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Quantifying wave exposure daily and hourly on the intertidal rocky shore of central Chile

Cuantificación diaria y horaria de la exposición al oleaje en roqueríos intermareales de Chile central

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ABSTRACT

To quantify wave exposure on the rocky shore coast of central Chile, maximum water velocity recorders (dynamometers) of three different designs were placed in the intertidal zone and observed for a two week period during february 1995. Maximum velocity is considered as a gauge of exposure. The three devices examined here are both inexpensive and simple to build. Included among the designs was a recorder developed by us to allow velocity readings in the intertidal to be taken from afar. Thus exposure can be measured as the tide rises. A thorough description of each device is included. They recorded comparable quantified measures of wave exposure at sites subjectively designated as: sheltered, semi-exposed and exposed. The maximum water velocity recorded was 8.7 m s^{-1} at the exposed site.

Key words: rocky intertidal, exposure, wave, dynamometer.

RESUMEN

Con el fin de cuantificar la exposición al oleaje en roqueríos intermareales de la costa de Chile central se utilizaron tres aparatos (dinamómetros) que miden velocidad del agua. Las observaciones se realizaron a lo largo de dos semanas durante febrero de 1995. La determinación de la velocidad máxima se considera como un indicador de la exposición del sitio. Los tres dinamómetros utilizados son de fácil construcción y de bajo costo. Entre ellos se incluye un nuevo diseño que posibilita realizar determinaciones desde la distancia, permitiendo así mediciones de velocidad del agua en el intermareal a medida que la marea sube. Se incluye una descripción completa de los tres dinamómetros. Ellos permiten determinaciones cuantitativas de exposición de oleaje comparables en los tres sitios elegidos subjetivamente como: protegido, semiprotegido y expuesto. La velocidad máxima del agua se determinó en el sitio expuesto y fue de 8,7 m s^{-1}.

Palabras clave: intermareal rocoso, exposición, oleaje, dinamómetro.

INTRODUCTION

An important factor in the population distribution of organisms within the rocky intertidal zone is the range of forces imposed by wave motion (Koehl 1984). Wave exposure is often included in a description of biological test sites. This most often consists of a qualitative description of the site, defining a site as "exposed" or "sheltered" for example, which is based upon subjective analysis or relative scouring of intertidal areas (Ballentine 1961, Doty 1971, Craik 1980) Attempts have been made to develop methods of quantifying the level of wave exposure (Jones and Demetropoulus 1968, Denny 1983, 1988, Guiñez 1996). When the level of exposure is being considered relative to the destructive effects of wave forces in the intertidal zone, a particularly useful method of doing this is by measuring maximum water velocities. Two simple and inexpensive maximum velocity recorders previously developed by Palumbi (1984) and Bell & Denny (1994) could be easily

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deployed at the rocky shore of the Estación Costera de Investigaciones Marinas (ECIM) at central Chilean. We created a third, similar design, to be easily read from afar.

The hydrodynamic forces experienced by an object in the intertidal zone are determined not just by the wave and water conditions, but also by the shape characteristics of the object itself. Given the same water conditions, different shapes will experience different drag forces, for example depending upon the shape's frontal area and the drag coefficient. Lift force is similarly a function of the particular objects area and lift coefficient. Impact forces scale as a function of area. Thus, simply measuring the force on a particular object, as is often done, does not provide a way of comparing various sites unless that same object is always used.

Measurements of maximum velocity (which in some cases can be extracted from these force measurements) do provide a comparable quantitative description of exposure irrespective of the object in question. This allows an easy comparison of experimental sites. Such measurements are doubly useful in that they can be used, with knowledge shape characteristics of any given object (such as an organism), to calculate the forces that the object would experience. It is often desirable to know the maximum force an organism might experience, and since the greatest force usually is based upon the highest water velocity, maximum velocity recorders are well suited to estimate the exposure most organisms might encounter in the intertidal zone.

The method used to measure maximum velocity is based on an approach to measuring exposure developed by Jones & Demetropoulos (1968). Their design consisted of a drag element (a drogue disk) attached to a spring scale. Water flow past the disk imparted a drag force so that was registered on the spring scale. A smaller, simpler version was developed by Palumbi (1984) utilizing a hollow hemispherical drogue and a combination of a rubber band and cable tie in place of a spring scale. This device has been used with success on the coast of Chile (Alvarado & Castilla 1996). Citing problems in the response time of the Jones & Demetropoulus (1968) design, and concerns of inaccuracy in that of Palumbi (1984), Bell & Denny (1994) created a more robust model using a practice golf ball as the drag element. They analyzed the dynamic response of the recorder. Additionally, they calibrated the recorder such that force measurements from the spring scale could be converted to water velocities.

