Standard texts in oceanography.

(b) Journals and transactions of the learned societies.

Summaries and comments on some of the more important papers on ocean waves are appended to this report.

Four aspects of wave study with which these papers deal are:-

(a) Ocean Waves and Swell

(b) Internal Waves

(c) Band Slicks

(d) Tidal Phenomena

Some general comments follow to indicate where these branches of ocean wave phenomena offer opportunity for profitable study in Atlantic waters.

Ocean Waves and Swell

Ocean wave phenomena present some attractive problems for study. The theory of wave motions in fluids had been extensively developed by nineteenth century mathematicians but this was confined chiefly to the way in which waves in ideal fluids should behave. Due to the difficulty of obtaining data, there existed a gap between the mathematically formulated description of ideal waves and the description of waves as they are in the ocean.

War-time studies of waves, aimed at the prediction of sea surface roughness and the relation of swell to distant storms, have closed this gap somewhat. Wind velocity, wave height, period, velocity and fetch have been investigated for interrelations; also the rates of growth and decay of waves have been studied. There remains a need of more data and some aspects of the phenomena are not completely understood.

The Atlantic Coasts of Nova Scotia and Newfoundland offer favorable locations for the observations of swell from distant points, including the South Atlantic. Such observations would supplement the data obtained by British and American observations.

Research in this field would involve first the design and construction of wave recording and analysing apparatus. Some detailed study of this was made, especially of the apparatus described by Munk, Iglesias and Folsom. This is an assembly of cylinders and capillary tubes through which air and oil pass, so giving the equivalent action of an electric filter circuit. Ways of simplifying this apparatus and its redesign for sensitivity in the period range of five seconds to five minutes were considered. Such a period range would then include both the periods of ocean swell and of the longer period non-tidal oscillations such as the seiches which have been observed in Saint John Harbour and which might well exist in Passamaquoddy Bay or Bras d'Or Lakes.

There remains some doubt of the feasibility of magnetic tape recording for this purpose. It is hoped to answer this, at least in part, during the coming winter.

Internal Waves

Existence of waves at the interface of two fluids of different densities has long been known. Ben Franklin had commented on some aspect of this phenomenon, and a hundred years ago Stokes had calculated the velocity of such a wave train. Only recently, however, have observations of such waves in the ocean become possible with the development of the bathythermograph and the Salinity-Temperature-Depth recorder. Various investigators have reported observations of internal waves in the oceans of periods approaching tidal periods. More recently, internal waves of much shorter periods (in the range ten minutes to two hours) have been observed.

The Scotian Shelf and the Gulf of St. Lawrence in Summer and Fall are most promising waters in which one might look for this phenomenon. The high degree of stratification would favour their positive detection and might permit the application of the simple two-layer theory of Stokes as a fair approximation. Some data now at hand for the Anticosti region of the Gulf of St. Lawrence does indicate the occurrence of internal waves of sufficient amplitude to constitute an important feature in the hydrography of the area.

Band Slicks

A study of band slicks by Ewing suggests that these may sometimes be caused by internal waves. Thus the band slicks which occur in the tidal currents of Passamaquoddy Bay invite investigation. Long time-lapse pictures with a motion-picture camera, perhaps one frame per second, would indicate the changing pattern of the slicks. Simultaneous bathythermograph or Salinity-Temperature-Depth recorder observations should aid in their interpretation.

Bay of Fundy Tidal Phenomena

The generally accepted explanation of the extremely high tides of the Bay of Fundy is that standing waves exist because the natural period of a body of water of its dimensions coincide with the tidal period. This hypothesis might be verified by the stepwise method of calculation which Defant has applied to Garda Lake and the Adriatic Sea. In "The Oceans" (Sverdrup et al. 1942 pg. 562) one reads "An exact computation of the free oscillations of the Bay of Fundy has not been undertaken, but according to rough estimates this period lies between 13 and 11.6 hours (Defant, Gezeitenprobleme des Meeres in Landnahe. Probleme der kosmischen Physik, VI Hamburg 1925)".

The profile and velocity of the Bore on the Peticodiac River is something that might well be observed and studied using instruments now available - the moving-picture camera and echo-sounding equipment. G.R. Deacon refers to "echo-sounding wave-recorders which stand on the sea bottom pointing upwards, recording echo-profiles of the surface ...... Two types are now available, a permanent station type made by the Anti-Submarine Establishment, and a semi-portable type made by the Admiralty Research Laboratory".

