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Radio Frequency Identification (RFID) technology applied to the definition of underwater and subaerial coarse sediment movement

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ABSTRACT

In this paper, Radio Frequency Identification technology has been applied to track both underwater and subaerial displacement of pebbles along an artificial coarse beach at Marina di Pisa, Italy. Several preliminary laboratory tests have been performed to adapt the RFID technique for underwater use, which has been the primary impediment to this promising approach to the study of coarse sediment transport and movement. Tests showed the reliability of low frequencies for this kind of work, since they enable good signal transmission and reception through water. Passive ABS plastic transponders were inserted into about 100 pebbles and released onto the beach in March, 2009. A CORE-125 reader was chosen as the operating antenna to continuously transmit low frequency (125 kHz) signals. An acoustic signal toned whenever a pebble was detected while the unambiguous identification code of the pebble is shown immediately on the screen of a laptop connected to the reader. The positions of the pebbles were recorded with a total station. After two months (May, 2009), 74 marked pebbles were retrieved, 77% of the total. The positions of the retrieved pebbles were also recorded with the total station, thus allowing calculation of the coarse sediment transport tendency. About 60% of the recovered pebbles (44 out of 74) were found on the upper shoreface. The analysis of the marked pebble trajectories revealed a divergent transport movement in the northernmost sector of the beach. This movement was probably triggered by an irregularity of the submerged breakwater fronting the shoreline. The southern sector is characterised by chaotic pathways related to the formation and evolution of beach cusps. This outcome highlights and confirms the importance of a complete definition of the beach system, with no separation between the underwater and the subaerial portion of the shore when it comes to sediment transport and movement. This successful application of RFID technology to the underwater environment provides a chance to broaden understanding of a topic in need of further study.

1. Introduction

Sediment movement is a topic that has drawn the interest of coastal researchers since the earliest studies on beach morphodynamics, given its significance in almost any aspect related to the coastal depositional environment. From the easiest assessment of sand displacement along a coast to the most complex prediction of grain behaviour in a given fluid, ongoing research has strived to better define every facet of sediment movement. Initial experiments focused mainly on finer sediments, mostly because sandy beaches are more commonly found. Moreover, coarse beaches were believed to be more difficult to study due to logistical issues (Buscombe and Masselink, 2006). Thus, there has typically been more interest in sandy coasts rather than coarse ones. Only recently have coarse sediments entered a period of revived interest thanks to new techniques enabling different and more complete approaches to their study, in particular the chance to track individual pebbles with devices that assure good rates of detection, at least in the subaerial environment (Allan et al., 2006). The lack of underwater pebble detection methods has been a major drawback of this technique.

Going back in time, the first laboratory and field experiments were carried out to improve understanding of sand displacement. Several methodologies were developed and tested. Analysis of sediment grain-size patterns (McCave, 1978; McLaren, 1981; Gao and Collins, 1992; Guillén and Hoekstra, 1996; Pedreros et al., 1996), provenance investigations by means of compositional analysis (Van Andel and Poole, 1960; Gandolfi and Paganelli, 1975; Salomons and Mook, 1987; Balsam and Beeson, 2003), magnetic susceptibility measurements (Sach and Ellwood, 1988; Ellwood et al., 2006), isotopic ratios (Biscaye et al., 1974; Grousset et al., 1988; Revel et al., 1996) and biogenic debris (Murray et al., 1983; Nigam, 1986; Gao and Collins, 1995; Benavente et al., 2005) as natural tracers, along with radioactive (Crickmore and Lean, 1962) and fluorescent tracers (Yasso, 1966; Komar and Inman,

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1970; Ciavola et al., 1998; Vila-Concejo et al., 2004; Balouin et al., 2005) have been the most widely used techniques over the years to gain a better all-around definition of sand transport and movement. Each one of these approaches has advantages and disadvantages, owing to the level of accuracy and effectiveness in regard to the ongoing research, the time interval studied by the experiments (active pathways of sediment distribution or mere provenance indications), ease of applicability, and cost. Currently, fluorescent tracers are experiencing a vast range of applications, especially for short-term surveys (Silva et al., 2007; Klein et al., 2007).

The recent strong impulse towards an in-depth understanding of the morphodynamics of coarse beaches has brought about consequent improvements in the definition of coarse sediment movement as well. Several experiments were needed to establish this point. Early work focused on textural parameters of pebbles like size, shape and sorting, and their influence in sediment transport (Carr et al., 1970; Williams and Caldwell, 1988). It was clear right away that the assessment of textural parameters alone would not have led to a precise understanding of coarse particle movement. Therefore, new approaches to this topic began incorporating tracing techniques like painting a certain portion of pebbles (Jolliffe, 1964; Osborne, 2005; Ciavola and Castiglione, 2009) or injecting allochthonous lithologies onto the beach (Hattori and Suzuki, 1978); marking pebbles with radioactive substances, magnets (Hassan et al., 1984; Osborne, 2005), aluminium (Nicholls and Webber, 1987), or electronic technologies (Bray et al., 1996); and coupling pebbles with a transponder to allow the recovery of each one by means of Radio Frequency Identification (RFID) technology (Nichols, 2004; Allan et al., 2006; Curtiss et al., 2009). The electronic techniques seem the most reliable and accurate, but they are expensive as well. The best ratio of efficiency to costs is probably attained by the RFID system, since it ensures high rates of marked pebble detection along with low operating costs (Allan et al., 2006). The major current shortcoming of RFID technology is the inability to detect marked samples underwater due to poor transmission of the radio signals through water, which prevents a thorough understanding of the transport path of coarse sediments. The aim of this study is to overcome this limit by setting up specific devices that are functional even through water, a refinement of the RFID technique already tested by Allan et al. (2006) and Curtiss et al. (2009). This allows detection of coarse sediments marked with passive transponders seaward of the mean low sea level and not just on the subaerial portion of the beach. This improvement allows the collection of more complete data sets on coarse sediment movement, and translates to a wider definition of coarse beach morphodynamics since no effective assumptions about sediment transport can be made without considering the beach system as a whole. Moreover, a better definition of coarse sediment transport pathways can lead to assist and stimulate the research on ancient gravelly shorelines (Pascucci et al., 2009), and give constructive insights on coarse sediment depositional processes.

