Influence of particle shape on pebble transport in a mixed sand and gravel beach during low energy conditions: implications for nourishment projects.

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Abstract:

Beach nourishments using coarse-gravel sediments are becoming a frequent practice to buffer coastal erosion, but usually little attention is spent on fill material characteristics. A better understanding of the influence of sediment characteristics on transport is crucial to establish the best compatibility of fill material with native beach sediments. Pebble transport is here investigated by means of the RFID tracing technique. The main purpose of the experiment was to verify whether the prevalent shapes populating the beach (disks and spheres) show a different transport under low energy conditions. Tracers were injected in a small and straight portion of a mixed sand and gravel beach, deploying couples of marked particles of the same size (one sphere and one disk-shaped pebble on the main geomorphic elements of the beach face), in order to avoid size influence on transport. Tracer recovery was undertaken 6 and 24 h after the injection and wave characteristics were measured during the whole experiment duration by means of a S4 directional wave gauge. After 6 h the marked pebbles already underwent significant displacement with a prevalent longshore component, which became evident after 24 h. The swash zone proved to be the most dynamic area of the beach. According to statistical analyses (t-tests), no significant difference among the displacement of different shapes resulted, even though spheres covered longer distances and resulted more dynamic than disks, thanks to their capability to roll-over in the swash zone. Lately, many experiments have been carried out with marked pebbles, but this is the first time that an experiment is conceived to prove how shape influences pebble transport. Disks are more subject to burial and due to their higher dynamicity spheres are preferred to disks for nourishment fill material. A fill material comprised of spheres is regularly responding to hydrodynamic forces and can positively speed up the beach recovery after storms especially in highly dynamic systems like pocket beaches, typically subjected to beach rotation processes. The results show an implication for coastal managers having to choose fill sources for replenishments.

Keywords: Sediment transport, Particle shape, Mixed beach, Swash, Gravel nourishment, Pocket beach, RFID, Tracers.

1. Introduction

During the last decades beach erosion processes have gained increasing attention in scientific and public medias, because of the negative effects they exert on coastal economies. For instance, a decrease in beach width would mean a loss of available space for beach resorts: this has social implications for regions where the economy revolves around tourism. Erosion issues are not a peculiarity of this century though. Coasts are a highly-dynamic environment, characterized by rapid modifications that might have nothing to do with erosion as we are used to know it. Progradation and retrogradation always existed due to natural processes that are tightly connected to factors such as sea-level rise, sediment supply, accommodation space. The main causes that determined the inception of the erosive state in recent decades, especially in countries around the Mediterranean coastline, are instead strongly related to anthropic activities such as river dredging, river damming and armoring, and reforestation (Billi and Fazzini, 2017). These factors contributed to a decreasing sediment load in rivers, which ultimately resulted in a harsh reduction of available sediments capable to feed the shorelines adjacent to river mouths. Consequently, beaches cannot be refilled naturally as incoming sediments transported by longshore drift are scarce and often intercepted by structures such as groynes, piers and breakwaters. Thus, artificial replenishments are increasingly used also as a form of coastal protection (Stive et al., 2013), because they are less invasive than hard protection structures. Their basic concept involves the introduction of significant sediment volumes into the coastal system, which is something that is desperately needed by starved beaches (French, 2001) or as an adaptation measure to future sea level rise (Dornbusch, 2017). Sand is not the only type of fill, coarse sediments are also occasionally used especially where wave motion is high and sand replenishments would be of short duration (López et al., 2018). Nourishment projects with coarse material (i.e. gravel or shingle) started in England in small scales and occasionally already in the 1950s and began to proliferate in the 1970s (Hanson et al., 2002; Moses and Williams, 2008); currently they are not only used to contrast erosion on natural coarse-grained beaches but also as an attempt at stabilizing originally sandy beaches (Takagi et al., 2001; Cammelli et al., 2004; Kumada et al., 2010; Bertoni and Sarti, 2011; Ishikawa et al., 2012). However, an issue often present is the availability of coarse material from sea-bed reservoirs, as this type of sediment is only available in continental shelf seas, where large fluvio-glacial deposits are available, like in the North Sea. The solution is to use sediment from inland quarries or crushed fill.

