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A PRELIMINARY ANALYSIS OF FLAT-GRAVEL TRANSPORT OVER A SANDY BEACH, PEHUÉN CO, ARGENTINA

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Abstract: Pehuén Co Beach, on the southwest coast of the Buenos Aires Province (Argentina), provides an example of an heterogeneous (mixed sand-gravel) sediment beach with gravels of the most diverse size and origin. Over 40% of the pebbles are carbonate flat gravels. Field observations included beach profiles, measurements of wave generated currents with an acoustic currentmeter (ADV), videos of 5 x 5 m grid located on the swash zone during inundation from a nearby tower. Video films where rectified and analyzed using PIV and wavelets. Based on the results, we demonstrated that flat gravels can be easily transported upbeach distances in excess of 5 m in about 1.5 h. This period corresponds to the high tide situation and covering the steepest beachface segment. Wave conditions during the experiment corresponded to low breaker height and short periods, but by no means they could be considered as storm waves demonstrating that gravels can be transported even by saltation during fair weather conditions.

Resumen: La playa de Pehuén Co, localizada en la costa sudoeste de la provincia de Buenos Aires (Argentina), es un ejemplo de playa con sedimentos heterogéneos (mezcla de arena y grava) con gravas de diversos tamaños y orígenes. Más del 40% de los clastos son gravas planas carbonáticas. Se efectuaron estudios en un sector de la playa que incluyeron perfiles, mediciones de corrientes generadas por olas con un correntómetro acústico (ADV) y videos de una grilla de 5 x 5 m en la zona de lavado durante el período de inundación desde una torre cercana. Los videos fueron rectificados y analizados usando PIV y wavelets. Basados en los resultados, se puede demostrar que las gravas planas puede ser transportadas fácilmente hacia la parte alta de la playa distancias mayores de 5 m en 1,5 hs. Este período corresponde a la condición de pleamar cuando el segmento más empinado de la playa frontal queda cubierto. Las condiciones de olas durante el experimento eran de rompientes bajas y períodos cortos, pero en ningún caso se pueden considerar como olas de tormenta, lo cual demuestra que estas gravas pueden ser transportadas, aún por saltación, durante condiciones de buen tiempo.

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Palabras Clave: playas heterogéneas, transporte de gravas, lavado ascendente, Pehuén Co, Argentina.

INTRODUCTION

Most beaches in the world are composed by sand of various sizes and composition. There are also beaches composed by pebbles (i.e., Patagonian beaches, southern coast of Portugal), carbonates (i.e., Bahamas) or shell fragments. However, there is increasing awareness that beach sediments are non-uniform in size and, in many cases, they are highly bimodal in composition (Komar, 1998; Short, 1999; Mason and Coates, 2001), meaning that there is a mixture of sand and gravel/shells or sand and mud. For instance, the beaches along the coast of Patagonia (Argentina) have rounded pebbles (derived from the Tehuelche Gravels Fm) at both extremes of the tidal cycle, whereas in between there is a mixture of fine sand and even silt (Perillo and Codignotto, 1989; Perillo, 2003). The difference is due to the longer winnowing produced by the waves on high and low tide stages which removes the finer material being later deposited in the terrace in between or exported offshore. These Patagonian beaches are considered as composite beaches following Karunarathna *et al.* (2012).

Pebble transport on beaches has been largely studied along the coasts of Great Britain where this type of material is dominant (i.e., Jennings and Shulmeister, 2002; Kulkarni *et al.,* 2004; Pontee *et al.,* 2004), in New Zealand (i.e., Matthews, 1980) or in Japan (i.e., Hattori and Suzuki, 1978). Austin and Masselink (2006); Buscombe and Masselink (2006) and Pedrozo-Acuña *et al.* (2006, 2007, 2008, 2010) presented significant advances in the dynamics of gravels, mostly on gravel beaches, including some analytical and numerical modeling of gravel transport.

In Argentina, Isla (1993) and Isla and Bujalesky (1993) have described the transport of pebbles on the Tierra del Fuego coast, especially along the Páramo Spit. A similar spit closes Caleta Valdés along the eastern border of the homonym peninsula. Both are excellent examples of southward littoral drift induced by swells mostly acting on rounded pebbles on a pebble-dominated beach.

Mixed beaches can be classified according to Ivamy and Kench (2006) into three distinct morpho-sedimentary types based on the relative abundance of sand and gravel and their spatial distribution within a beach: a) pure gravel; b) mixed sand and gravel beaches in which sand and gravel-size sediment is fully mixed across the beach system and c) composite beaches where gravel comprises the steeper upper beach and sand-size material comprises a lower gradient intertidal platform at the base of the beach (Kirk, 1980; Jennings and Shulmeister, 2002). However, we could add a fourth type: d) sand-dominated mixed beaches, where most of the beach is sandy but they have significant amount of gravels distributed along the whole beach profile.

Therefore, the concept of mixed beaches (sand and gravel mixture) is still today unclear as to what proportion of one or the other material defines the limit between pure sandy or pure gravel beach as all beaches have a proportion of both type of sediments in their composition (Mason and Coates, 2001). There is relatively little research for type d) beaches where sand is the dominant fraction but gravels appear on the beach frequently, sometimes covering large portions of the swash zone and concentrates on different segments but their location and concentrations vary significantly from one tide to the next.

Knowledge of the distribution of sediment sizes is important to establish the dynamic processes and the geomorphologic changes that occur on the beach. Processes like swash-backswash along the beach face produce substantial transport mostly related to fine sand both as bedload and suspended load. Winnowing of the finer material induces an offshore sediment flux that appears as small rip currents just at the water-beach boundary resulting in a continuous sediment sorting. This situation is enhanced when the backwash becomes supercritical, which can be manifested by the formation of antidunes and higher sediment transport as bedload and suspended load (Perillo, 2003). These processes are very common in all sandy beaches, but there are few studies of gravel transport over a sandy beach surface due to the swash-backwash process.