An artificial gravel beach at Marina di Pisa (Tuscany, Italy) has proved to be the ideal site for this research due to its peculiar setting: it is located between groynes at each end, and it is bounded seaward by a submerged breakwater. This configuration makes it behave as a closed sedimentary system. There is definitely no pebble exchange between the area landward of the breakwater and the area seaward of the breakwater. About 100 pebbles (-4.5 to -6.5 ϕ mean diameter) were sampled on the beach, coupled to transponders, and then released again on the beach to prove the applicability of the RFID technique in the underwater environment.

2. Method

Radio Frequency Identification is one of the most common automatic identification technologies, and it is currently used in many different applied fields, from industrial tracking to access control. An RFID system is basically composed of two different kinds of devices, the reader and the transponders (generally referred to as "tags"). The reader is the device used to perform the actual identification operation: it generates an electromagnetic field operating at many different frequencies that is used to interrogate the tags. The tags are the smart devices coupled to the item to be identified. They can be passive or active depending on the presence of an on-board battery. They can be realised in many shapes and materials and they are provided with a small memory, which contains an unambiguous identification code. Thus, each one of the pebbles associated with a tag can be unequivocally identified.

Due to the characteristics of the site in which the RFID technology was employed, preliminary studies and tests were undertaken to develop an efficient technique, even underwater. First of all, several considerations on radio transmissions had to be made in order to obtain a system that would work underwater. Pure water is an insulator, which means that technically no radio transmission is possible. However, dissolved salts or other materials turn natural water into a partial conductor. The signal attenuation depends on the frequency of the electromagnetic field and on the water conductivity. The signal attenuation (α) can be calculated with the following approximate formula:

$$\alpha = 0.0173\sqrt{(f\sigma)},$$

where f is the frequency, and σ is the conductivity. The sea water conductivity depends on the water temperature and salinity, and varies from 2 S/m in the arctic regions to 8 S/m in the Red Sea. The average value is around 4–5 S/m, and its contribution in the calculation of the signal attenuation can be considered constant (Butler, 1987). Thus, to achieve the best signal transmission, the lowest frequencies possible must be chosen. Currently, the lowest frequency bands available for RFID systems are the low frequency (LF) band (125–135 kHz) and the high frequency (HF) band (13.56 MHz). The reading range of the HF systems in ideal conditions is wider (up to 1 m) than the LF band, but this higher frequency poses many problems for electromagnetic compatibility.

Some tests were initially made with a 13.56 MHz system, but the attenuation was too high to achieve a reliable transmission. A Feig CPR.PR50 HF 13.56 MHz USB reader was used. This device was insulated with a plastic layer, and the reading range was analysed by detecting a Texas Instrument RFID tag positioned under water. Although the detection of the transponder was assured, the reading range was reduced from 15 cm (ideal conditions) to 3–4 cm, making the use of this system impossible. The best results were eventually obtained using a 125 kHz system.

Fig. 1. The CORE-125 reader chosen as the operating antenna. It is connected to a pair of 12 V-7 A batteries and the laptop computer. These long-life batteries allow several hours of fieldwork without further charge.

Table 1
Reading range of the "smart" pebbles coupled to the three types of transponders; tests were conducted under different subaerial conditions.

Tag type	IC range (cm)	P range (cm)	GP range (cm)
Nylon	55	53	50
ABS	63	61	58
PVC	49	47	43

Notes: The IC range represents the reading distance measured under ideal conditions (without external influences); the P range stands for the reading distance measured in the presence of a 40 cm thick layer of pebbles; the GP range stands for the reading distance measured in the presence of a 40 cm thick layer of gravel and pebbles.

Table 2
Reading range of the "smart" pebbles coupled to the three types of transponders; tests were conducted with different underwater conditions.

Tag type	AW range (cm)	F range (cm)	S range (cm)
Nylon	46	42	41
ABS	55	53	51
PVC	41	39	36

Notes: The AW range represents the reading distance measured with the reader out of the water; the F range stands for the reading distance measured keeping both the reader and the pebbles in fresh water; the S range stands for the reading distance measured with both the reader and the pebbles in salt water.

Once the ideal operating frequency was discovered, ad hoc devices were tested to find out which would fit with the remaining equipment. For starters, a common CORE-125 reader (CoreRFID ltd.; Warrington, WA2 7LT, United Kingdom), generally used for access control, was chosen as the operating antenna (Fig. 1). It was embedded in a waterproof box that also contained connectors to the battery and the data acquisition device. The reader was wired to a laptop and placed on a small boat or on the beach. The system enabled both the instantaneous detection of a pebble by means of an acoustic signal as well as recording of data from the recovered pebble.

Three kinds of transponders (PartItalia srl; Milano, Italy) were then tested to compare their performance under different conditions as well as their resistance to stress and water contact:

- 25 mm diameter passive Nylon tags;
- 30 mm diameter passive ABS plastic tags;
- 23 mm diameter passive PVC tags.

Three "smart" pebbles coupled to the three kinds of tags were used in the laboratory experiment. These pebbles were detected in subaerial conditions to first determine the maximum reading range without anything between the reader and the pebbles (ideal conditions), then beneath a 40 cm thick layer made of pebbles of the same grain size as the "smart" pebbles, and finally beneath a 40 cm thick layer made of a mixture of gravel and pebbles (Table 1). The passive ABS plastic tags showed the best performances in terms of reading range and resistance to water, highlighting the dependence of the reading range on the size of the tag. Both the diameter (30 mm) and the absence of a battery requiring periodic replacement make the ABS tags the best choice.