Regarding nourishment projects made with coarse material, particle shape is an important factor to consider along with grain size. The most common scheme used to describe particle shape is the one proposed by Zingg (1935), which is based on particle’s axis ratios., Domokos et al. (2010) recently introduced a shape descriptor based on the number of static balance points of the particle. The first studies attempting to explain the transport of different particle shapes date back to the 1940s and 1960s.. Krumbein (1942) noted already that under traction spheres move faster than any other shape: this was later explained by Shephard and Young (1961) and by Kuenen (1964) as disks have lower pivotability, and a lower pivotability means a lower mobility in traction (Bluck, 1967). Bluck (1967) distinguished among four cross-shore facies of gravel distribution based on size and shape of particles. However, the Bluck (1967) cross-shore size and shape segregation is not recognizable everywhere: the clarity and number of these cross-shore facies tend to diminish when the beach system is dominated by longshore transport (Carter et al., 1990a, b; Carter and Orford, 1991). According to Orford et al. (2002) particle shape represents a major complicating factor in sediment cross-beach differentiation. The degree of shape zonation on the beach is a function of wave energy conditions and an increase of shape segregation is produced by swell wave action, depending also on wave phase and breaker type (Orford, 1975). Carr et al. (1970) analyzing different shape ratios and indexes concluded that c-axis (i.e. particle thickness) is the most decisive factor in determining pebble sorting by wave action. Shape is also important parameter that controls the slope angle of pebble stockpile due to imbrication that may occurs and can influence pebble sorting (McLean and Kirk, 1969). According to Williams and Caldwell (1988), particle shape predominates when wave energy condition are low, whereas size and weight influence sediment sorting when energy conditions are high. Thus, a better understanding of the influence of particle shape on sediment transport is crucial in nourished beaches characterized by low energy conditions. On gravel beaches there is an important saltating population made by sphere-shaped pebbles when the bed is dominated by disks or oblate shapes (Isla and Bujalesky, 1993). Individual clast motion is surely dictated by a number of micro-mechanical factors ascribable to shape and size over a heterogeneous bed (Buscombe and Masselink, 2006). Ciavola and Castiglione (2009) experimented that disk-shaped pebbles in a microtidal mixed sand and gravel beach moved down towards the beach step under higher wave energy and slided-up the beachface as conditions turned milder. Grottoli et al. (2015) already showed some preliminary results on differential transport of pebbles according to shape and size, but those findings were based on post-experiment reconstructions and not direct observations as the process was taking place. As previously demonstrated, coarse sediments do move under fair-weather conditions especially in the swash zone, which consequently is the area where sediments show the highest mobility rates also in short timespans (Bertoni et al., 2013; Grottoli et al., 2015). Based on the huge mass loss reported on marked pebbles injected on artificial gravel beaches (Bertoni et al., 2012; Bertoni et al., 2016), or on native coarse-grained beaches (Matthews, 1983; Latham et al., 1998; Chen and Stephenson, 2015; Cox et al., 2018) the durability of gravel nourishments is strongly affected by the type of filling material (Dornbusch et al., 2002). In this sense, insights about the relations between particle shape and transport may be crucial in supporting coastal managers making the best decisions when designing coarse sediment replenishments. The aim of this paper is to improve the understanding of transport behavior (or patterns) of coarse sediments in relation to their shape under low energy conditions. Implications for coastal managers having to choose fill sources for gravel nourishments are found.

2. Study area

The experiment was set up on a mixed-sand-and-gravel beach (in accordance with the classification of Jennings and Shulmeister, 2002) at Portonovo, a small village located in the northern part of the Conero Headland (Fig.1), about 9 km southeast of the city of Ancona (central Adriatic Sea). The Portonovo seaside is divided in two sectors, separated by a small armored headland; these protections were built to defend an historical tower from severe damage during major storms. The eastern part of the beach was selected for the experiment as it is just 500 m long (the western sector is 700 m long) and delimited between two protection structures that prevent any sediment exchange with the adjacent sectors, especially coarse particles. Beach width is variable (about 20 to 60 m) and largely depends on the direction of storms, which eventually determine the complete rotation of the beach (Grottoli et al., 2017). The prevalent grain-size is gravel, which usually piles up on the backshore; the coarsest sediments accumulate on the swash zone, especially on the step. The sandy fraction is mainly present in the upper portion of the backshore and offshore of the step. However, as sediment redistribution after storms is high on this beach, the mutual position of each grain-size is particularly dynamic. Limestones and marls mainly constitute gravel and pebbles; the sand is produced by progressive disaggregation of the coarser fraction. Portonovo's beach was naturally fed just by limited cliff erosion, as no rivers flow within. The erosion issues experienced in the last decades along the local shores pushed local administrations to invest funds in coastal protection structures (groynes, armoring), but as beach retreat would not cease, they also undertook artificial replenishments to compensate for sediment loss. Almost 20000 m^3 of alluvial material from inland quarries were unloaded on the western side of the Portonovo seaside between 2006 and 2011; unfortunately there is no record of the volume that was released on the eastern sector. The fill material was constituted by pebbles and cobbles of average diameter of about 4-100 mm; textural parameters and lithology were akin to those naturally present on the beach (personal communication by local authority). As beach concessions occupy this sector of the coast, the backshore is subjected to artificial flattening in April, in order to enlarge the beach width for the summer season, a common practice on most Adriatic beaches (Harley and Ciavola, 2013). Although the beach is highly anthropized, it recovers quite fast in response to forcing (Grottoli et al., 2017): the beachface slope is typically 0.2, while the seafloor is about 0.01. The most intense storms are northeasterlies and southeasterlies, which correspond to the dominant winds, "Bora" and "Scirocco" respectively. The most typical wave height is comprised in the interval between 0.25 and 2 m. The average tidal range at spring tide is 0.4 m.