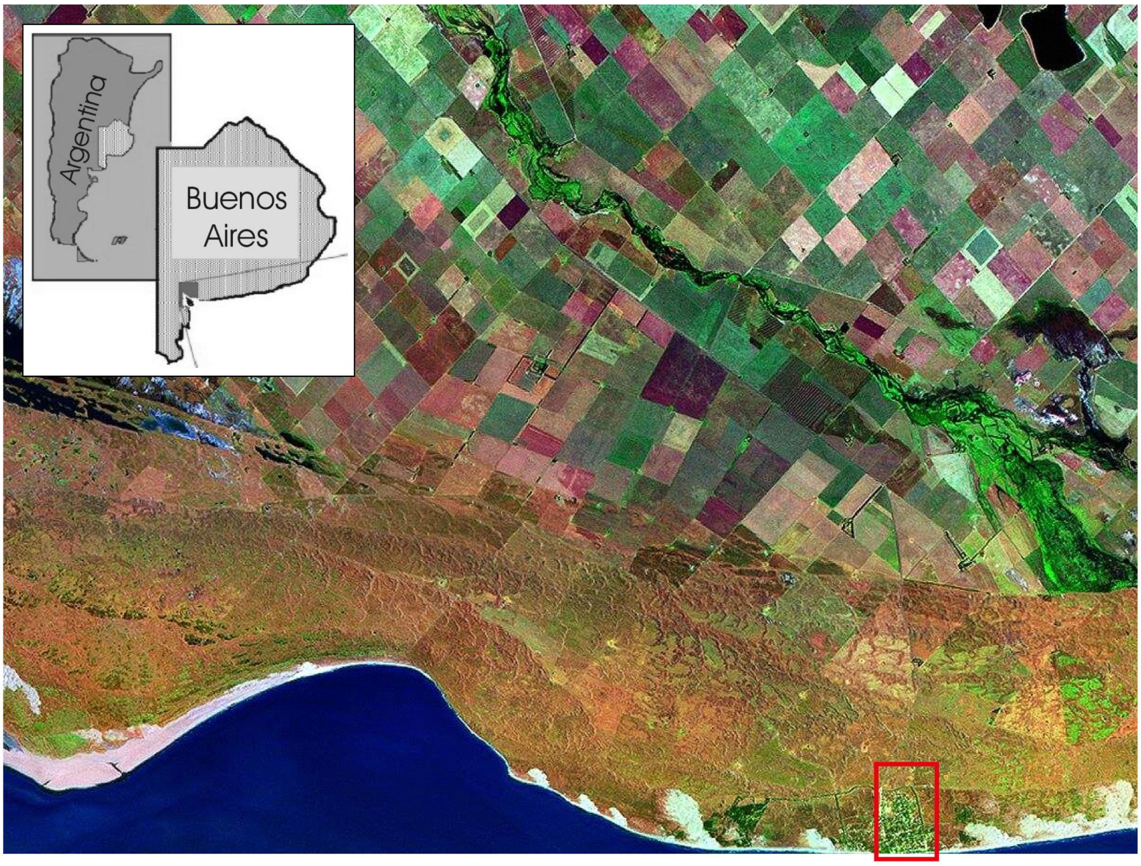

Figure 1. Location of Pehuén Co Beach and the study site.

Butt *et al.* (2004) indicate that in the swash zone the water may be shallow enough for bore turbulence to act over the bed. Furthermore, they also indicate that there are laboratory evidences that suggest that the uprush may be dominated by bore turbulence. Such turbulence could be large enough to move gravels even with small waves.

There have been some old studies by Landon (1930) and Bluck (1967) describing the differential transport between oblate (planar) and nearly spherical, rounded gravels, but all of them consider gravel transport on a gravel beach. Although rounded pebbles seem to form the larger population of gravel sized material on beaches, flat gravels are also common features in many beaches worldwide (Komar, 1998). But descriptions of their transport mechanism on beaches are still lacking in the literature. Nevertheless, Nott (1997, 2003) described the movement of large boulders due to storm wave activity along the Australian coast, which has been recently corroborated by de Lange *et al.* (2006) for an island in New Zealand.

The main aim of the present article is to describe the dynamics of the swash zone integrated with the transport of one of the gravel types found in Pehuén Co Beach, namely the flat gravels which are by large, the most important gravel population along the beach under study. Furthermore, our field measurements, were designed under the assumption that regular, low energy waves can easily transport the gravels up the beach contrary to the common knowledge that only storm-type energy are required to make such transport and to concentrate them on the backshore (Wang, 1998; Komar, 1998).

STUDY AREA

Pehuén Co Beach, on the southwest coast of the Buenos Aires Province (Argentina, Fig. 1) provides a good example of an heterogeneous (mixed sand-gravel, *sensu* Jennings and Shulmeister, 2002) beach where the coarser fraction can be found at any place on the profile over the sandy substrate (Fig. 2). Another peculiar characteristic is that most of the gravels are broken pieces of $CaCO_3$ from the cemented bottom of a former lagoon (Fig. 2a, d) and pieces of cemented tubes of the shrimp *Callianassa* (Mouzo *et al*., 1989; Vega *et al.*, 1989 (Fig. 2c). These

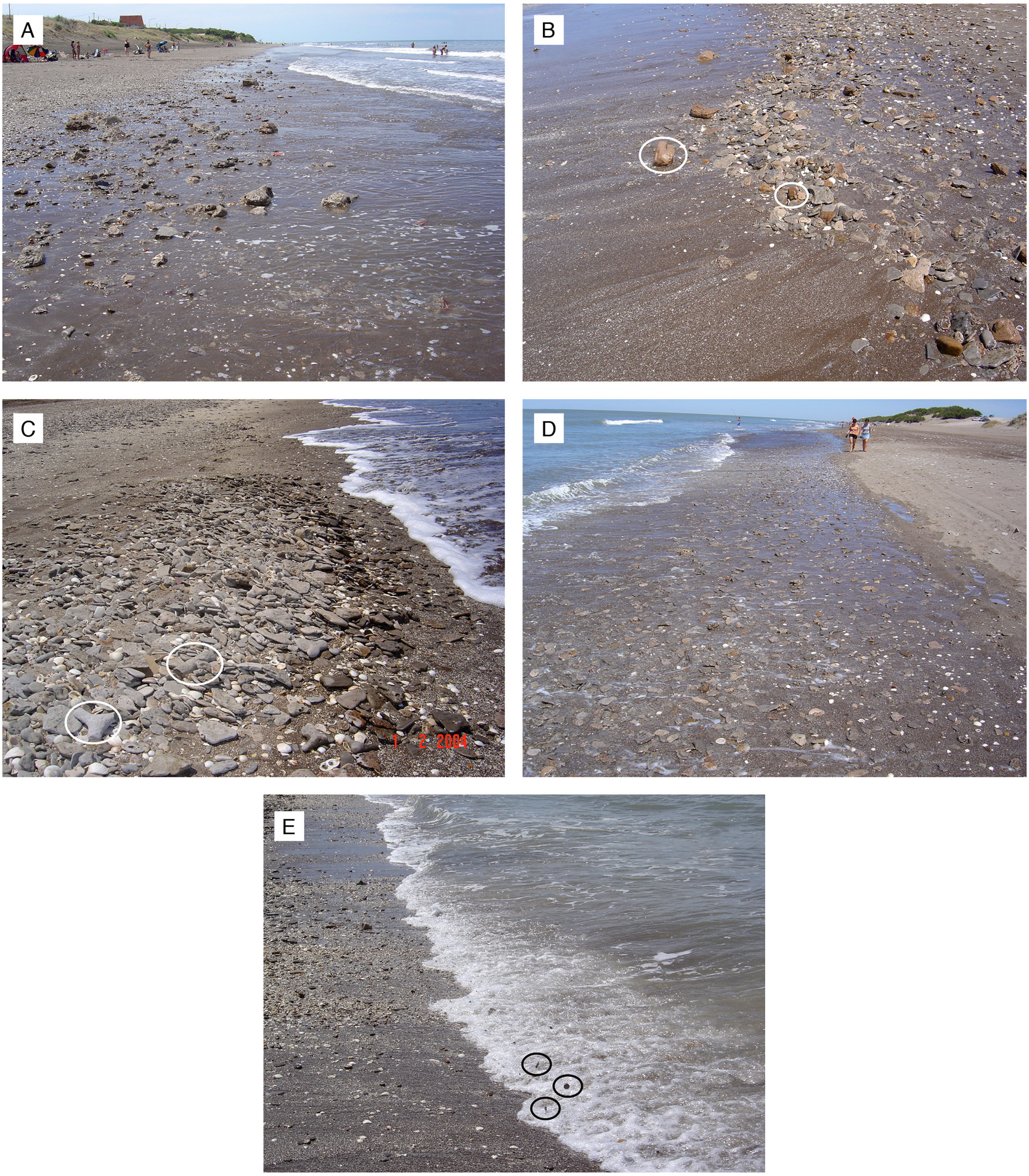

Figure 2. Examples of the types of gravels commonly found along the beach surface at Pehuén Co. a) The beach is commonly covered by all types of gravels including some construction bricks. b) Some gravels also correspond to mudrocks (upper circle) derived from an Holocene former freshwater lagoon that outcrops at the backshore and quartzite rounded pebbles (lower circle) of fluvial origin. c) Typical accumulation of the flat $CaCO_3$ pebbles analyzed in the present study combined with rounded *Callianassa sp.* tubes (circles). d) View of the swash area of the beach at low tide with the typical distribution of gravels. e) One of the most common ways in which flat gravels are transported is by saltation during the uprush, the photo (circles) show an example of various gravels being displaced in this way.