Finally, this test was repeated in a configuration that attempted to simulate the environment in which the system would be employed. A large deep plastic bin was filled with fresh water, pebbles and gravel. The reading range of the above mentioned "smart" pebbles was measured again under three different conditions: in the first case, the reader was kept out of the water while the "smart" pebbles were placed at the bottom of the bin; in the second and third cases, both the reader and the "smart" pebbles were kept underwater with fresh water for the second case and salt water with a salinity typical of the Ligurian Sea for the third case. The results of the underwater experiment showed that the ABS "smart" pebbles were detected at up to 50 cm, even under a 40 cm layer of gravel and pebbles; no significant reduction in the reading range was noticed (Table 2).

After the first phase in which the proper technique and devices were discovered, about 100 pebbles (-4.5 to -6.5 ϕ mean diameter) were collected randomly on the beach. The only restriction was that the minor axis could not be lower than 40 mm to prevent the pebbles from breaking during the preparation procedure. Then, they were brought to the laboratory for the insertion of transponders. The pebbles were carefully drilled to a depth of 2.7 cm with a core drill (Fig. 2A). The transponders were pasted onto the bottom of the 3.2 cm diameter hole by means of a strong two-component epoxy adhesive. The hole was plugged with a marble core moulded to fit the hole. Voids were filled with a synthetic resin (polyester) to seal everything up (Fig. 2B). The marble cores were taken from slabs of the same lithology as the marked pebbles. That way the particles' physical properties (shape, weight, hydrodynamic response) should be only slightly affected by the preparation procedures. After about 40 h to let the glue and resin dry, the pebbles were ready for release on the beach.

3. Field test

3.1. The study area

This technique was tested in the field in the spring of 2009 in order to prove its efficacy. The area of Marina di Pisa (located 11 km southwest of Pisa, Tuscany, Italy) was chosen for the experiments due to the presence of an artificial pebble beach perfectly suitable for this kind of test (Fig. 3).

Fig. 2. A core drill (A) was used to drill precise and sharp holes in the pebbles. After preparation (B), the pebble's shape and weight are not significantly modified. The black disks represent the transponders used during the experiment.

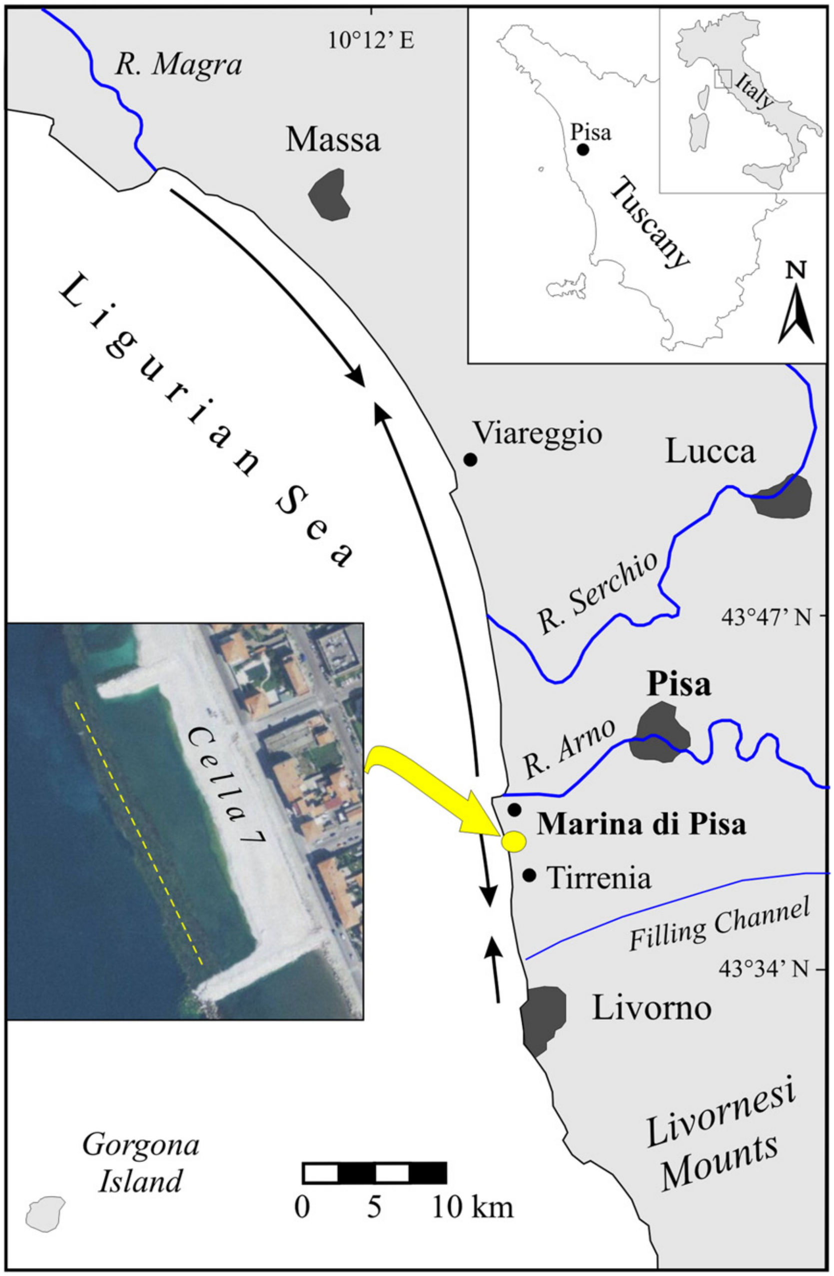

Fig. 3. Locality map of the study area. The thin black lines show the direction of the longshore drift throughout the River Magra-Livornesi Mounts physiographic unit, which includes the Pisa coast. The dashed line depicted on the aerial view of Cella 7 shows the submerged breakwater.