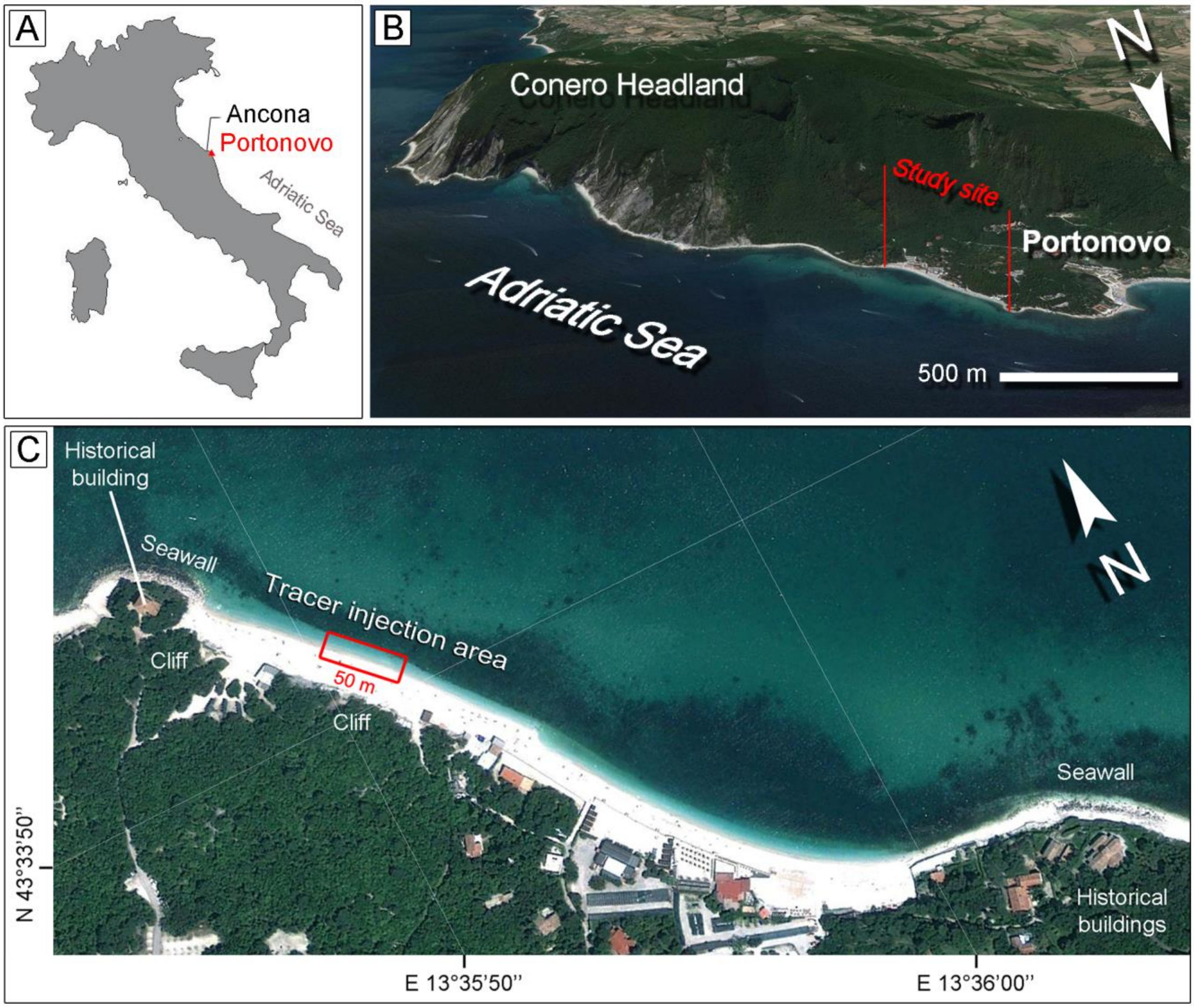


Figure 1 - Portonovo study site: geographic location relative to Italy (A); local geographic location (B); Portonovo beach overlook and experiment area (C).

3. Materials and methods.

3.1 RFID technique and tracer preparation.

Tracer displacement was investigated by means of the Radio Frequency Identification (RFID) technology. This technology allows the unambiguous identification of an item by means of radio transmission. In particular, an RFID system is composed of two devices: an RFID reader, which generates an electromagnetic (EM) field that is used to interrogate, and eventually power, the second device, i.e. the transponder (or tag). The tag is the actual electronic label that is positioned on the item to be identified, i.e. the element allowing the unambiguous identification of the pebble to which is coupled: it can be either passive (powered by the EM field generated by the reader) or active (powered by a battery) and it is provided by an hexadecimal code and a variable amount of memory (from few bytes to some tens of kB). RFID systems can operate at different frequencies, ranging from Low Frequencies (LF) to Ultra High Frequencies (UHF) and microwaves. Since the solution used to track the pebbles had to operate also underwater, a Low Frequency 125 kHz RFID system was used: indeed, at lower frequencies the EM field is able to penetrate water for limited distances. The 125 kHz RFID reader used for the experimentation proved to detect the presence of tags also underwater for distances up to some tens of cm: in particular, the reader generates a spherical EM field with a 40 cm radius, which represents the maximum detection range both underwater and in subaerial environments. To operate underwater, an ad-hoc waterproof reader was used, able to work at depths up to some meters and for prolonged periods of time, up to some hours. Differently from previous solutions (Benelli et al., 2012) for this experiment the reader was equipped for the first time with a Bluetooth data transmission channel able to send the code retrieved by detecting a marked pebble directly to the smartphone held by the operator, thus avoiding the use of a wired laptop connected to the reader. The Bluetooth transmitter was placed outside the water together with the 12 V lead-acid battery powering the reader, connected to the reader by an RS232 Serial cable. Once a tracer particle was detected, a message appeared directly on the smartphone of the operator in charge of data collection, while an acoustic signal was also emitted by the Bluetooth transmitter as an additional warning sign of pebble detection.