Recommendations:

These problems i.e. (a) the fundamental study of ocean waves and swell, (b) the study of internal waves in Atlantic waters, (c) the investigation of band slicks and the associated water structure in Passamaquoddy Bay and (d) the profile and speed of the Bore in the Peticodiac, could be profitably investigated and are appropriate to Atlantic oceanography.

As a beginning the following recommendations are put forward:-

(a) that further study be given to the possibility of constructing wave recording and analysing equipment, particularly with regard to magnetic tape recording at slow speeds.

(b) that internal waves on the Scotian Shelf or in the Gulf of St. Lawrence be investigated when the thermocline is fully developed in late Summer. Initial observations could be made over a period of forty-eight hours at an anchor station.

(c) that an investigation of slicks in Passamaquoddy Bay be made combining time-lapse motion pictures of the changing pattern with simultaneous bathythermograph and/or "Salinity-Temperature-Depth" Recorder readings.

(d) that information be sought on the characteristics of the echo-sounding wave-recorder, especially the semi-portable type made in the Admiralty Research Laboratory and that the use of one be requested.

(e) that observations be made on the profile and velocity of the Bore on the Peticodiac River using motion-picture recording of a staff gauge together with the echo-sounding wave-recorder referred to in (d).

APPENDIX

Summaries and Comments on some of the more important papers on Ocean Waves.

Deacon G.E.R. Ocean Waves and Swell. Occ. Papers of the Challenger Soc. No. 1 (1946).

Summary of wave properties. Measured pressure electrically at depth. A description in more detail is in Barber and Ursell's paper. Also used echo sounding device in reverse less effectively. Two models of latter for this purpose now available; permanent station type made by Anti-Submarine Establishment and a semi-portable type by the Admiralty Research Laboratory. General description of the wave analyser and relation of the record to the storm situation. Refers to intention of analysis at the storm area (this to be attempted in mid Atlantic and Cornwall). An instrument is required to measure direction of swell. Preliminary experiments promise possibility of useful information on wave periods by frequency analysis of the pitching of a trawler.

Sverdrup H.U. and Munk W.H. Empirical and Theoretical Relations between Wind, Sea and Swell. Trans. Amer. Geophys. Union 27: 823-827 (1946).

Effectively a condensation of Hydrographic Office Pub. 601 Wind, Sea and Swell, Theory of Forecasting by same authors.

Munk W.H. Tracking Storms by Forerunners of Swell. Jour. of Meteorology, 4: 45-57 (1947).

Description of underwater unit and analyser. Bellows actuates potentiometer contact. Slow leak filters out long periods; position at depth filters out the short period oscillations. Current variations recorded photographically. This record, of varying width, is passed at varying speed by a photo-electric scanner which in turn, provides a current through a vibration galvanometer with a sharp resonance characteristic, so giving a frequency spectrum record of the waves present.

The period of the waves received from a distant storm gradually decreases, as the first waves received are those which travel most rapidly. It is shown that the time of travel t is $t = \frac{T}{-\left(\frac{\partial T}{\partial t}\right)}$ where T is the period. Also the distance x is $x = \frac{g\,T^2}{4\pi^2\left(\frac{\partial T}{\partial t}\right)}$

Graphical method of calculating by plotting the decreasing wave period with time permits location of the storm centre and its movement.

Data on three storms observed at Pendeen are discussed.

Barber N.F. and Ursell F. Generation and Propagation of Ocean Waves and Swell. Philos. Trans. Royal Soc. (London) 240: 527-560 (1948).

Summary of theory of waves from a localized source of short duration. Wave recorder, an inductive type hydrophone (American powerphone) on sea-bottom at 110 ft. connected to a recording fluxmeter. Later form, elastic metal bellows converting its deflection into resistance change in a bridge circuit. Preferred a pressure indicator to the inverted echo sounder, being more easily recorded, also pressure changes are more nearly sinusoidal and so preferable for harmonic analysis.

Three storms are analysed and results discussed. Evidence noted of the effect of tidal currents in modulating incoming wave trains. Appendices on pressure on sea bed, frequency analysis, length and spacing of records and effect of depth on travel time.