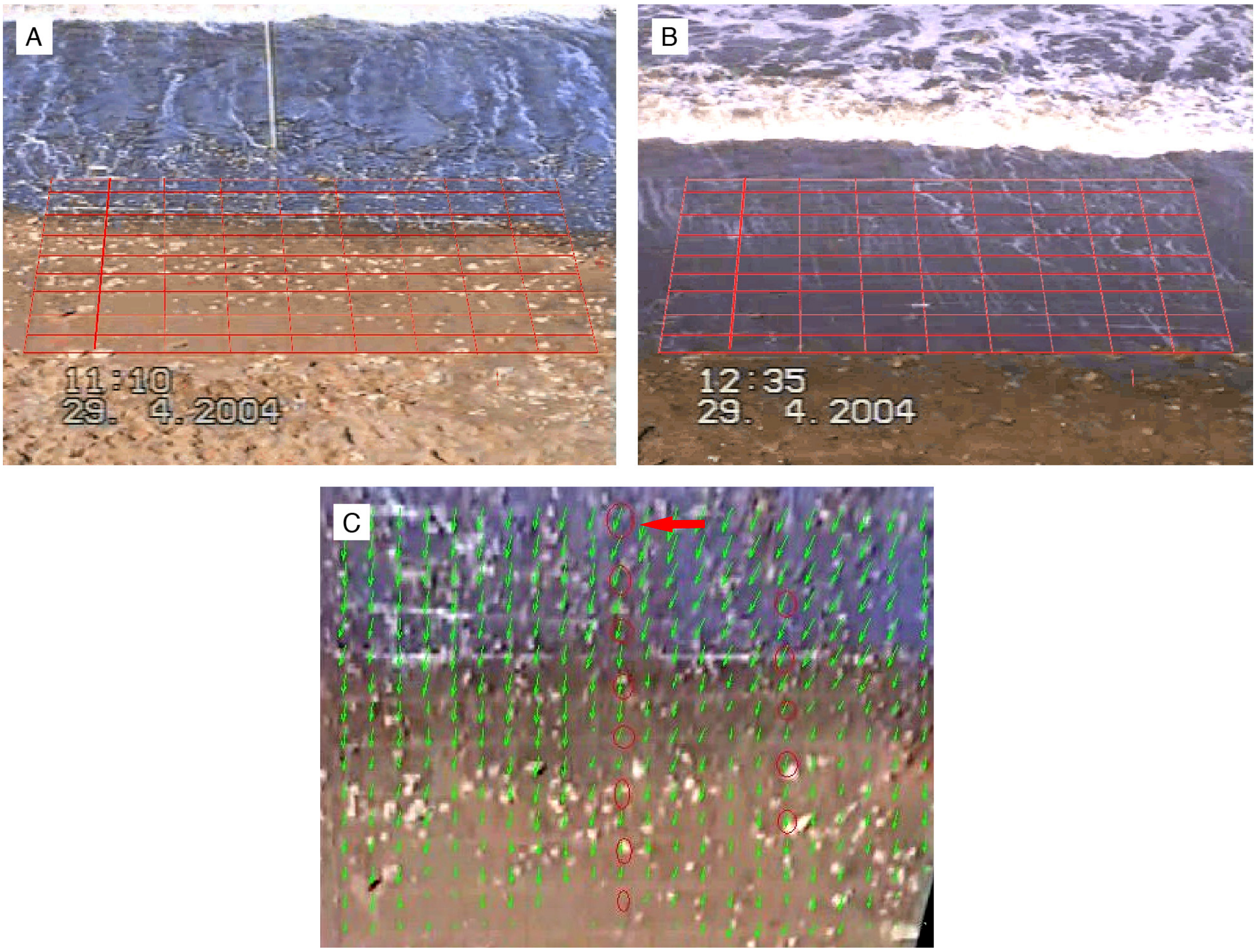

Figure 3. Control grid (5 x 5 m) considered in the present study. a) Situation previous to the initiation of the experiment on April 23, 2004. b) Situation after the experiment on the same day. Note that all gravels have been transported outside of the grid and the beach has only a sandy surface. c) Example of the vectors estimated using the PIV method. Although marked in the figure, those vectors outside the water boundary where not taken into consideration in the analysis. The circles indicate the grid points used in the analysis of velocities and accelerations. The arrow points to the grid point that had the longest water coverage which is presented in figure 8.

gravels are embedded on a former offshore beach or shoreface sedimentary rock of Early-Mid Pleistocene age (Vega *et al*., 1989) (Fig. 3). Also, there are boulders of silt that are derived from the outcrop of a former freshwater lagoon which contains an unique ichnite field of *Megatherium*, *Macrauchuenia, as well as* deers and birds from the early Holocene (Fig. 2b). Other gravel types commonly observed along Pehuén Co Beach correspond to well-rounded quartzitic pebbles (Fig. 2b) from the Ventania Range located some 120 km northward that were transported by the Sauce Grande River when it flowed into this coast.

Although the outcrops of the shoreface sediments tend to be at the lower end of the beach face, most of the times at the channel landward of the swash bar, they appear due to various erosive/accumulation processes. Their distribution ranges from periods in which they are completely covered by sand to others in which large segments of the beach are completely depleted of sand and the rock is exposed. Within these outcrops, the *Callianassa* tubes form a network indicating the importance of this fauna during the Pleistocene, but it has not been found at the present time even though they have been described for the southern coast of Brazil (Cervellini, pers. com).