The marked pebbles were prepared by drilling a hole along the longer axis in order to have enough space to accommodate the tag (cylinder glass tag with a diameter of 3 mm and a length of 22 mm, Fig. 2A); the hole was sealed with a waterproof resin, resulting in a weight loss not exceeding 3 g from the original weight. The size limit for sediment tracing was 24 mm, depending on the size of the tag of choice. Pebbles were randomly collected from the beach surface (backshore and beach face) avoiding to exceed the size limit for drilling operations and making sure to collect sediments representative of the beach grain size. Spheres and disks were separated, matching those with similar size. Once marked, tracers were painted with two different colors (red disks and blue spheres, Fig. 2B) in order to make their identification easier during the short-term experiment. The pebble displacements were measured recording their location by means of an RTK-DGPS (Trimble R6, instrument accuracy approximately ±3 cm). Analyses on tracer displacement were also undertaken by means of statistical analyses (t-tests and box plots).

3.2 Experiment set up

The field test was set up on a central straight portion of the beach distant enough from longshore protections and from the embayed shoreline typically affecting the southeastern sector (Fig. 1). These factors can alter pebble displacements as experienced in previous experiments on the same study site (Bertoni et al., 2013; Grottoli et al., 2015). According to Grottoli et al. (2017), Portonovo beach is subjected to an intense sediment displacement after storms depending on the direction of incoming waves. This process is responsible of beach rotation around a focal point, which usually does not experience huge modifications. The present experiment was carried out on this sector of the beach in order to reduce the influence of sediment redistribution or loss in case wave motion would have increased during the time frame of the research. That was just a precaution as weather forecast was carefully taken into account to avoid the concomitance of a high-energy event. At 10:00 am of 20th May 2014, 60 marked pebbles (30 spheres and 30 disks) were injected along 10 cross-shore profiles, 5 m spaced, covering a whole longshore extent of 50 m. All tracers had approximately the same characteristics (weight min. 70 g, max. 188 g; mean diameter min. 39 mm, max. 59 mm). Tracers were injected on the beachface of each profile as it follows: 2 tracers (1 sphere and 1 disk) on the fair-weather berm; 2 tracers (1 sphere and 1 disk) at the swash mid-point and 2 tracers (1 sphere and 1 disk) on the beach step. As pebble shape was the only characteristic to be investigated in relationship to their displacement, tracers were coupled in order to avoid large difference in size and weight (Fig. 2B). Since the detection range of the RFID antenna was approximately 0.4 m, only displacements greater than 0.5 m were considered significant for our results. The wave characteristics were recorded using an InterOcean S4 directional wave gauge during the whole experiment time. The sensor was deployed underwater few meters seaward of the beachface (-1.5 m below the Mean Sea Level) for the entire experiment. Recording time of 20 min per each hour with a separation of 10 min was set, measuring the water level and wave parameters at a frequency of 2 Hz. RTK-GPS measurements of the 10 profiles where tracer injection took place were undertaken both at the injection and at the final tracer recovery in order to record the topographic variation of the experiment area.