The aims of this paper are: (a) to test three inexpensive and simple to build dynamometers in rocky intertidal central Chile shores, (b) to provide the constants allowing the transformation of forces into water velocity, (c) to provide access to apparatus permitting marine ecologists to quantify waves impacting the rocky shore, so to quantify exposure.

MATERIALS AND METHODS

Equipment

Three maximum velocity recorders were studied. The first is the meter designed by Palumbi (1984), the second, the Bell & Denny (1994) model and the third, a new design developed to be easily read from afar, referred to here as the ECIM design (Fig. 1).

In the Palumbi design, a elastic band is attached to the ribbon of a cable tie on one end and the sliding head at the other. Also attached to the sliding head is a fishing line of approximately 5 cm in length that is connected to the drogue. For this, half of a plastic fishing float, of diameter 3.75 cm was used. The fishing line was attached to the center of the outside of the hemisphere. The end of the elastic band joined to the cable tie ribbon, along with the ribbon, were connected to a metal ring that could be mounted on a rock in the intertidal. When water motion pulls on the hemisphere, the

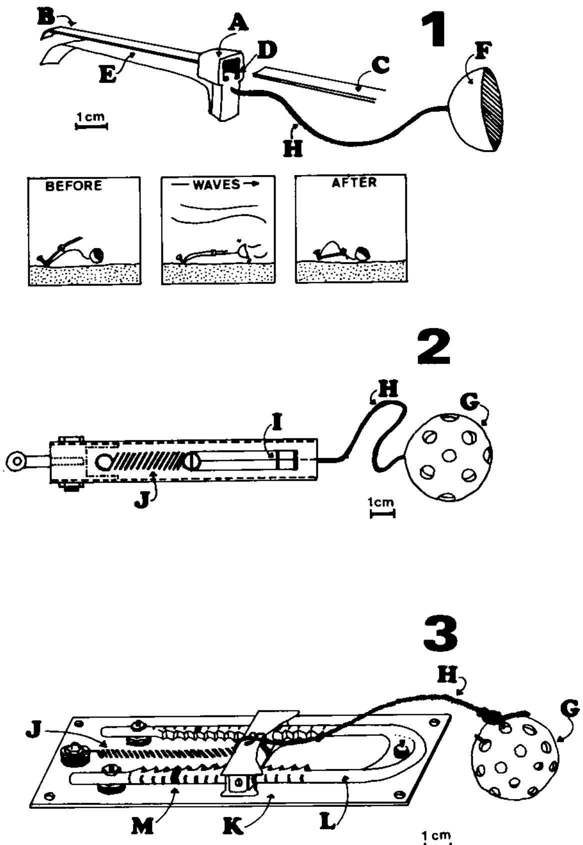

Fig. 1: Schematics of the maximum force dynamometers used: (1)- Palumbi (1984); (2)- Bell & Denny (1994); (3)- ECIM (this paper). (A) sliding head; (B) uncut end of cable tie; (C) cut end of cable tide; (D) restrain tab on sliding head; (E) elastic; (F) hollow hemispheric plastic wave drogue; (G) practice golf ball; (H) monofilament line; (I) rubber indicator; (J) spring; (K) aluminum base; (L) Gerber child-proof cabinet lock; (M) color marks.

Diseños esquemáticos de los dinamómetros usados: 1.- Palumbi (1984); 2.-Bell & Denny (1994); 3.-ECIM (este trabajo). (A) cabeza deslizante; (B) sección final, no cortada, de aprisionador de cables eléctricos; (C) sección final cortada del aprisionador; (D) lengüeta de retención en la cabeza deslizante del aprisionador; (E) elástico; (F) semiesfera hueca de pelota plástica; (G) pelota de golf usada para prácticas; (H) monofilamento plástico; (I) indicador deslizante de goma; (J) resorte; (K) base de alumminio; (L) candado plástico para gabinetes -productos para niños, Gerber- ; (M) marcas de colores.

elastic band is extended, pulling along the head of the cable tie. After the wave has passed, the head remains in place, though the elastic band contracts (the ribbon of the cable tie bends). The maximum force experienced by the hemisphere is recorded by the maximum distance along which the cable tie head has slid. To measure this force, a standard spring scale dynamometer can be used to pull the elastic to the extension to where it matches the position of the cable tie head, and this force recorded. The device can then be reset for another measurement period. This is done by pushing the sliding head back to the end of the non-tensioned spring. A small adjustment to the cable tie head may be necessary to allow this. The cable tie used was of length 10 cm; a 5 cm length of a rubber band used for model airplanes was used for the elastic band.