For the casual observer walking the Pehuén Co Beach at high tide, it is possible to identify the places where the outcrops exist because there is a direct correlation between the number and density of gravels and the presence of the outcrops as well

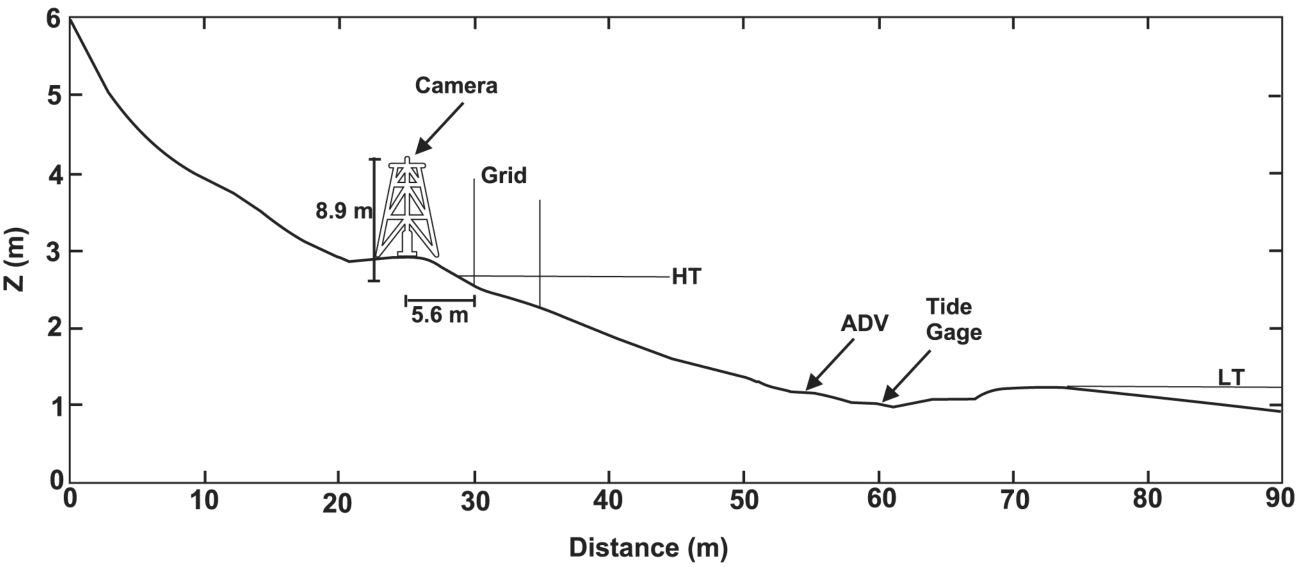

Figure 4. Beach profile measured during the second day of the experiment and relative position of the grid, observation tower and instrumentation.

as a steeper beachface. Usually, where there are no outcrops, the beach face slope is on the order of 1º and only a few gravels can be found. Also there is, although much lower, a correlation between the presence of beach cusps and these steeper slopes and outcrops. When beach cusps are present, they tend to concentrate gravels and bivalve shells at the horns in such quantities (Fig. 2c) that walking barefoot over them is almost impossible. These gravels and shells are transported from the cusp bays towards the horns at the initiation of the cusp development, but then wave winnowing takes precedence and wash out the sand matrix from the horns leaving a very coarse sediment layer that sometimes reaches up to 15 cm high in relation with their cusp bay. Although cusps can also be developed at less steep beach faces, in these cases, they have very little or no concentration of gravels and shells at the horns.

METHODS

A small sector of Pehuén Co Beach was selected as a test study site (Fig. 1). Tidal range is mesotidal mixed semidiurnal with maximum spring tides of 3.59 m and medium range of 2.48 m. Field data was collected during the rising diurnal tides for the period 22-23 March 2004. A square grid, 5 m on the side was marked with 1 mm in diameter, 0.5 m long iron stakes (Fig. 3) on the extreme points of the grid. The grid was located on the mid foreshore having the upper position at about 0.50 m below the maximum estimated uprush for the predicted tide. A Super VHS Camera was positioned at a tower located at a height of 8.9 m and at a distance of 5.6 m from the landward side of the grid (Fig. 4). Every care was taken to set up the grid without perturbing the beach and the gravels within and offshore of it (Fig. 3).

A total of 100 gravels (Fig. 5) with nominal diameters larger than 100 mm where spray painted on site with fluorescent aerosol paint for easier identification in the video. They were located within the offshore boundary of the grid and within 1 m seaward of the grid. Gravels located inside the grid in other positions were not painted to avoid perturbation of the beach sediment.

Tidal data were collected using a pressure transducer on the low tide terrace 0.1 m above the bed. Data were recorded during all the period the equipment was cover by the water at 1 min interval. Simultaneously an Acoustic Doppler Velocimeter (ADV) Sontek was placed near the pressure transducer for estimation of current and wave data. This system measured the three components of the velocity at a frequency of 10 Hz during the whole inundation period at a distance from the beach surface of 3.5 cm. The ADV lacks a pressure sensor; therefore, it was not possible to measure waves directly. Location of the sensors in relation to the grid is given in figure 4. Wind and other meteorological variables were gathered from a Estación de Monitoreo Ambiental Costero (EMAC) which has been designed and built at IADO located 2 km to the west of the study site on

Figure 5. Examples of gravels collected as they were transported outside of the control grid. Most of them have irregular shapes with various degrees of reworking.

top of the foredune. Beach profiles were made before each day experiment at a position 10 m to the east of the grid under the assumption that the beach did not change significantly in this distance. Profiles were made employing a modified Emery Method (Gelós *et al.*, 1998). This position was selected to avoid perturbing the grid area and to insure the normal transport of the gravels. The relative positions of the instruments in relation to the beach profiles are indicated in figure 4.

As the run up reached the first gravels at the seaward portion of the grid, the camera started recording (Fig. 3a) and ending as the backwash did not longer act over the grid area (Fig. 3b). The experiment lasted about 1.5 h and, in both days, all gravels in the camera view were transported and the beach face ended up without any gravel on sight at the surface. During the experiment gravel movement were visually monitored and they were picked up when the swash transported them out of the grid for later analysis at the laboratory. The cell through which the gravel left the grid was recorded.

The video was processed in the office for both definition of the gravel transport and path and, also to estimate the velocity field of the swash. The former was made by identification of the gravels frame by frame when they were not covered by water and digitizing their position in the grid. The operation of gravel tracking is very difficult due to several factors, namely: a) change in gravel aspect, b) partial burial by sand, c) partial burial by other gravels and d) exportation of the gravel outside the frame area. All these mechanisms seriously affected the estimation of gravel path and transport of many of the clasts and only a reduced number of them were possible to actually track part of the way. For future experiments, we have developed a system that allows to follow individual pebbles even underwater

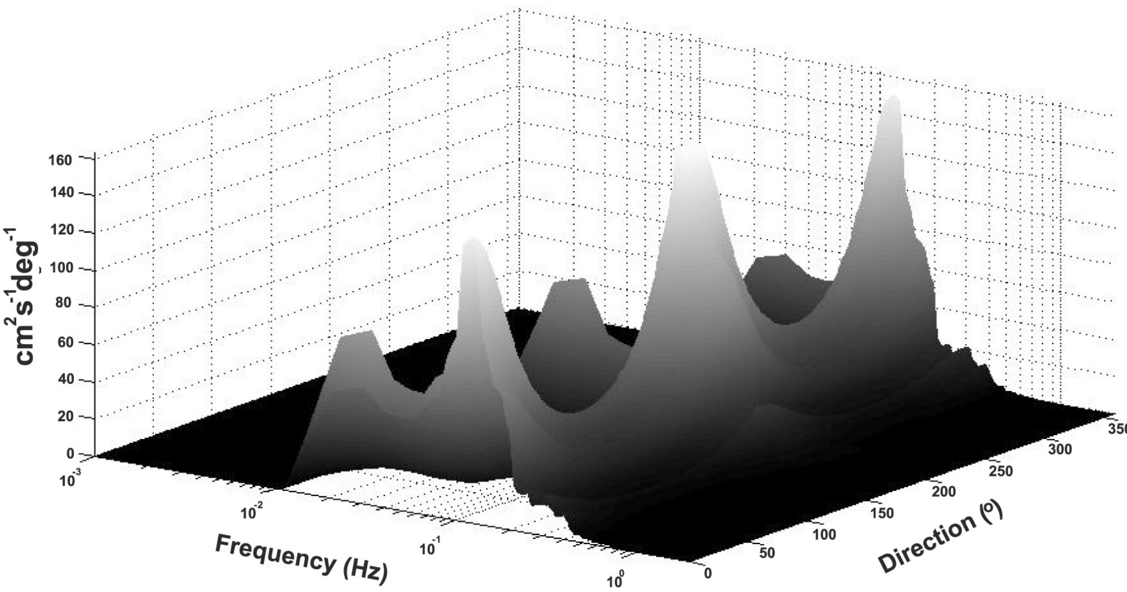

Figure 6. Directional spectrum for the ADV output. Principal direction of the wave was 189° measured from the north. Three peaks were detected at 8.3, 20.4 and 2.3 s period.