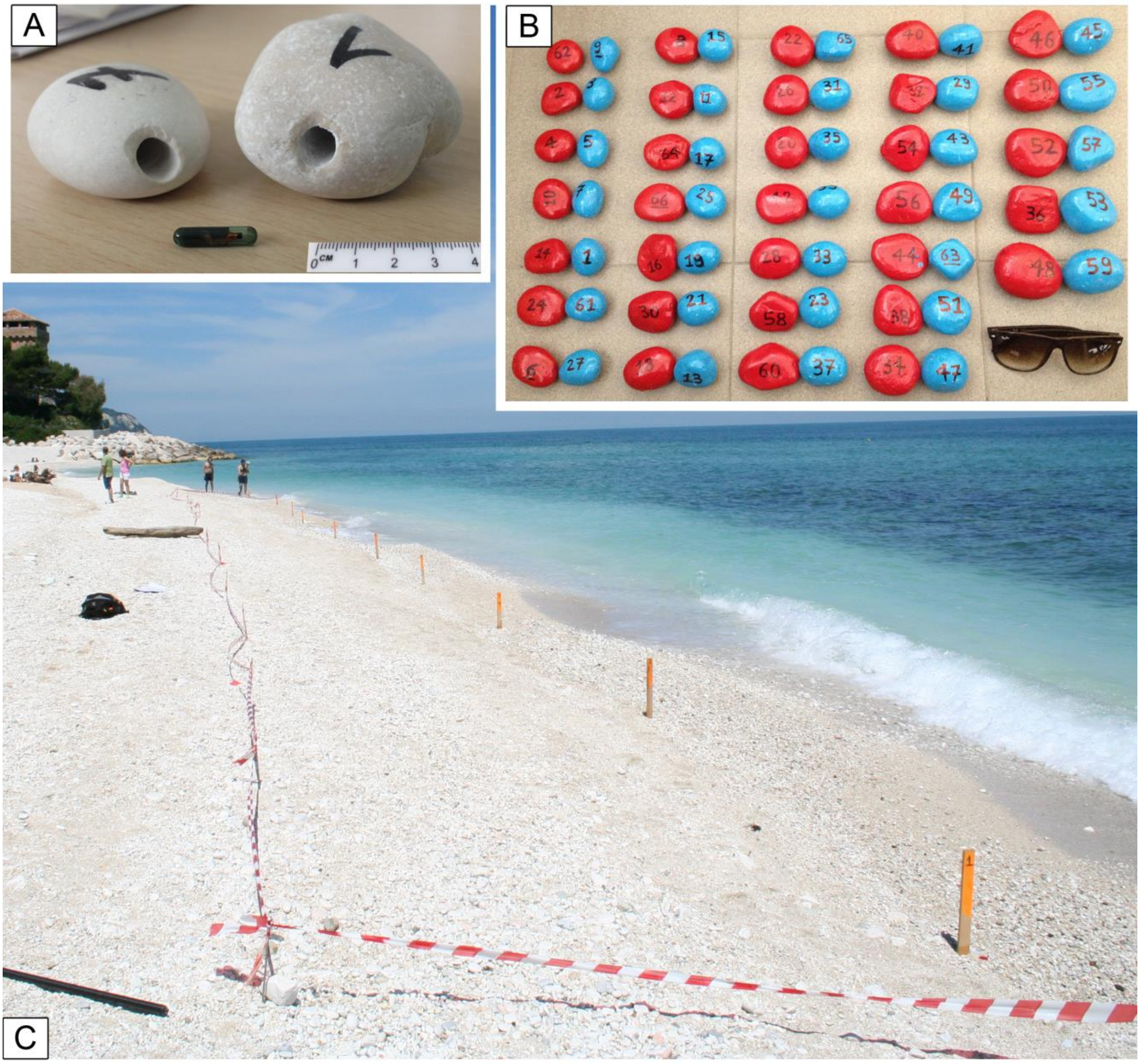


Figure 2 - Tracers and experiment set up: drilled pebbles and tag sample (A); couples of marked pebbles with red disks and blue spheres (B); experiment beach area at 12.00 am of May 20th 2014 (C).

4. Results

4.1 Wave energy conditions.

During the experiment, low energy conditions were recorded by the S4: an average value of 0.1 m of significant wave height and an average value of 6.2 s of peak wave period were registered. The wave direction was predominantly from E (Fig. 3). The maximum significant wave height value

(0.23 m) was registered at the very beginning of the experiment, whereas the maximum water level (0 m above mean sea level) was recorded after the 6 h tracer recovery and remained stable for few hours (Fig. 3). According to the computed surf scaling parameter (Battjes, 1974; Guza and Inman, 1975), wave breaking during the experiment occurred as surging or collapsing, which is typical on reflective and steep coarse-grained beaches.

4.2 Tracer displacement.

Tracer recovery after 6 h reached 88% (93% spheres and 83% disks), but decreased to 75% after 24 h (80% spheres and 70% disks). Most of the tracers moved more than 0.5 m (62% of the whole) after 6 h, with a maximum displacement of 19.5 m covered by a sphere-shaped pebble. After 24 h, 45% of the recovered tracers moved more than 0.5 m and the maximum displacement resulted 35 m, also this time traveled by a sphere. Considering the shape of pebbles, 63% of spheres and 60% of disks moved more than 0.5 m 6 h after the injection. After one day, 57% of spheres and 33% of disks moved more than 0.5 m.

After 6 h most of the displaced tracers moved along the beach face with a stronger longshore component, which affected in particular the tracers injected in the southeastern sector of the experiment area (Fig. 4). Among the displaced tracers, those injected in the swash zone and step resulted more dynamic both among spheres and disks (Fig. 4 and Fig. 5A). No tracers moved from the berm to the step: as a matter of fact, considering profiles 1 to 6, berm tracers basically did not move, whereas those injected in profiles 7 to 10 shifted down the beachface toward the swash zone, especially among spheres (Fig. 4 and Fig. 5A). Swash tracers moved along the swash zone especially among spheres, which resulted more dynamic if compared to the disks (Fig. 5A). Disk-shaped step tracers moved preferentially toward the swash zone, whereas the spheres injected in the step zone moved both toward the swash zone and to the fair-weather berm (Fig. 4 and Fig. 5A).

The longshore component of tracer transport became more evident 24 hours after the injection (Fig. 4). Again, the tracers injected in the step and swash zone resulted more dynamic (Fig. 4 and Fig.