The beach, named Cella 7, is 240 m long and 30 m wide; it is bounded at both ends by groynes and seaward by a submerged breakwater 50 m off the coast (Fig. 4A). The mean grain size varies along cross-shore transects: $-5.5\ \phi$ (45 mm) on the backshore and $-4.5\ \phi$ (24 mm) on the foreshore. At the base of the step, where the mean grain size increases to $-5.5\ \phi$, there is a transition from coarse sediments to medium-to-fine sand, which is the grain size naturally present on the coast of Marina di Pisa. Cella 7 is defined by a steep beachface and a pronounced step, which at times exceeds 60 cm in height. The portion of the sea bottom that is within the beachface and the breakwater reaches a maximum depth of 4 m (mean slope of about 4%). The depth falls steeply to over 6 m at the seaward side of the structure. The backshore is characterised by a huge storm berm that is 3 m high throughout the whole beach (Fig. 4B). The fair-weather berm is barely outlined and was obliterated by the development of beach cusps, especially in the southern sector of the beach. The littoral drift is directed southwards (Fig. 3) throughout this sector of the Pisa coast (Aiello et al., 1975; Pranzini, 2004). Major storms commonly come from the southwest and the typical wave direction is west–southwest (Cipriani et al., 2001). Tides are not a major controlling factor, and the tidal range is hardly higher than 30 cm.

3.2. The experiment

A total of 96 “smart” pebbles were released on the beach on March 16, 2009 along 32 cross-shore transects to cover the whole beachface area. Three pebbles per transect were deployed (Fig. 4), more precisely on the fair-weather berm, on the foreshore, and on the upper shoreface (step crest). This configuration covered a 9 m spaced grid, which allowed the identification of pebble transport tendencies

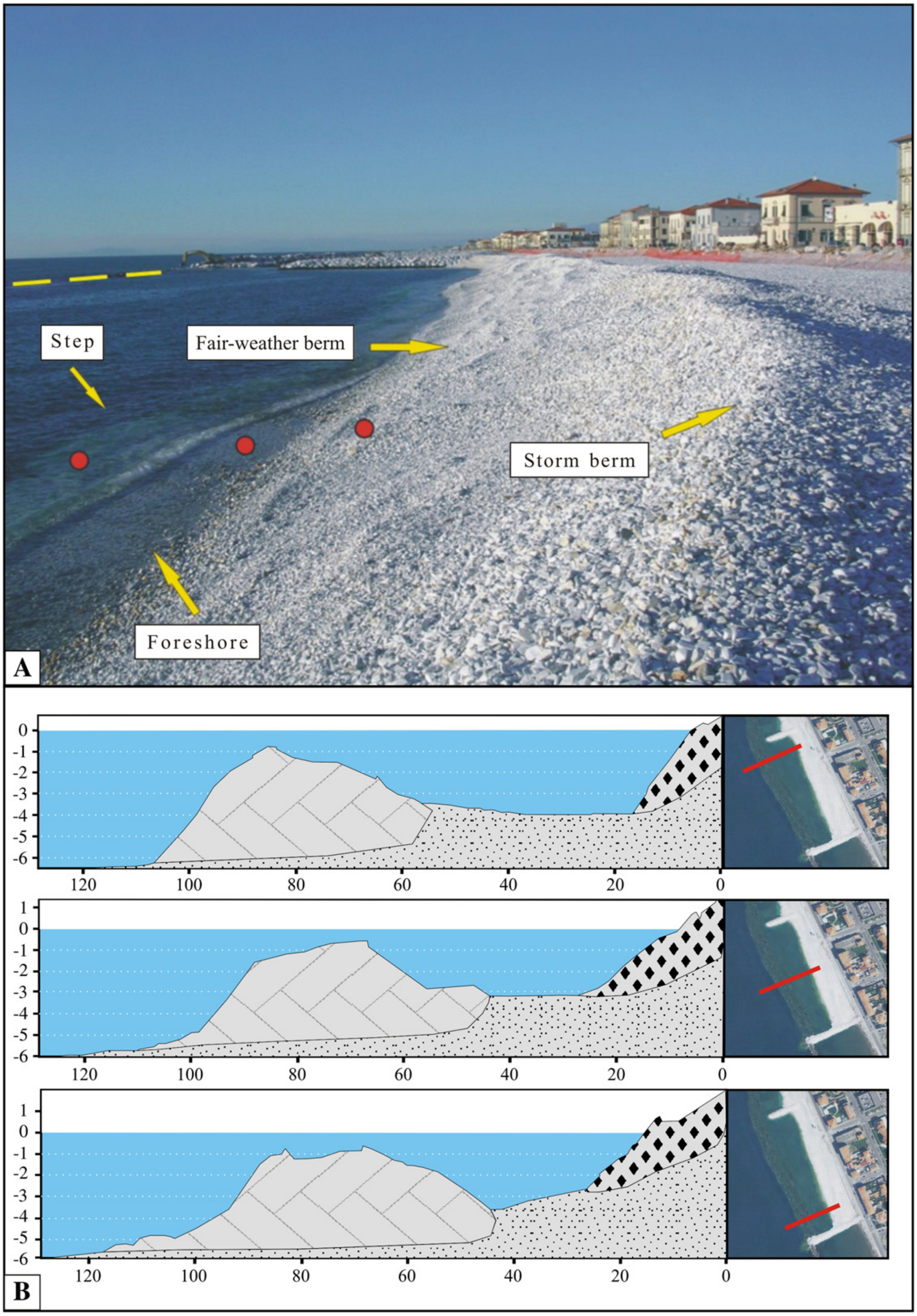

Fig. 4. (A) A picture of Cella 7, the beach where the experiment was carried out. The dashed line on the left shows the submerged breakwater. The dots show where the "smart" pebbles were originally placed from left to right on the upper shoreface (step crest), on the foreshore, and on the fair-weather berm. (B) Three sections showing the beach profile in distinct portions of Cella 7. The lines depicted on the small images on the right show where the sections were traced out. The large brick theme in the background indicates the submerged breakwater; the fine dots indicate the sandy portion of the beach; the large dots indicate the pebble replenishment. Distances are expressed in m.