by using 25 cm long rubber coated springs attached to both flat sides of the pebble with a small red or blue flag at the end. We can then set up about 5 or 10 of the local obtained pebbles and their path can be followed during the actual transport and also observe how they are transported.

On the other hand, the estimation of swash velocity and direction was made with a Particle Image Velocimeter (PIV) technique employing a Matlab toolbox MatPIV V1.6.1. MatPIV developed by Prof. Johan Kristian Sveen (Dep. of Mathematics, Mechanical Division, Oslo University, Norway: http://www.math.uio.no/~jks/matpiv/) which is freely available and partly modified by the authors. The software works under the premise of recognizing similar patterns from two successive images. A grid is developed over the first image and the best correlation between grid points are estimated from the second image. A movement vector is calculated at the center of the grid cell which, in this case, are square with 0.25 m on the side. The vector direction is defined by the change in position of the water parcel being tracked and the module is the ratio of the distance and the time interval between successive images. Due to the slope of the foreshore and the height and angle of the camera, every frame employed in the calculation had to be corrected to avoid errors in the estimation of vector module and direction. Failure to make this correction produces large errors which are more pronounced (up to 30°) in the vector direction. We also made corrections for the vibration of the camera due to the wind which is a major source of error in vector estimation using PIV. However, parts of the video could not be corrected with enough precision and were not employed in the analysis.

RESULTS

The southwestern coast of Buenos Aires Province from Bahía Blanca to Necochea is a 300 km stretch of intermediate/dissipative beaches with general W-E trend. Pehuén Co Beach is located at a small point which tip coincides with the downtown area (Fig. 1). The study site was located as the point is turning into an ENE-WSW direction. The beaches at the study area are intermediate (Bustos, 2012) (Fig. 2a, d) with a very low total gradient and the formation of at least two offshore bars and one swash bar. They are backed by a vegetated foredune and the backshore was defined at the time of the study by a berm which is not a permanent feature in the beach. The average slope of the beach at the grid was 3.4°. During the experiment, we observed an outcrop of the former beach sedimentary rocks between the beach face and the swash bar.

During both days of the study period wind conditions varied between 2 and 10 m s^{-1} from the SW. Therefore, most of the waves reaching the area were locally generated with heights that ranged from

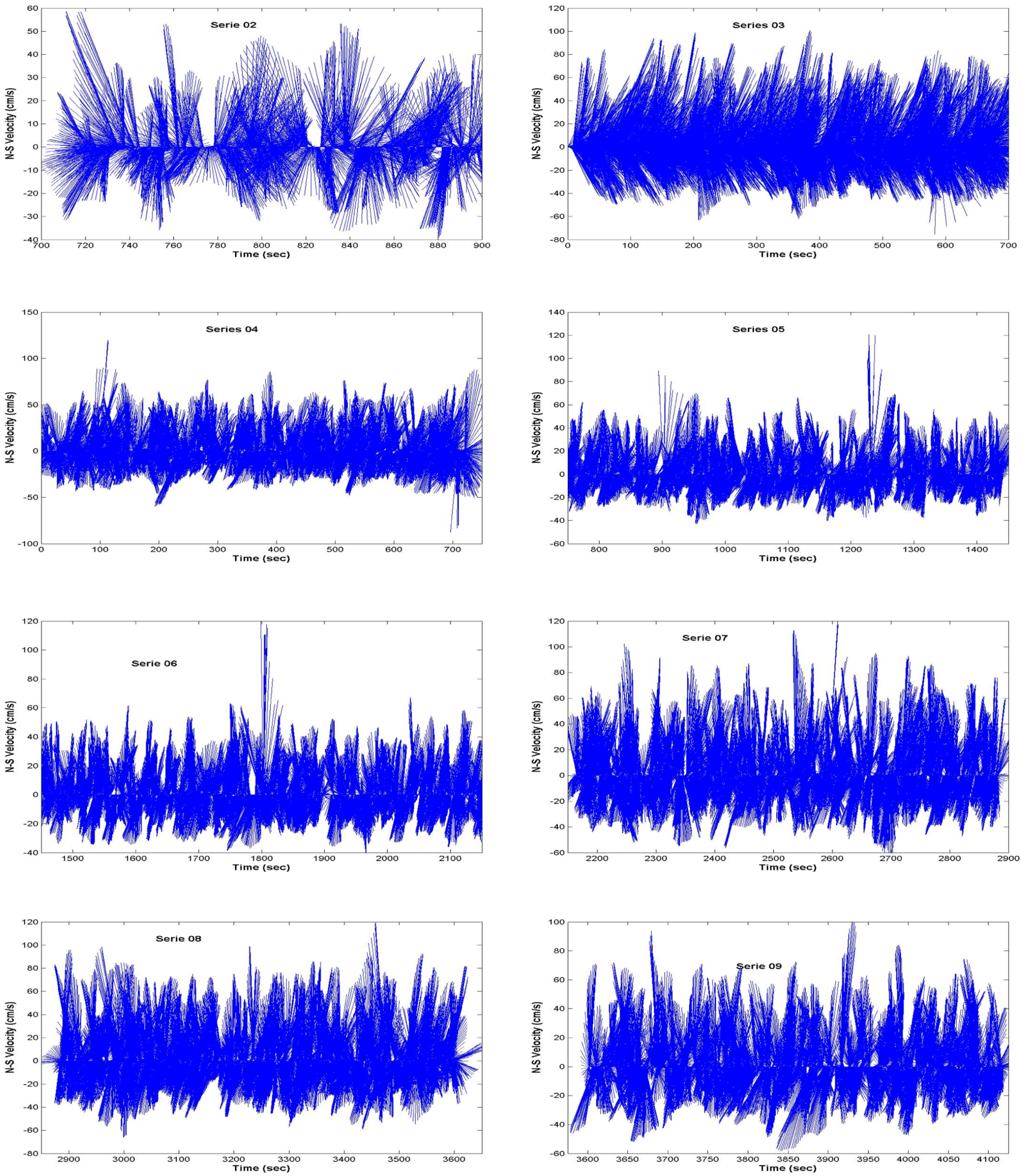

Figure 7. Vector plots for the eight runs determined with the ADV coincident with the period of grid inundation. The series show the time variation of the flows intensity and directions. Peak velocities reached up to 120 cm s^{-1} for the swash and 75 cm s^{-1} for the backswash.