5B) both among spheres and disks. The 50% of disk-shaped tracers injected in the swash zone was not detected (Fig. 5B) and 50% of berm tracers (both among spheres and disks) did not move: those tracers were placed in profiles 1 to 5. Sphere-shaped tracers injected in the swash zone did not shift to any of the adjacent zones (70%, Fig. 5B), but experienced a significant displacement alongshore (Fig. 4). Half of disk-shaped tracers injected in the swash zone were not detected, whereas 30% of them moved alongshore in the swash zone (Fig. 4 and Fig. 5B). Sphere-shaped tracers injected in the step did not show a preferential recovery zone, but resulted very dynamic as well. Half of disk-shaped step tracers moved towards the swash zone, whereas the other half did not move (Fig. 4 and Fig. 5B).

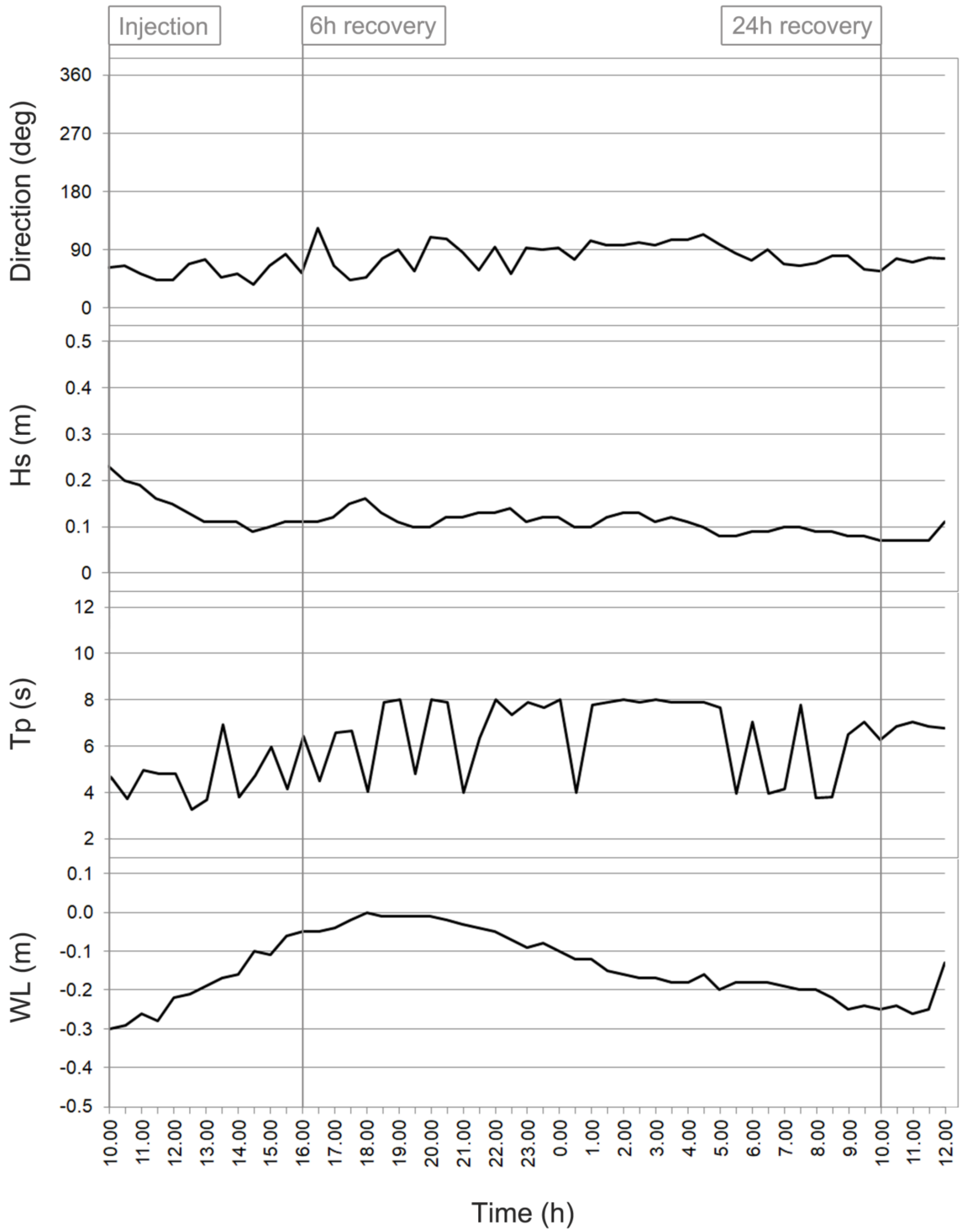


Figure 3 - Wave and water level conditions during the tracer experiment.