throughout the entire beach. The placement and recovery positions of the pebbles were recorded with a Sokkia SET-610 total station (SOKKIA TOPCON CO., Ltd.; Kanagawa, Japan) so that the displacement pathways could be traced and the trends of transport inferred.

Topographic monitoring of the backshore and the sea bottom of Cella 7 was carried out to characterise the morphology and to underline any existing feature that might affect the transport pathways of the pebbles. The subaerial portion of the beach was surveyed in May, 2009 using an

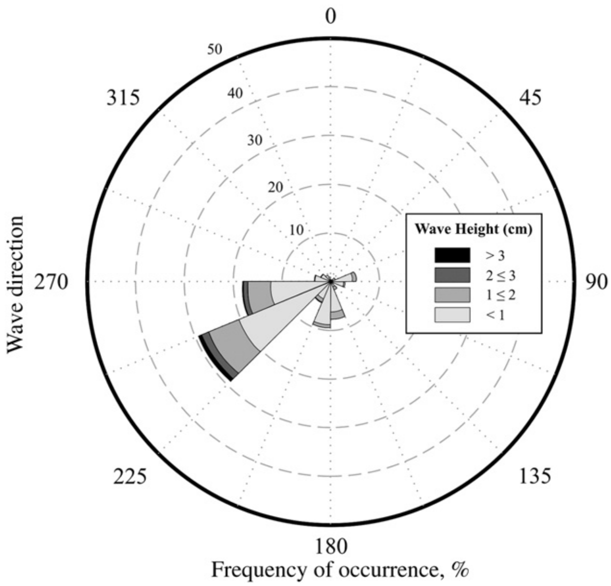

Fig. 5. A polar diagram showing wave direction and frequency of occurrence during the study (wave data provided by the Tuscany Hydrological Service).

Fig. 7. A snapshot of the recovery campaign: when a pebble is detected, the identification code of the tag pops up on the screen of the laptop placed on a small boat. An acoustic signal aids in the retrieval operation. The diver uses a rope tied to poles to follow predetermined paths. In this way, he avoids patrolling the same area multiple times.

RTK-GPS (Leica RTK 1200) with an instrument error of about 1 cm. A point every 6 m was recorded along the main longshore features of the beach. These features included the step crest, the coastline, the storm berm crest, and the landward toe of the storm berm. In addition, any embayment and horn of the existing cusps was tracked to further characterise the beach morphology. The topographic survey of the sea floor was performed in mid-April, 2009 using an echo-sounder single beam instrument (Actisense DST-2-C supplied with a transducer AIRMAR SS510). This device was set up on a small motorboat and recorded a point every second. Little distance was left between

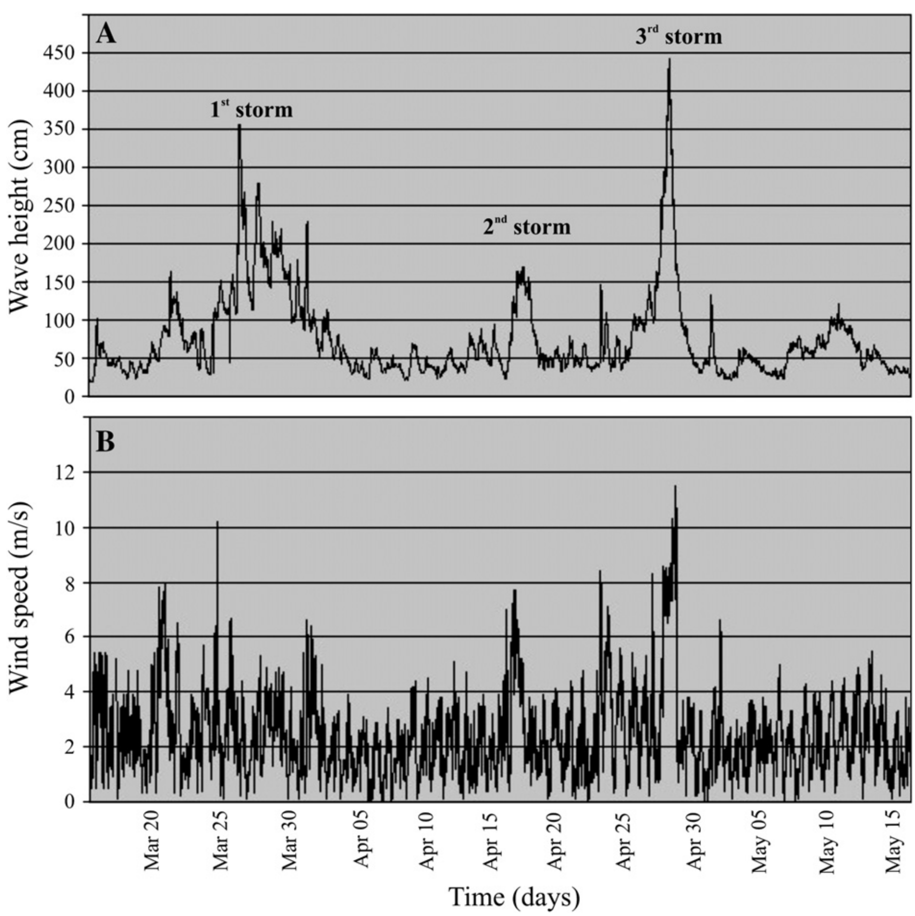

Fig. 6. Sea weather characterisation: (A) significant wave height and (B) wind speed recorded by the wavemeter and the anemometer during the study. The wave and wind data were provided by the Tuscany Hydrological Service. The three major storms that occurred are shown on the plot.