10 to 45 cm and periods between 2 and 5 s as visually observed. None of the available sensors were able to measure wave height. Most of the data that will be presented hereafter were obtained during the second day of observations due to the fact that on the first day runup did not cover completely the grid and, even though we observed gravel transport, gravels were not moved fully out of the grid.

time (sec)	module (swash) (cm s^{-1})	direction (swash) (º)	module (back) (cm s^{-1})	direction (back) (º)
0 - 200	31.92	60.55	27.48	116.98
0 - 700	29.95	57.85	23.68	120.73
0 - 750	28.33	51.65	23.01	129.46
750 - 1450	29.01	55.874	21.19	132.36
1450 - 2150	25.12	43.52	19.21	141.61
2150 - 2900	30.49	46.76	19.07	143.35
2900 - 3650	29.17	37.36	22.31	127.52
3650 - 4150	26.05	40.62	18.94	146.81

Table 1. Resultant mean velocity vectors for the swash and backswash from selected ADV data series during the period in which the grid was covered. Initial time corresponds to the first swash acting on the grid at 10:57 a.m.

Directional spectrum (Fig. 6), using the u and v components of the flow measured with the ADV for the second day, shows pairs of peaks from the S and N which correspond to the positive and negative orbital components. Three "double" peaks are visible at 20.5, 8.3 and 2.7 s period. Practically the same is obtained with the unidirectional spectra (not shown) for u and w for all the series measured, with the difference that an extra peak of 10.2 s appears, which is supposed to be an interaction or reflection

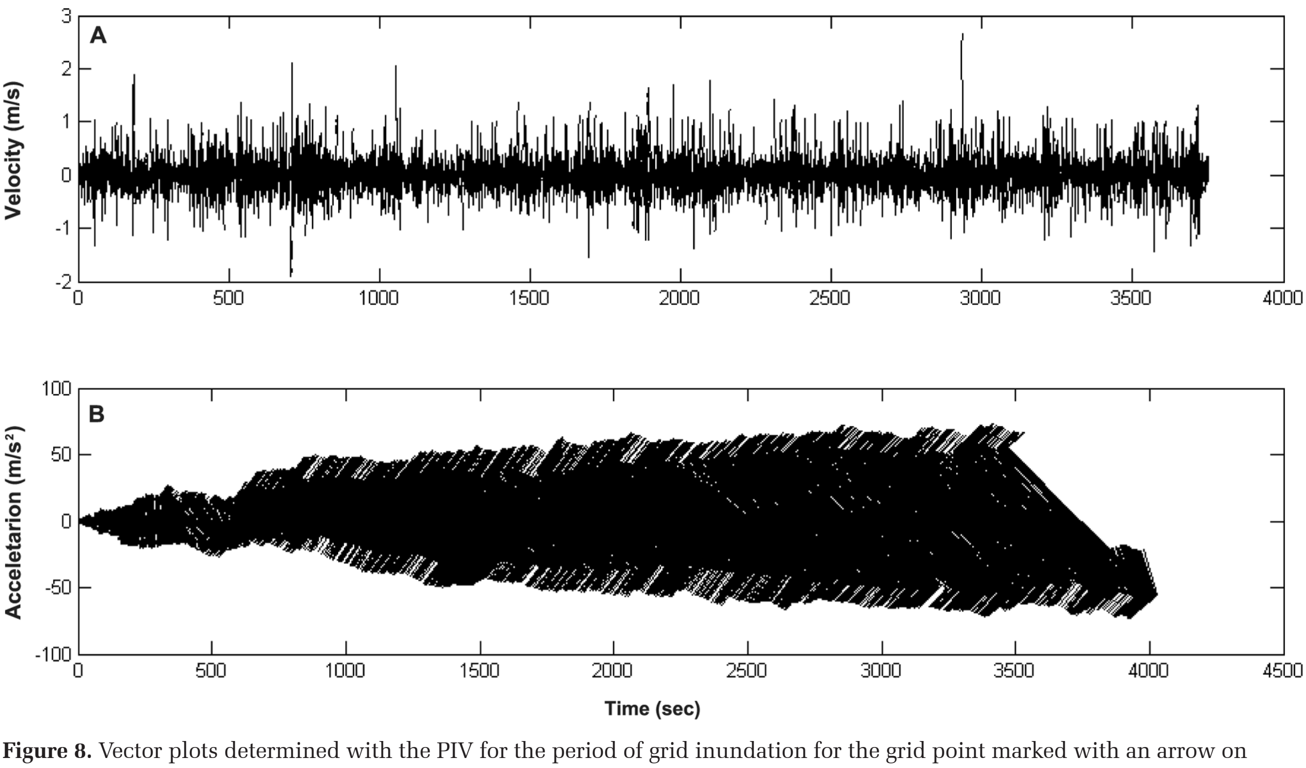

Figure 8. Vector plots determined with the PIV for the period of grid inundation for the grid point marked with an arrow on figure 3c. The series show the time variation of the flow intensity and direction (a) and the flow acceleration (b). Note the marked increase in speed towards the end of the period. Peak velocities reached up to 0.75 m s^{-1} for the swash and 0.55 m s^{-1} for the backswash. Maximum accelerations reached were 3.78 and 3.76 m s^{-2} for the uprush and backwash, respectively.

time (s)	module (swash) (cm s^{-1})	direction (swash) (º)	module (back) (cm s^{-1})	direction (back) (º)
0 - 120	22.67	69.51	29.55	113.39
1140 - 1250	22.00	71.88	24.91	113.34
1740 - 1850	22.67	70.03	26.294	111.63
2220 - 2310	39.64	77.66	45.85	106.29
2580 - 2700	42.33	77.71	39.97	105.61
3050 - 3200	42.59	77.37	45.07	103.33

Table 2. Resultant mean velocity vectors for the swash and backswash from selected PIV data series during the period in which the grid was covered. Initial time corresponds to the first swash acting on the grid at 11:05 a.m.

with the beach. Visual observations indicated that the larger waves were those related to the shortest period with heights of the order of 30 cm or less. The energy of the longer waves was negligible and did not play a major role in the transport of the gravels. Considering the peak in the spectrum for the period of 2.7 s which is 155 cm^2 s^{-2} deg^{-1} and a depth of 1 m at the sensors, the wave height estimated is 25 cm.

Current vectors produced by the swash-backwash at the ADV position (20 m offshore of the grid) where plotted for the period in which it acted on the grid (Fig. 7). Although the ADV did not measure directly the current behavior at the grid, magnitude and direction of the currents were likely to be on the same order of magnitude and they could be considered adequate to describe the flow field at the grid. During most of the time landward flow was directed to the N and NE. Resultant vectors were directed to the NE with average magnitudes between 25 and 35 cm s^{-1} (Table 1). The increase in values corresponded to an increase in wave height as a result of SW winds blew stronger. Similar increase occurred for the backwash where the velocities where systematically larger than the uprush. Wind effect is also appreciated as