<u>Munk W.H. Iglesias H.V. and Folsom T.R., An Instrument for Recording Low Frequency Ocean Waves. Rev. Scientific Instruments 19: 654-658 (1948).</u>

An instrument to measure low amplitude wave periods between ocean swell and tides. Maximum sensitivity at 15 minute period with good response in the range 2 minutes to 2 hours. Vertical standpipe 5" diameter with lower end 15' below m.s.l. and filled with refined petroleum. The oil enters a long pipe inside the standpipe through a capillary. The upper end of this pipe is connected to a reservoir which in turn, is in series with several vertical air cylinders with oil at the bottom and joined by capillaries through which oil passes. Capillary air-leaks to the atmosphere are placed in each cylinder. The whole is equivalent to an electrical capacitance-resistance filter. The final stage actuates an electric straim gauge which records pressure on a Leeds and Northrup micromax recorder.

The instrument was checked for response against known tidal data, against a well defined swell, and against controlled pressure changes of a square wave form. Good agreement with calculated response from the design parameters.

Records reveal a complex system of waves covering the whole frequency range of the instrument. It is proposed to analyse records by use of magnetic tape recorder run at very slow speed and then to play back at greatly increased speed (x 10^5) to a wave analyser.

Seiwell H.R. Results of Research on Surface Waves of the Western N. Atlantic Papers in Physical Oceanography and Meteorology Vol. X No.4 (1948) 56 pgs.

Results of Research on Surface Waves in the Western North Atlantic.

1. Investigation of bottom pressure fluctuations and surface waves.

II. Results of sea surface roughness determinations at Woods Hole and Bermuda. Comparison of pressure records with sea surface (height record photographically against anchored buoy). Periodograms given for sea surface data and also harmonic analysis by arithmetic. Pressure data periodograms by a mechanical analyser. Proportionality factor deduced to give wave height from pressure at depth.

III. Statistics on monthly sea surface roughness. Observed increased wave height H with lower periods. T. Growth and decay rates almost equal.

$dH/dt = - 0.42 \; dT/dt$ for Cutty Hunk, and factor 0.255 for Bermuda. Defines operational wave height as mean of highest one-third of waves, considering this a convenient and significant measure. This is 1.57 mean wave height. Includes summaries of sea states by months giving per cent of time waves are in a given range, also less than a given range, all presented graphically.

Folsom T.R. Sub-surface Pressures due to Oscillating Waves. Trans. Amer. Geophys. Union 28: 875-881 (1947).

Experiments in tank indicate wave heights about 10% greater than by theoretical calculation from pressure measurements at tank bottom. Pressures measured by pressure pick-up unit operating with an impedance bridge and recording oscillograph. In it, a metal diaphram moves a permeable slug located on the axis of a coil, so altering the inductance of the coil. Wave heights measured by a point gauge - two electrodes immersed in the water and supplied with D.C., so that the current is proportional to the depth of immersion.

Klebba A.A. Details of Shore-based Wave Recorder and Ocean Wave Analyser N.Y. Academy of Sciences 51: 533-544 (1949). Conference on Ocean Wave Surfaces.

Displacement of bellows moves coil in a strong magnetic field. Recording fluxmeter gives displacement. Paper strip record, part black, part white by photography. Record strip is placed on rim of heavy wheel rotating with deceleration. 125 cycles/sec tuned amplifier response gives frequency analysis.

Deacon G.E.R. Waves and Swell Quar. Jour. Roy. Met. Soc. 75:227-238 (1949).

Symons Memorial Lecture outlining recent progress in study of surface waves. Refers to evidence of speed reduction when swell travels through regions of strong winds - reduction by as much as 20%, even in regions of following winds. Questioning significance of frequency analysis by Seiwell and Wadsworth is referred to. Influence of tidal streams on swell frequency observations. Correlation of microseisms and swell forerunners.

Donn W.M. Studies of Waves and Swell in the Western North Atlantic Trans. Amer. Geophys. Union 30: 507-516 (1949).

Swell off western Cape Cod falls in two groups - short 5.5 sec to 11 sec which is correlated with southerly winds - and a longer period group of more distant origin. Some general conclusions on relations between storm positions and swell are given, based principally on the Sverdrup and Munk forecasting method.

S. Ishiguro An Electrical Recorder for Sea Water Pressure. Oceanographical Magazine Vol. 1 135-141 (1949).

Pressure applied to a diaphram with stiff restoring spring. Movement makes a change in a mutual inductance which modulates r.f. oscillation. An oscillator, amplifier, a standardizing unit, pen-recorder with steady drive make up the system.