Table 3
The results of the recovery campaign at Cella 7, including the number of pebbles detected relative to the release locations and their percentage.

			Release location						
			Fairweather Berm	Beachface	Step Crest	TOTAL	% REC.	% A/U W	% OL
Recovery location	Storm Berm	Subaerial	7	4	7	18	24	40	30
	Fair-weather Berm		0	0	0	0	0		
	Beachface		2	8	2	12	16		
	Step Crest	Underwater	12	12	12	36	49	60	64
	Step Base		3	1	4	8	11		
	TOTAL		24	25	25	74	77		

Note: % REC. is the recovery percentage of the pebbles in their recovery location; % A/U W signifies the percentage of pebbles detected on the subaerial portion of the beach as opposed to the percentage of pebbles retrieved under the water; % OL stands for the percentage of pebbles that were recovered on the subaerial portion of the beach, but sarted out the underwater portion and vice versa.

consecutive points, provided the speed of the boat never exceeding 3 m/s. The survey was carried out using a series of both longshore and cross-shore back-and-forth routes in a closely-spaced grid. The area above the submerged breakwater was monitored to evaluate whether its crest is equally large and deep throughout the length of the beach. The echo-sounder was wired to the RTK-GPS to increase the accuracy of the recording up to an instrument error of about 2 cm for the positioning and about 10 cm for the elevation. The obtained data were processed using ArcGIS software (ArcGIS 9.2) to merge the underwater and subaerial topographic surveys.

3.3. Wind and wave measurements

Both wind and waves were measured to characterise the sea and weather during the experiment. The wind direction and speed were recorded by an anemometer located close to the River Arno's mouth, 1 km north of the experiment site. These data were measured every 15 min for a total of 6240 measurements. No prolonged gaps in the wind data were reported during the fieldwork. Wave data were collected by a buoyant wavemeter deployed offshore of Gorgona Island (Fig. 3), about 40 km southwest of the study area. The device recorded the period, direction, and significant height of the waves about 48 times a day (Fig. 5). Although on some days data collection was irregular, no relevant lack of measurements needs to be acknowledged.

Three high-energy events occurred during the experiment. All of these events came from the sector between 225° and 270° (WSW). Both wave and wind data presented peaks during these storms (Fig. 6A, B), which happened on March 24th (240°), April 16th (230°), and April 29th (240°). The first storm lasted for six days, and the significant wave height never fell below 1 m. Two different peaks, which were separated by 1 day intervals, were characterised by wave

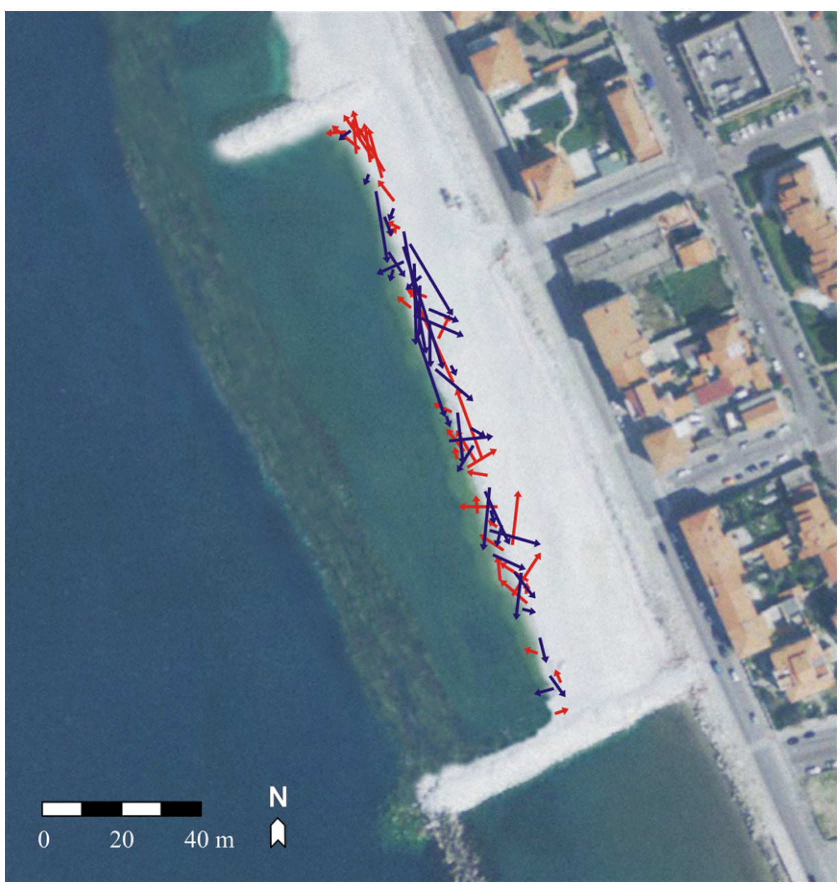

Fig. 8. Transport pathways of the marked pebbles at Cella 7. The thick, red lines represent the pebbles that shifted northwards. The thick, blue lines point out the pebbles characterised by a southwards movement.