The second device is described by Bell & Denny (1994). The basic design is a spring attached to a drag element by a fishing line. In this case, the element is a practice golf ball. The spring is housed within a 1.25 cm diameter PVC pipe 16.5 cm in length. A bolt, to which one end of the spring is attached runs through the pipe. The other end of the pipe is plugged, but with a hole just large enough to run fishing line through. A 7.0 x 0.4 cm slot is cut in the pipe along its length toward the plugged end. The spring is attached at one end to the bolt, and at the other to the fishing line. This line runs through the pipe and out through the hole in the plug. The practice golf ball is attached to the line 20 cm from the end of the pipe. The practice golf ball is 4.20 cm in diameter, plastic and hollow, and has a number of holes around its surface. It was chosen by Bell & Denny (1994) for use as the drag element because it is light enough to respond rapidly to passing waves and has simple hydrodynamic behavior. A small square of rubber is mounted on the fishing line inside the pipe such that it can slide along the line. When a the drag on the practice golf ball extends the spring, this square is pushed back along the line by the plug, registering the maximum extension of the spring. As in the previous device, this extension can be measured by a spring scale dynamometer. To reset the maximum velocity recorder, the square is pushed up to the plug inside the housing with forceps or needle nose pliers. The maximum velocity recorder can be mounted in the intertidal rocky shore with a hook or wire through the end bolt.

Since both the devices described above require the experimenter's presence at the dynamometer to read the measurements, they are best measured at low tide, when the velocity recorders can be reached. Real time measurements, especially while the tide is rising, are impossible (or at least, not recommended). To allow for real time measurements from afar, the third ECIM device was designed. As in the Bell & Denny design, a practice golf ball (Wilson) is used as the drogue. It is connected by a fishing line to a plastic mount that is attached to a spring; this mount runs along a two toothed plastic strips. The plastic mount and teeth are taken from a child-proof cabinet lock (Gerber). The teeth allow motion in one direction, but not backward motion. As the ball is pulled and the spring extended, the mount is pulled to the extension of the spring and locked there by the teeth. The spring and plastic teeth are fixed to an aluminum plate that is marked with colored lines along the length of the teeth; thus the position (measurement) of the mount can be seen with binoculars from afar and noted.

For the Bell & Denny and the ECIM designs, springs must be chosen that will give measurable extension in the range of forces expected. Following the spring equation: Force (N) = k * x + c, where x is the extension in meters and k is the stiffness spring constant in N m^{-1}, springs with k values near 1000 N m^{-1} were selected.

Calibration

In the rocky intertidal, the predominant force experienced by the drogue is due to hydrodynamic drag. Drag force is often represented by the following standard equation:

$$F = 1/2 * rho * S * Cd * u^2$$

where, F is the drag force (in Newton), rho is the density of the fluid (in kg m^{-3}), S is the characteristic shape factor (in m^2), Cd is the drag coefficient, and u is the fluid velocity (in m s^{-1}). In the case of the hemisphere and ball, the shape factor is the cross sectional area of the object (pi * $radius^2$).

In the intertidal zone, water density can be considered constant, as can the drag coefficient within the range flow conditions experienced. Shape factor is also a constant. Thus the relationship between drag force and velocity for a given object, the following equation can be used:

$$F = a\ u^b$$

where, a and b are constants determined experimentally.

Bell & Denny (1994) calculated these constants by placing the drogue in a water channel and measuring the force experienced at various velocities. A power curve of the above form was fit to the data. We applied the same technique to the hemisphere used in the Palumbi meter, and the combination mount and ball in the ECIM meter. Tests for these devices were done in a water channel at the Escuela de Ingeniería of the Universidad Católica de Chile. The resulting constants are presented below:

	a	b
Palumbi (1984) dynamometer	0.247	2.19
Bell & Denny (1994) dynamometer	0.575	1.93
ECIM dynamometer (this paper)	0.590	2.09

With these constants and a force reading from the meter, the water velocity can easily be calculated using the formula:

$$(F/a)^{1/b}$$

with velocity (u) in m s^{-1}, and force (F) in Newton.

Experimental procedure

Three sites were selected in the rocky intertidal zone of the Estación Costera de Investigaciones Marinas (ECIM) in Las Cruces (33° 30′ S, 71° 38′W). The sites varied in qualitative measure of exposure from most exposed to relatively sheltered, and were thus designated: "exposed", "semi-exposed", and "sheltered". Four maximum velocity recorders of each design were mounted at each location. Over a two week period, in early february 1995, the maximum velocity recorders were read and reset twice daily. Additionally, the position of the ECIM meter was recorded hourly for 37 h. The hourly tides and the daily maximum tidal heights were also recorded.