Folsom R.G. Measurement of Ocean Waves. Trans. Amer. Geophys. Union 30: 691-699 (1949).

Observations demonstrate theoretical magnitude of the pressure ratio, K is low by 10 to 20%. $K = (dP / dP_o)_z$

dP at depth z, dP_o at surface.

Shore recorders are discussed, two models (1) with bellows actuated potentiometer, (2) a thermopile type of compact and inexpensive design in which the temperature variation with the adiabatic changes inside bellows is the basic feature; (3) for use in deep water a spar buoy with a large damping disc at depth supporting a pressure recorder at an intermediate depth. An echo sounding device was also used, with the spar buoy and disc to hold absolute position. Some discussion of the virtual mass of the buoy and disc system and its motion.

Isaac J.D. and Wiegel R.L. Measurement of Wave heights by means of a float in an open pipe. Trans. Amer. Geophys. Union 30: 501-506 (1949).

Attempt to use open end pipe with float recorder to measure wave heights. The main problem was resonance which was pronounced in the range one to six seconds in the arrangement used. Shown that with the frequencies present in ocean waves, it would be difficult if not impossible to analyse waves by this method. (Magnification factors of the order of ten with arrangements described.)

Munk W.H. Surf Beats Trans. Amer. Geophys. Union 30: 849-854 (1949)

In the presence of high wind waves, regular oscillations observed on tsunami recorder of several minutes period. Data interpreted to account for the slow period due to variability in the period and height of the incoming waves. Volume of shoreward transportation by each breaking wave is proportional to the breaker height, resuling in rise during an interval of larger than average waves. The long period effect is shown to be related to an expression which the author develops and which he terms the "intergrated swell record".

Seiwell H.R. and Wadsworth G.P. New Development in Ocean Wave Research Science 109: 271-274 (1949).

A generalized harmonic analysis is applied to ocean wave observations. Wave patterns are assumed generated by systematic wind action together with random effects due to random motions of water and intermittent wind. Authors conclude (a) that the usual periodogram analyses indicating bands of periods do not necessarily possess physical significance, (b) that generalized harmonic analysis indicates a single sinusoidal wave on which is imposed an oscillatory component. This procedure is applied to a typical wave record.

Ursell F. On Application of Harmonic Analysis to Ocean Wave Research Science 111 445-446 (1950).

Refers to Seiwell and Wadsworth above. Objection to the assumption that swell component consists of just one sine wave.

Seiwell H.R. (Letter in reply to above) Science 111; 446 (1950).

Maintains general harmonic analysis provides more information. Promises an early paper in Science about this.

Munk W.H. Increase in period of Waves travelling over Large Distances Trans. Amer. Geophys. Union 28: 198-217 (1947).

Munk W.H. Note on Period Increase of Waves Bull. of Seismological Soc. of Amer. 39: 41-45 (1949). Scripps. Inst. Contribution 409 (1949).

The second paper appears to withdraw and correct conclusions of the first. Accepts the Sverdrup explanation that the observed increase applies to "significant waves" and involving selective absorption of the shorter waves.

Sverdrup H. Period Increase of Ocean Swell Trans. Amer. Geophys. Union 28: 407-417 (1947).

Attributes observed period increase with distance from disturbance to selective absorption due to air resistance which affects the shorter period components in a greater degree.

Groen P. and Dorrestein R. Ocean Swell: Its decay and period Increase Nature 165: 445-446 (1950).

Decay and period lengthening involves eddy viscosity as a factor of importance. Comments on the assumption of Sverdrup and Munk that the sheltering coefficient is the same for wind waves as for swell.

Sverdrup H.U. and Munk W.H. Wind, Sea and Swell; Theory of Relations for Forecasting U.S. Navy; Hydrographic Office (1947).