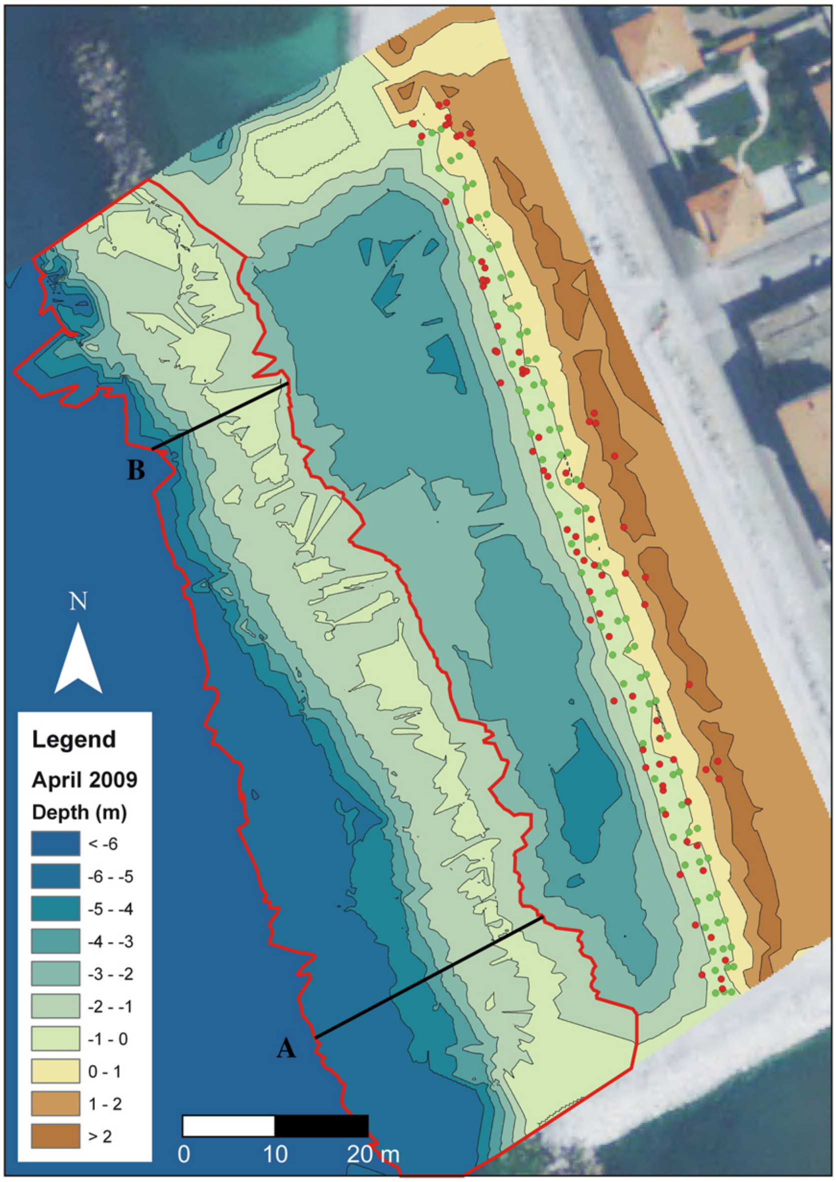

Fig. 9. Sea bottom and subaerial morphology of Cella 7 in April, 2009. The green dots represent the release positions of the pebbles, and the red dots represent the recovery positions of the retrieved pebbles. The thick red line defines the area of the sea floor representing the submerged breakwater. Lines A and B highlight the different width of the breakwater.

heights higher than 3.5 m and 2.5 m. respectively. The second storm was mild (1.7 m maximum wave height). The third was short (less than two days) but definitely the strongest of the three storms. The wavemeter recorded wave heights of 4.5 m, which was the highest value measured during the study. Aside from the major events, the most frequent wave directions were westerly and southwesterly waves, which constituted almost 60% of the incoming waves recorded during the two-month long experiment. Southwesterly winds were less frequent, but they presented the highest speeds (up to 11.5 m/s). These high speeds support the notion that these winds trigger the most powerful storms.

4. Results

The recovery campaign, carried out in May, 2009, provided consistent results in terms of tracer detection (Fig. 7). A total of 74 pebbles out of 96 (77%) was retrieved. Table 3 shows that the likelihood of finding the marked pebbles was not affected by the release location, since the same number of tracers was recovered for each release location. Twenty-four (38%) of the pebbles originally placed on the subaerial portion of the beach were detected on the step crest, where the bulk of the pebbles (49%) was retrieved.

Only 8 tracers were recovered on the step base. Four of them were released on the beachface and on the fair-weather berm. Of the 12 pebbles detected on the beachface, only four came from other release locations, whereas 7 out of the 18 tracers retrieved on the storm berm were originally placed on the step. Summarising, 60% of the marked pebbles were found underwater, and 40% were found on the subaerial portion of the beach. The remarkable aspect of these results is that 64% of the pebbles that were recovered underwater moved there from the beachface and the fair-weather berm.

The trajectories of the recovered pebbles show a distinct tendency of the tracers to move northwards in the northernmost sector of the beach. Pebble transport is generally southwards in the sector immediately next to it to the south (Fig. 8). Further to the south the direction of the movement becomes somewhat either scattered or

Fig. 10. The central and southern sectors of Cella 7 are characterised by widespread beach cusps, which largely control the direction of pebble displacement.

chaotic. This pattern only appears to be disorganised because it is strictly connected to the development of beach cusps. This process will be discussed in detail later on. The longshore transport is prevalent over the cross-shore. Longshore trajectories often display longer distances covered by the pebbles rather than cross-shore trajectories. Longshore trajectories are usually over 10 m as opposed to less than 5 m.

The sea floor fronting Cella 7 is mainly characterised by the toe of the submerged breakwater, which extends up to the −6 isobath. Fig. 9 shows that the depth progressively decreases towards the southern sector of the beach seaward of the breakwater. This reduction of the sea bottom depth reflects a configuration of the toe that was not planned by the project. The resulting breakwater presents a constriction about 40 m south of the northern groyne, which is narrower (15 m) in this sector of the beach relative to the southern sector (30 m).