RESULTS

Fig.2 shows the average daily measurements from each of the three dynamometers. In the case of the Bell and Denny dynamometer the mean maximum daily velocities correspond to the qualitative evaluations of the sites, with the exposed site recording the highest velocities, between 6.2 and 8.7 m s^{-1}, the semi-exposed site between 4.3 and 5.3 m s^{-1} and the sheltered between 3.0 and 5.2 m s^{-1}. There was a clear distinction between the exposed site and the other two. The maximum velocity recorded was 8.7 m s^{-1} at the exposed site. The average daily maximum velocities registered by each type of dynamometer fell within the standard error of the other meters for each day and location with two exceptions (Fig.2). From february 9 through 12-13, 1995 it was not possible to reach the meters in the exposed site for measuring. Thus there are no velocities shown for the Palumbi and Bell & Denny dynamometers. Nevertheless, the ECIM dynamometer was readable and velocities are noted (Fig.2). From february 4 through 8, 1995 the ECIM meters in the sheltered site did not register water flow. In these cases the water velocity was below the activation energy of this dynamometer and the events are not recorded (Fig.2).

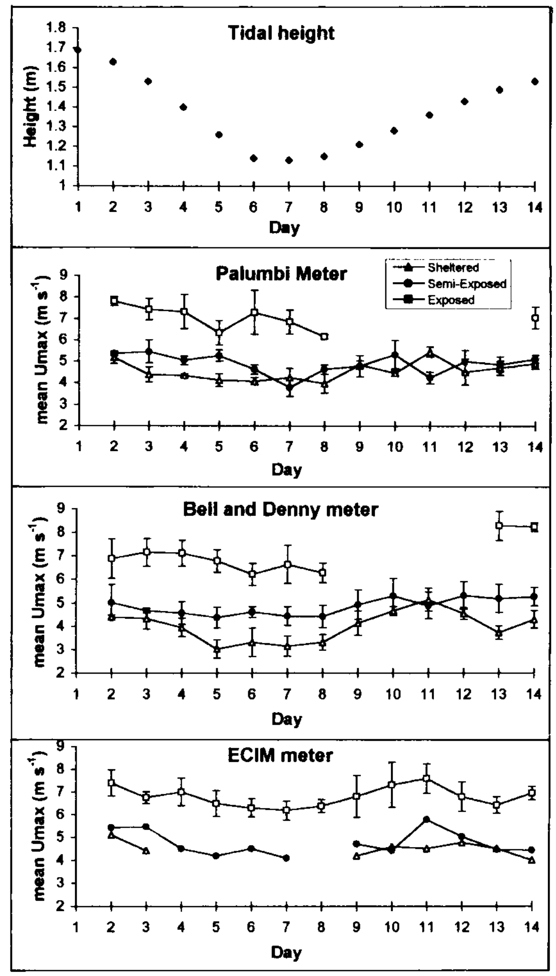

Fig. 2: Mean maximum daily velocity, february 2-14, 1995, at the three sites measured by each dynamometer, showing the daily height of the tide. Values are means (N= 4) with one standard deviation. For the Palumbi and Bell & Denny meters readings were not feasible between 8 and 13-14 february at exposed site due to sea conditions. The ECIM meter was not activated during several days at sheltered and semi-exposed sites.

Velocidades máximas promedio diarias, febrero 2-14, 1995, en los tres sitios en que se realizaron mediciones con los dinamómetros; se incluye la altura de las mareas. Los valores son medias (N= 4) con una desviación estándar. Para los dinamómetros de Palumbi y de Bell y Denny no fue factible realizar mediciones durante los días 8 al 13-14 de febrero en el sitio expuesto debido a las condiciones del mar. El dinamómetro ECIM no se activó durante varios días en los sitios protegido y semiprotegido.

The true utility of the ECIM design is in the real time measurement of maximum velocity and thus exposure. The meter proved functional at measuring exposure during a rising tide. Fig. 3 shows the readings from the ECIM meter and the height of the tide hourly during a 37 h period. After the high tide, and highest water velocities, the maximum velocity recorder must be reset to measure velocities as exposure decreases. Since this was *impossible to do safely, no* measurements were taken during the falling tide.

DISCUSSION

The maximum velocity recorders used at Las Cruces rocky intertidal are inexpensive and simple to construct. They are based upon the idea of measuring maximum drag force. The advantage of these devices is that maximum force can be converted into a velocity reading. Such values can be easily compared between sites. For instance, the Bell & Denny dynamometer maximum water velocity reported for Las Cruces exposed site of 8.7 m s^{-1}, is comparable with the readings reported by Bell & Denny (1994) at Granite Beach and West Beach, Monterey, California: 9.2 - 9.5 m s^{-1}. Additionally, above readings can be used directly in biomechanical calculations.