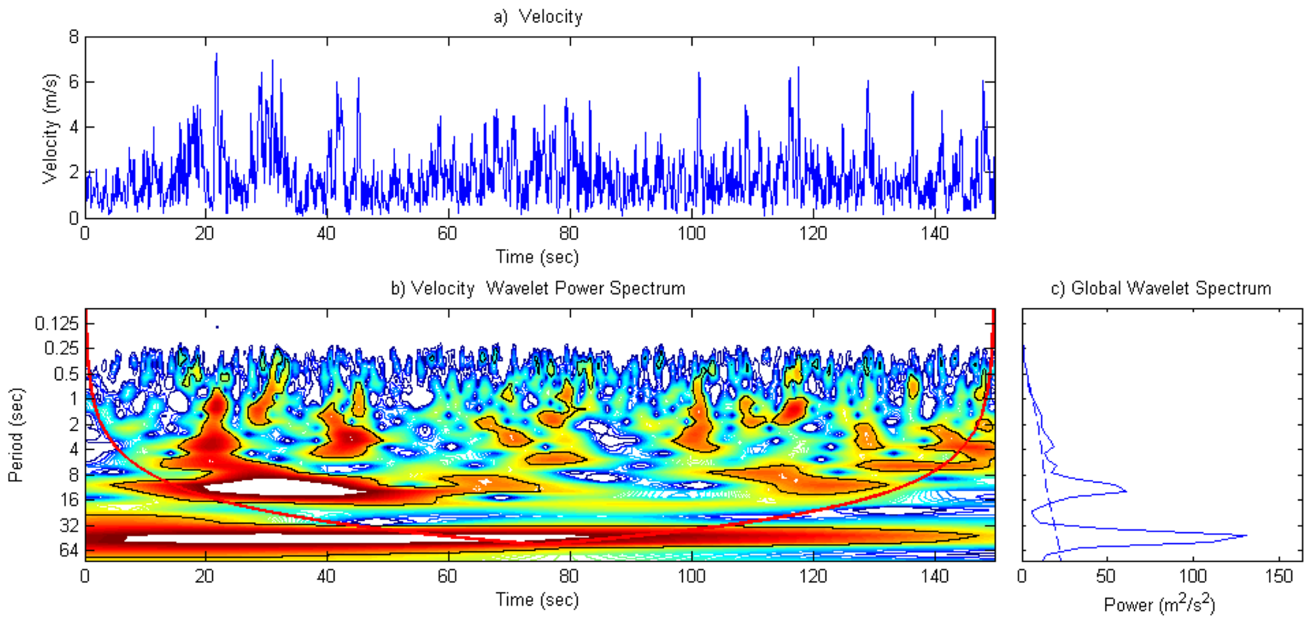

Figure 9. Wavelet analysis of the PIV time series (a) recorded the grid point marked with an arrow on figure 3c. The red curve in (b) indicates the 95% confidence interval. Values below the curve are not statistically significant and are not considered in the analysis. c) Global wavelet spectrum showing the most important peak at 8 s. The peak at 32 s is below the 95% confidence level.

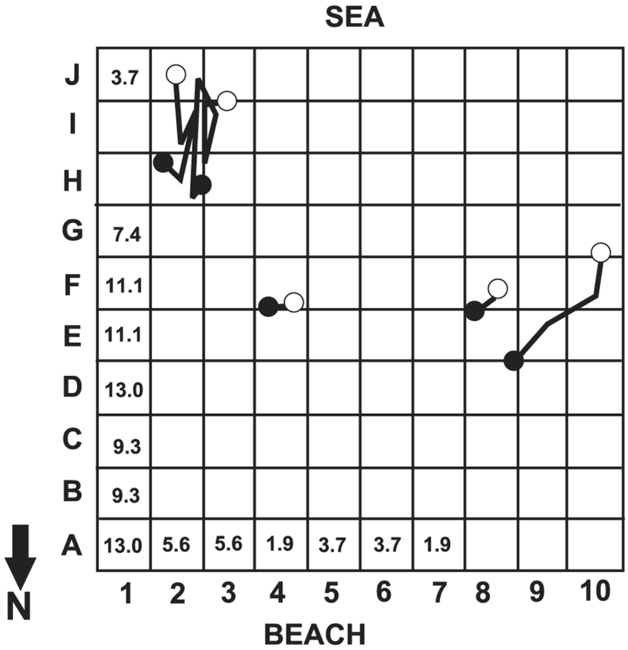

Figure 10. Displacement of the five gravels that was possible to distinguish from the video over the schematic representation of the grid. Numbers on the cells are percentage of gravels that output the grid throughout that cell.

the mean backswash direction was ESE to SE but most of the vectors had a SE and S direction (Fig. 7).

As indicated, the waves coming from the SW evolved into a runup with preferring main direction towards the NE and ENE whereas the backwash was S and ESE as determined from the PIV analysis of the water particle movement (Fig. 8). However, there were clear differentiations in the backwash direction depending in the location across the swash-backwash system. The outer part of the system follows much more clearly the described path directions, whereas as we move up slope the swash stays in the general direction but the backwash is in the largest percentage perpendicular to the coast. Figure 8 represents the total data gathered using the PIV for a grid node which was covered by water during the whole experiment (Fig. 3c). Again the intensity of the flow is greater towards the end of the inundation period. In the case of swash-backwash acting over the grid area there is a much clear increase in velocities with time with mean values for the swash from 22 to 43 cm s^{-1} and 24 to 46 cm s^{-1} for the backwash (Table 2). Mean directions for the former are ENE and ESE for the latter, although individual vector direction are closer to those described by the ADV.

We also estimated flow accelerations from the PIV vectors. Maximum accelerations were on the order of 3.75 m s^{-2} which are very high and provide the best explanation why the flat gravels are transported and even jump up to 50 cm out of the water. Even though the waves acting on the beach were breaking as spilling or plunging, the latter were having a second breaker right before the grid area and, therefore, water surging was more intense there. The accelerated flow reaching the gravel from underneath easily transported them. We also analyzed the velocity data from the PIV employing wavelets (Fig. 9). This tool is very effective in showing when the various processes are active and their intensity as the power spectra is plotted as a function of time (Fig. 9b). The maximum energy is detected at the 8 s period but the most intensive is during the first part of the inundation as the water level is the least. Kinetic energy from the swash reduces as the water level increase over the grid node and starts to be more intense (but not at the same level than at the beginning) near the end of the coverage period (Fig. 9b). Other periods like 4 and 2 s are also important but acting at different stages of the coverage indicating that wave activity, although somewhat constant, was non uniform during the study period having some peaks that may be due to processes like surf beat.

Figure 3 shows the study site before (Fig. 3a) and after (Fig. 3b) runup was active within the gridded area. The difference in gravel coverage is a clear evidence that all gravels that originally were located within and around the grid where transported elsewhere. We were not able to locate under the sand of the grid area any of the painted gravels as we looked for signs of gravel burial. On the other hand, we could not account for the total painted gravels as we only were able to recover 78 out of the original 100 that were marked. However, we noted for 65 gravels the grid cell from which they left the grid. The other 13 gravels that came out of the grid moved during the swash undetected and appeared on the beach and were not considered in our analysis. Therefore, from the total of marked gravels, we lost 22% of them that may have been transported far away from the study area to be located, most likely offshore as they were not visible in a range of 50 m at both sides of the grid. Based on the outgoing cell (Fig. 10), all gravels went out either from the eastern side of the grid (78%) or through the seven easternmost cells of the upper row (22%). As the swash had a preferred

Figure 11. Examples of flat gravel disposition over the sandy beach. a) Lateral view showing the typical seaward angle between the gravel and the beach; b) Top view of a flat gravel after a backwash episode, note the erosional depression formed at the seaward tip produced by the hydraulic jump; c) Backswash flow overpassing a flat gravel. Note the near laminar flow on top of the gravel and the hydraulic jump at the tip and the afterward turbulent flow.