The backshore is mainly defined by a unique, 3-m-high storm berm. The seaward face of this berm presents several cusps, particularly in the southern sector of the beach. Towards the north, the cusps are replaced by a large, gently-sloping embayment just opposite the constriction of the submerged breakwater.

5. Discussion

The pebble tracing experiment performed on Cella 7 shows the importance of the underwater detection of the pebbles because more than 50% of the tracers were found back on the step. The RFID technology can be used even in an underwater environment. The maximum detection range reached by the antenna during the fieldworks on the subaerial portion of the beach was about 40 cm. The water affected the transmission of the signal in a limited way and reduced the detection range to 30/35 cm. No peculiar transport tendencies were observed for the release locations, meaning that whatever the initial position, the chance of retrieving a given pebble is not biased by any particular factor. Another aspect that did not exert any control on the transport trends is the weight of the pebbles because light pebbles (less than 500 g) were found on the step and the storm berm as often as heavier pebbles (more than 1 kg). The collected data showed a divergent movement pattern of the tracers in the northernmost sector of the beach. No distinct tendency was observed in the central and southern sectors. To explain the longshore movement tendencies of the marked pebbles, the sea bottom effect on the incoming waves must be taken into account. The effect is so large that the wave crest is refracted and approaches the coast with no angle. At Cella 7, the waves undergo refraction and breaking processes further offshore because of the submerged breakwater. Thus, the slightly different direction of the three storms that occurred during the experiment did not have a strong effect on the transport tendency. The typical littoral drift, which is directed to the south throughout this sector of the Pisa coast, cannot drive any major movement because its intensity is too low to entrain coarse sediments such as the pebbles used as tracers. In addition, the huge groynes bounding the beaches hinder the course of the drift, reducing its effect on the nearshore. Assuming that the incident wave angle and littoral drift do not generate any transport trend along the beaches, another controlling factor that must be considered to describe the resulting pathways is the submerged breakwater. The present configuration of this breakwater leads to perturbations in the way incident waves break and approach the shoreline along Cella 7. The constriction of the breakwater reported about 40 m south of the northern groyne, just opposite the recognised divergence area, lessens the efficiency of the offshore structure. The crest of this structure is narrower and deeper where the constriction occurs. The toe is characterised by a steeper slope (Fig. 9). The wave energy dissipation is reduced over that area. Therefore, the incident waves approach the coastline at a faster rate and focus their energy on a limited portion of the nearshore. This focusing in turn prompts a divergent transport of the pebbles. This very sector of Cella 7 is defined by the lowest width of the entire beach (Bertoni, 2010), which confirms the reported transport tendency.

The lack of distinct transport tendencies in the southern sector of Cella 7 means that wave breaking processes do not generate fluxes capable of triggering peculiar trends. This lack is possibly due to the close proximity of the breakwater to the coastline (25 m as opposed to 45 m to the north). This proximity reduces the distance to the nearshore and the likelihood that defined transport patterns will form. The absence of any preferential pattern is supported by the lower distances of displacement of the tracers throughout the southern sector of the beach. These tracers experienced an average movement of 10 m, and the tracers in the north experienced an average movement of over 15 m.

The chaotic movement of the pebbles throughout the southern sector of Cella 7 is associated with several, well-developed cusps, which are closely spaced and about 10 m wide (Fig. 10).

As the swash further develops the cusps, the pebble movement is constrained by the morphologic forms that are created. The tracers are preferentially displaced following the fluxes that are responsible for the development of the cusps and display an opposing direction of movement within the limited distances between the cusps. The number of cusps progressively diminishes to the north, and the cusps disappear where the coarse sediments begin to experience the effects of the divergent fluxes established in the northern portion of the beach. Compared to the southern part of the beach, the backshore in the north is characterised by a more gently-sloping, cusp-less seaward face of the storm berm due to the focusing of the swash, which generates frequent overwashing past the storm berm.

6. Conclusions

The RFID system, previously developed and tested by Nichols (2004) and Allan et al. (2006), has been here refined in order to enable the underwater detection of pebbles marked with passive transponders. The employment of low frequency signals along with waterproof equipment to protect the antenna provides a chance to extend the research on coarse sediment movement beyond the intertidal zone. The detection rate shown by the results of the field experiment reaches the 77% mark and is consistent with previous works (Allan et al., 2006; Curtiss et al., 2009). This successful demonstration of the method opens up new scenarios for this kind of survey. In particular, it enables a more complete definition of transport paths and trends, which is essential for a precise reconstruction of coarse sediment dynamics on beaches.

The results obtained by tracking 96 pebbles on a coarse-grained artificial beach at Marina di Pisa (Italy) show that the primary factor controlling their displacement is the modification of incident waves induced by irregularities of the sea bottom morphology, which in this case is characterised by the presence of a submerged breakwater. Because of the constriction of the breakwater width close to the northern groyne, the energy of the incident waves is not dissipated as much as in other sectors of the beach, inducing a divergent transport movement in the northernmost area of Cella 7. No distinct longshore trend is observed elsewhere, indicating that the pathways of the pebbles are controlled by the presence of beachface forms such as beach cusps. All of these indications might be useful to improve the comprehension of coarse-grained beach morphodynamics as well as lead to an optimization of artificial beach fill, both in terms of efficiency and durability. This positive outcome can also benefit the reconstruction of ancient coastal depositional environment. According to Allan et al. (2006), this technique could also be useful to address other sedimentological aspects such as roundness and abrasion rates. In addition, the rate of burial on the backshore and seaward of the intertidal zone can be assessed. Analysis of digital images will be employed to carry out this aspect of the research: the “smart” pebbles will be photographed before release and after recovery to obtain direct comparisons of their shape and roundness.

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