1. Summary of equations on wave velocity, energy gain and dissipation, period, particle orbits, group velocity etc.
2. Energy transfer (a) by normal pressure (b) by tangential stress. Authors maintain Jeffrey's explanation of energy transfer by normal pressure is adequate only for initial stages of growth of waves and that growth also takes place by action of tangential stress. It is then shown that waves can continue to grow after wave velocity exceeds wind velocity (in agreement with observations, authors state). The parameter β = C/U wave velocity/wind velocity, shown to be a significant factor in wave phenomena as a measure of the age of a wave. Authors conclude viscosity is a negligible factor in the dissipation of wave energy except for very small values of wave age β.
3. Significant waves defined as the average of the one-third highest. Another non-dimensional wave parameter, δ the wave steepness = H/L. Authors find that δ is usefully expressed as a function of β, the wave age. With increase of age, δ reaches a maximum of about 0.10 at β = 0.4 and then diminishes rapidly for older waves. Data from many sources fitted into an empirical curve of some consistency. Wave heights and wave velocity are expressed as non-dimensional parameters (a) gH/U^2 (b) $C/_U$ (c) fetch $gF/_U2$ and (d) wind

duration as gt/U. (a) and (b) are plotted in turn against the fetch parameter (c) and the wind duration parameter (d) using data from a variety of sources. These plots are discussed by the authors at some length.

4. Energy considerations are used to deduce a relation for the ratio of the period at the end of the decay distance D, to that at the end of the fetch. Also for the travel time in the decaying phase as a function of the period ratio etc. Decay in height is similarly expressed. The ratios T_d/T_f, H_d/H_f, t_d/T_f, are plotted against $\frac{D}{g\,T_f^2}$ where D is the distance of decay, T_d and T_f the wave periods respectively at the end of the decay distance and at the end of the fetch, H_d and H_f wave heights, and t_d travel time.
5. The Admiralty rule "waves lose roughly one-third of their height in travelling a distance in miles equal to their length in feet" is shown to be in approximate agreement with the plotting of H_d/H_f above with $\frac{D}{g\,T_f^2}$.
6. Some discussions of the problem of increasing wave period in the region of decay - see papers of Sverdrup and Munk.

<u>Ufford C.W. Internal Waves in the Ocean. Trans. Amer. Geophys. Union 28: 79-86 (1947).</u>

Observations of internal waves of period one to two hours and heights up to one hundred feet, also waves of ten minute period up to twenty feet. Data from boat travelling 13 knots with bathythermographs every four to five minutes. Assumes time from crest to crest not much different from the period.

Another set of data from a drifting ship with bathythermographs at intervals from half an hour to two minutes. This shows time variation of the depth at which the temperature is a constant value. Time between crests and amplitude were read by inspection. (Data was not analysed for period detection). Next observations reported, give rise and fall of a submarine balanced at the thermocline; period 15 min. wave heights about 12 feet. A third method involves rapid response electric thermometers at fixed depth, using a spar buoy or anchoring to bottom and with a submerged buoy. Response of three such thermometers showed waves of from 5 min. to 15 min. period.

C.W. Ufford Internal Waves measured at three Stations Trans. Amer. Geophys. Union 28: 87-95 (1950).

Bathythermographs every two minutes from stations at the bow, waist and stern of ship provided data giving regular oscillation of period 8 min. lasting fifty minutes. Phase differences noted between stations.

Other experiments with bathythermographs from three ships positioned at angles of a triangle. Again, three thermocouples placed in thermocline at points approx. 1000 ft. apart in triangle. Period of order 30 min. with thermocline moving 15 ft.

C.W. Ufford Theory of Internal Waves. Trans. Amer. Geophys. Union 28: 96-101 (1947).

Author extends theory developed by Stokes for two layers of constant density separated by a discontinuity, to the case of three linear gradients. Measured and theoretical values compared to show some agreement, (Stokes development is in Lamb pg. 370 1932 edition).

Haurwitz B. Internal Waves of tidal Character. Trans. Amer. Geophys. Union 31: 47-52 (1950).

Shows that, because of rotation of the earth, the velocities of long internal waves are greater, and the periods of long internal waves are much shorter, and in consequences much more favourable to resonance with tidal forces. (Uses Sverdrup's formula for the phase velocity c, of long waves of wave-length L in a homogeneous layer of depth H, on a disc which is rotating with an angular velocity W $c^2 = \frac{W^2 L^2}{4 \pi^2} + g H$

Ewing G.C. Relation between Band Slicks at the Surface and Internal Waves in the Sea. Science 111; 91-94 (1950).

Primary mechanism of band slicks, a film which lowers surface tension where ripples are absent. This uneven distribution attributed by author to internal waves as dominating factor for low wind velocities, and to roll wind vortices etc. in air giving wind shear. Author obtained bathythermographs in rapid succession from a moving ship and found slicks in each case corresponding to a depression of the 60°F. isotherm (approx. 15 ft. variation).

Listing of characteristics of Slicks.