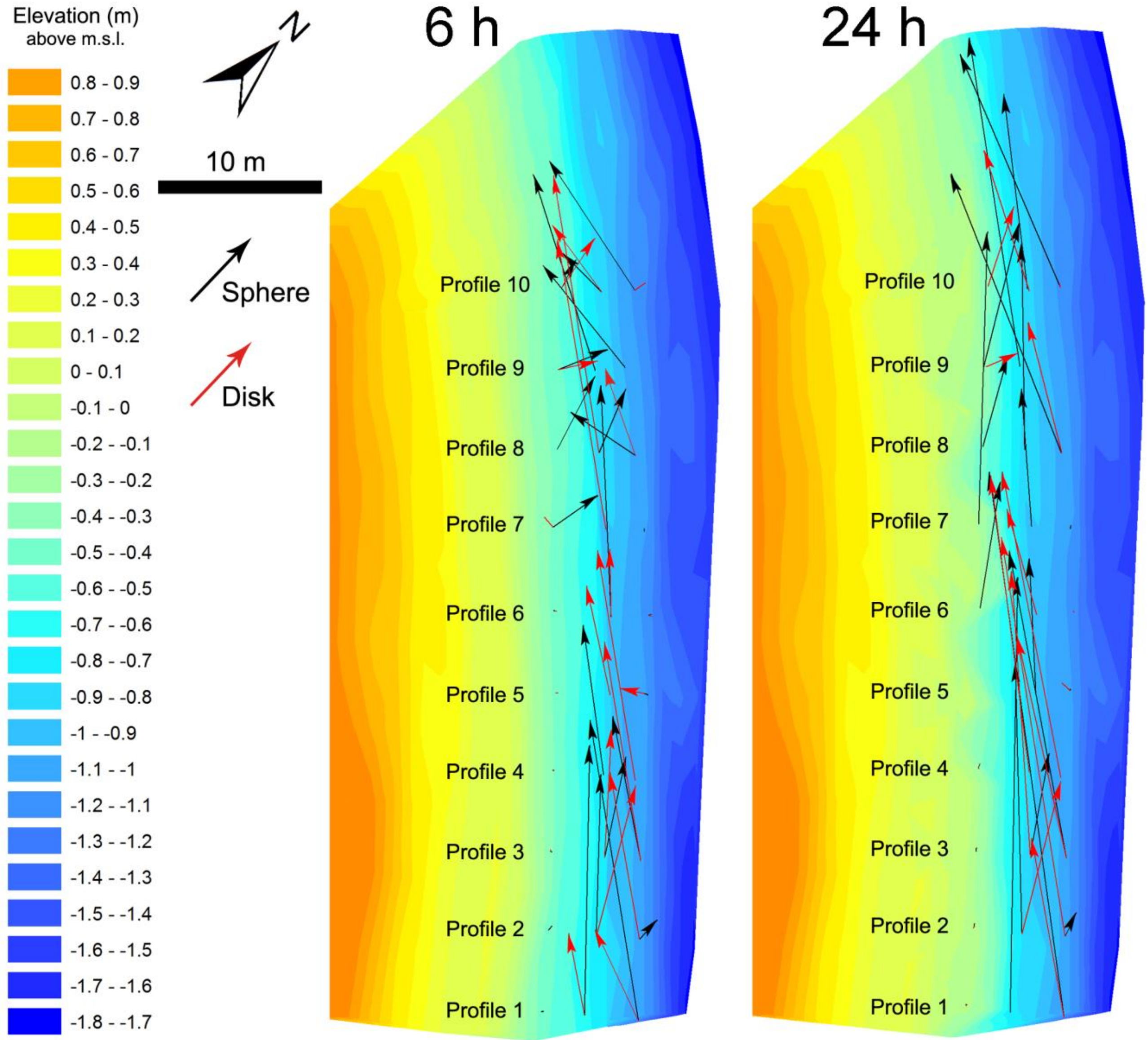


Figure 4 - Displacement map 6 and 24 h after the tracer injection according to tracer shape.

A

6h position / Injection position	Spheres				Disks			
	berm	swash	step	undetected	berm	swash	step	undetected
berm	60	40	0	0	70	20	0	10
swash	20	60	10	10	40	30	10	20
step	30	20	40	10	0	60	20	20

B

24h position / Injection position	Spheres				Disks			
	berm	swash	step	undetected	berm	swash	step	undetected
berm	50	30	0	20	50	20	0	30
swash	10	70	0	20	10	30	10	50
step	30	10	40	20	0	50	40	10

Figure 5 - Position change of spheres and disks 6 (A) and 24 (B) hours after the injection. Values are given in percentage.

After 6 hours the displacement distributions of both shapes are quite similar: their distributions are skewed and the median and mean displacements are around 4 m and 5.5 m respectively, with an interquartile range comprised within few centimeters and 10 m. Twenty-four hours after the injection sphere-shaped pebbles reached larger distances compared to disks. This is confirmed by higher median and mean values (8.7 and 10.5 m respectively) and a larger interquartile range (i.e. greater dispersion), which is comprised between few centimeters and 18 m (Fig. 6A and Table 1). According to unpaired t-tests the difference between the displacements of spheres and disks is not statistically significant since the P value, considering the two recoveries (6 and 24 h), equals to 0.96 and 0.24 respectively (Table 1).