NE direction, the gravels followed a path that was clearly dictated by the water circulation.

DISCUSSION

The most difficult task in the data analysis was to obtain without any doubt the actual path followed by the marked gravels on the video. There were several difficulties (already mentioned) that allowed to follow five gravels for only part of the time (Fig. 10). In all cases, the general movement was in the direction of the main swash. The distance traveled by the gravels varied significantly and are not directly related to the velocity of the swash but rather to the way that the gravel laid on the beach (see discussion later on).

Peak backwash velocities measured both using PIV and ADV were up to 0.75 m s^{-1} (Figs. 7 and 8), respectively. Whereas, peak swash velocities were as much as 0.70 m s^{-1}, PIV data showed that there is a spatial and time variation of the velocities, both with the tide rising and lowering, being the previous up to 20% stronger across the whole inundation zone. It is evident, that these peak velocities are large enough to overcome the threshold of large gravels embedded in a bed of similar gravels. Furthermore, the accelerations calculated from the PIV vectors are very high and represent very strong instantaneous kinetic energies beyond that needed to move the gravels. However, the protrusion here is practically 100% as the gravels lay on top of the sand (Fig. 11) and only in few cases are partly covered by a thin veneer of sand. Then, they can receive the full thrust of the uprush and be transported upslope.

On the other hand, seaward transport is less effective even though backwash peak velocities may be larger. In these cases, there are three reasons which difficult gravel initiation. First of all, the upslope gravel tends to be at the same level of the sand and the drag force does not have enough area to be applied (Fig. 11a). When the border of the flat pebble is fully exposed, then the gravel is transported seaward by traction and sliding over the sand surface. In this case, there is also an upward flow component that helps in developing a lift force and flow separation on the gravel upper rim.

A second reason is that the gravel profile, when positioned at the same level of the sand surface, also induces no flow separation and no lift force, the flow conformably maps the gravel until it reaches the seaward edge of the gravel (Fig. 11b). In this point, there is a flow separation that produces an erosion of the sand surface at a certain distance (we did not correlate this distance with any other variable) downstream at the reattachment point (Fig. 11c). Water also flows along the sides of the gravel and converges at about the reattachment point, developing a comet type surface marking thereon which is notable by the higher concentration of shell fragments.

The last reason could be classified as a scour-lag mechanism. Gravels that have been moved certain distance up slope into the area where the maximum runup reaches cannot be moved by the slow currents that occur at this zone, since gravitational acceleration does not have enough time and distance as well as water mass to produce a drag force to move them.

This study was initiated by the observation that there is an intense onshore-offshore transport of all types of gravel induced by wave runup and backwash along the beach face. Gravels are transported in four different ways. There is the common transport by rolling of the *Callianasa* tubes but this also depends if the tube is one single cylinder or it has ramifications. In the latter case, rolling is rare. However, rolling downslope favoured by gravity is common for the tubes.

Other transport mechanisms observed during the experiment is by gravel rotation, surfing and saltation. The former corresponds to the gravel pivoting around a fixed point or side. This mechanism is favored by the fact that backwash flowing over and around a gravel produces sand erosion on the downslope side of the gravel, then the gravel forms an angle with the beach surface and a notch develops underneath. Although many gravels also tend to fully relax over the beach surface, the formation of an angle (Fig. 11a,b) is very common and most gravels pass through both conditions at one time or another during the whole process. Then next runup induces a pressure underneath the gravel which is forced to pivot upslope (we believe although it was not measured, that this pressure is applied on the frontal part of the gravel). Due to the same notch situation, if the pressure is applied in a different part of the gravel base, the gravel can then be transported either by flotation or by saltation.

Flotation or surfing transport occurs when a gravel is lifted completely and a layer of water, normally a few mm thick up to 1 cm, sustains the gravel and displaces it up beach for a certain distance. Normally this distance is of the order of 10 to 35 cm depending on beach slope and the velocity of the runup. The latter is especially important because this also depends on the runup finding the gravel immediately as it starts at the beach toe or further up slope. Also, the runup has little effect in transporting the gravel if it is at or close to its maximum reach.

Although intuitively seems unlikely, even large gravels are commonly transported by saltation during runup. We have observed and filmed flat gravels up to 20 cm in their longest diameter to jump up to 50 cm above the water surface during a runup even with waves that have less the 30 cm in breaking height at the beach toe. There are examples in which we observed more than 10-15 gravels jumping out of the water almost simultaneously. However, saltation normally occurs when gravels are close to the initiation of the runup rather than further up slope.

Perillo *et al.* (2004) suggests, based on theoretical studies, that gravel transport on the beach surface is a function of where the maximum pressure is applied on the gravel base within the notch. Pivoting occurs when the maximum pressure is applied by the runup to the tip of the gravel, whereas flotation is induced when the maximum pressure is applied at the vertex formed by the gravel and the beach surface. Finally, saltation occurs when the pressure is distributed homogeneously on all the lower surface of the gravel. However, further studies are necessary to fully understand all the variables acting on the transport of these gavels.

Many geological studies associate the aggregation of flat gravels on beaches and shoreface deposits to storm generated transport (i.e. Kazmierczak and Goldring, 1978; Sepkopski, 1982; Aigner, 1985; Myrow *et al.*, 2004). In particular, Myrow *et al.* (2004) describe Upper Cambrian to Lower Ordovician strata having large concentrations of flat pebbles which they relate to reworked and condensed deposits which record winnowing and reworking cycles. Basically, what it is observed in Pehuén Co Beach is a similar process where the flat gravels are transported by the swash-backswash but with a general tendency to pile them at the high tide level reinforcing the idea of winnowing as primordial process. Although storms may induce a large wave set up and, combined with high tide conditions, may help to concentrate gravels at the backshore, the swash-backswash under fair weather situations is dynamically enough to transport the gravels upbeach.

CONCLUSIONS

Pehuén Co Beach is characterized by the presence of a large percentage of gravels of different sizes on a sandy surface. Gravels have a diversity of shapes and composition as well as origin, including biogenic (i.e., shells) and artificial (i.e., bricks, pieces of masonry) ones. The most common, comprising about 40-50% of the total, are the flat $CaCO_3$ pebbles which are subject to a remarkable transport by the swash-backswash generated even by very small waves. Flat gravels, normally associated with beach rocks, are relatively uncommon sediments in beaches. Nevertheless, they are an excellent example that large sized sediments do not require high energy waves to be transported. During this study, waves less than 30 cm high were able to transport out of a predefined grid more than 100 gravels with mean longer diameters larger than 10 cm.

Measurements made employing current-meter and analysis of video images allowed the determination of typical flow velocities and directions during the grid inundation period. Wind direction during the study was a major factor in defining the transport pattern of the gravels and influenced the swash and backswash. A series of factors that help low energy waves to be able to move the flat gravels: 1) gravel angle with the beach; 2) point where the incoming runup applies its maximum pressure; 3) degree of acceleration of the runup.

The study at Pehuén Co Beach could be considered as a preliminary analysis of the problem and it requires more detailed measurements. However, our results provide a clear demonstration that many interpretations on the geologic record that consider beach gravel deposits to be associated with storm events may not be a correct interpretation as gravels can be transported even in low energy conditions.

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