A few problems were encountered with the devices. Most notable is the problem of fouling or lost meters. There were 4 occurrences of failure of each type of meter. At both the semi-exposed and exposed sites, the Palumbi device failed due to breakage of the plastic drogue. The Bell & Denny meters were damaged by dislodgement at the exposed site (caused to its relatively large size moving with the water flow). The ECIM dynamometer suffered fouling of the plastic mount and loss of the drogue at the exposed site.

The Palumbi and Bell & Denny dynamometers rotate around the base of the spring, and thus can measure water velocity in all directions. A flaw in the design of the ECIM meter is that the spring and mount remain attached stationary to the rock. This restricts freedom of motion for measurement

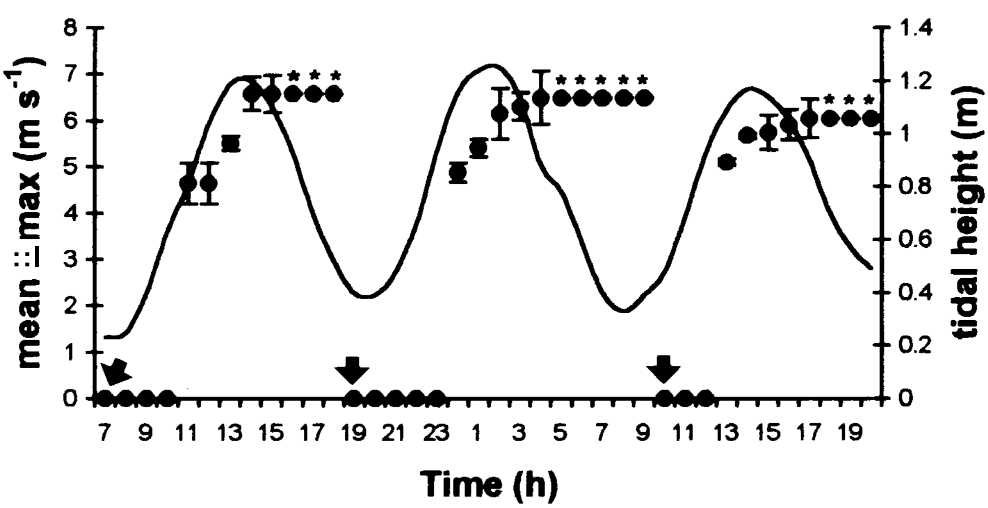

Fig. 3: The mean maximum hourly velocity, february 4-5, 1995, as recorded by the ECIM dynamometer. Values are means (N= 4) with one standard deviation. Tidal height is shown in continuous line. Arrows indicate setting of the dynamometer to initial position. Asterisks indicate maximum velocity readings.

Velocidad horaria máxima, febrero 4-5, 1995, registrada por el dinamómetro ECIM. Los valores son medias (N= 4) con una desviación estándar. La altura de la marea es indicada en línea continua. Las flechas indican el momento en que el dinamómetro fue ajustado a su posición inicial. Los asteriscos indican mediciones máximas de velocidad.

in only one direction. Thus the ECIM meter might not register the maximum flow if that flow is not in the direction it is mounted. As flow patterns in the intertidal zone are unpredictable, the ability of the Palumbi design and the Bell & Denny design to measure force in any direction is an important feature.

Both the Palumbi design and the ECIM dynamometer suffer from resolution restrictions. Resolution is limited by the separation of teeth on the cable tie in the Palumbi device, or those on the plastic bars of the ECIM device. The resolution of the Bell & Denny design is limited only by that of the dynamometer used to read the meter (the reading could alternately be taken by measuring the distance the marker is moved from the plug and applying the spring equation). A particular resolution problem is that of activation velocity. Both the Palumbi the ECIM meters required a force high enough to reach the first tooth of the cable tie or plastic strip. In the case of the ECIM meter, the velocity necessary for this was found to be 3 m s^{-1}. This proved to be a problem, as noted in the results, in the sheltered site (Fig. 2) The meter could be modified by using strips with a longer region of teeth. This could alleviate the activation velocity problem. Additionally, strips with more teeth per length would increase resolution. Furthermore, motion over the teeth in the Palumbi meter and the ECIM meter might yield a frictional loss in the device. For this reason, and its higher resolution, velocities from the Bell & Denny meter were presented above in the abstract and in the results section.

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