Elevation variation among pebbles showed smaller dispersion since both disks and spheres changed their elevation within ±0.6 m during the whole experiment and always showing a symmetrical distribution (Fig. 6B). After 6 h disk-shaped pebbles showed lower variation of their elevation position if compared to spheres. Spheres showed the largest variation of the whole experiment already after 6 h (i.e. greater interquartile range, Fig. 6B). By comparison after 24 h the disks showed larger distribution and interquartile range if compared to spheres, which moved back closer to the injection elevation except for two outliers. Mean values were around few centimeters for both shapes, showing in both cases a mild increase in elevation compared to the 6 h recovery. Median values of spheres were negative, whereas disk values were positive; mode values attested at 0 m for both shapes. Again, no statistical significance resulted from t-test calculated on the elevation difference between spheres and disks (Table 2).

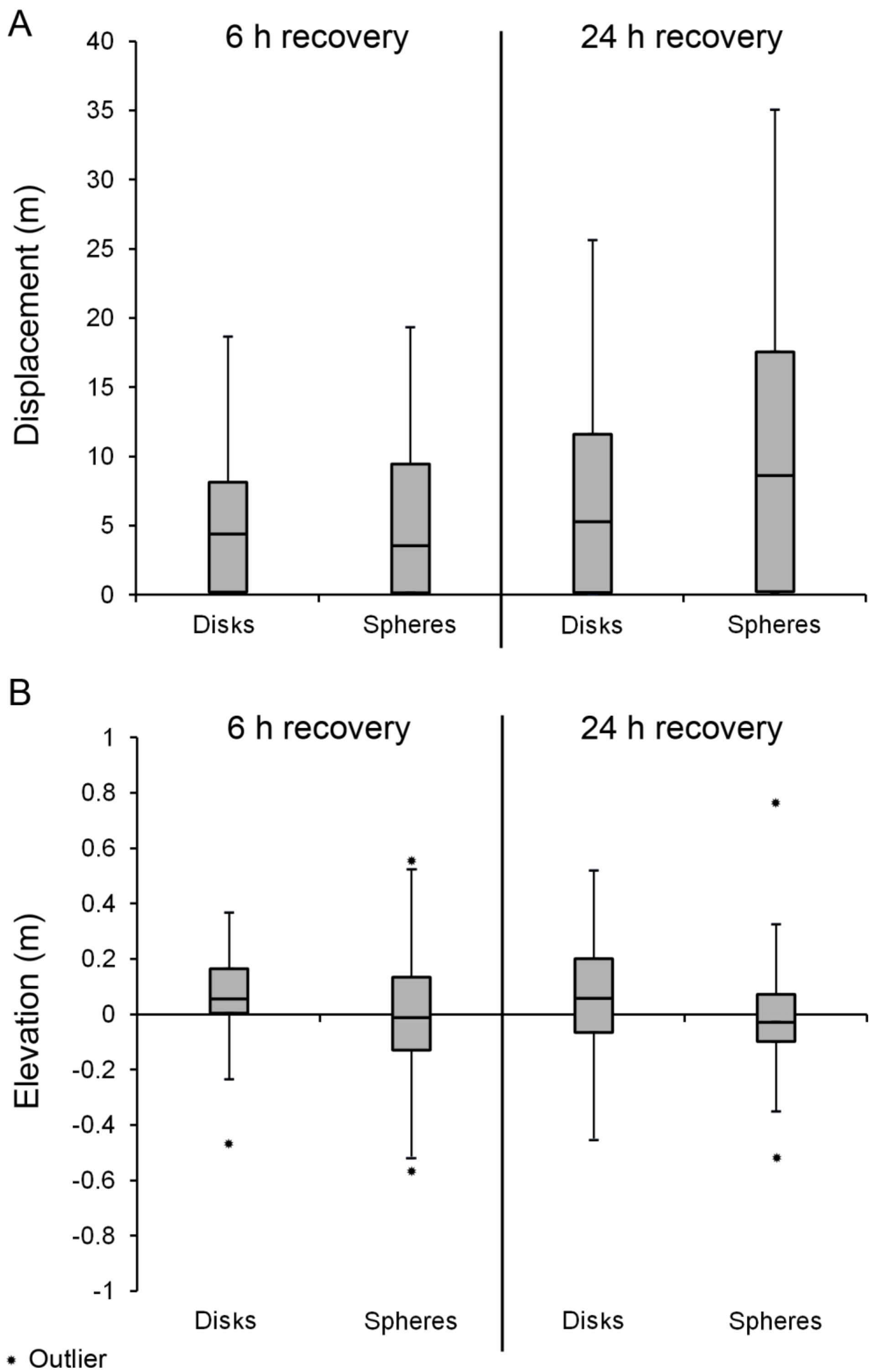


Figure 6 - Box plots showing the displacement (A) and elevation (B) distribution of tracer recovery according their shape.

Displacement	Disks (6 h)	Spheres (6 h)	Disks (24 h)	Spheres (24 h)
Mean	5.54	5.47	7.27	10.49
Median	4.38	3.56	5.34	8.68
Mode	0.84	3.51	0.07	0.22
SD	5.87	5.65	8.13	9.82
SEM	1.17	1.07	1.77	2.00
N	25	28	21	24
t-test (P value)	0.96		0.24	

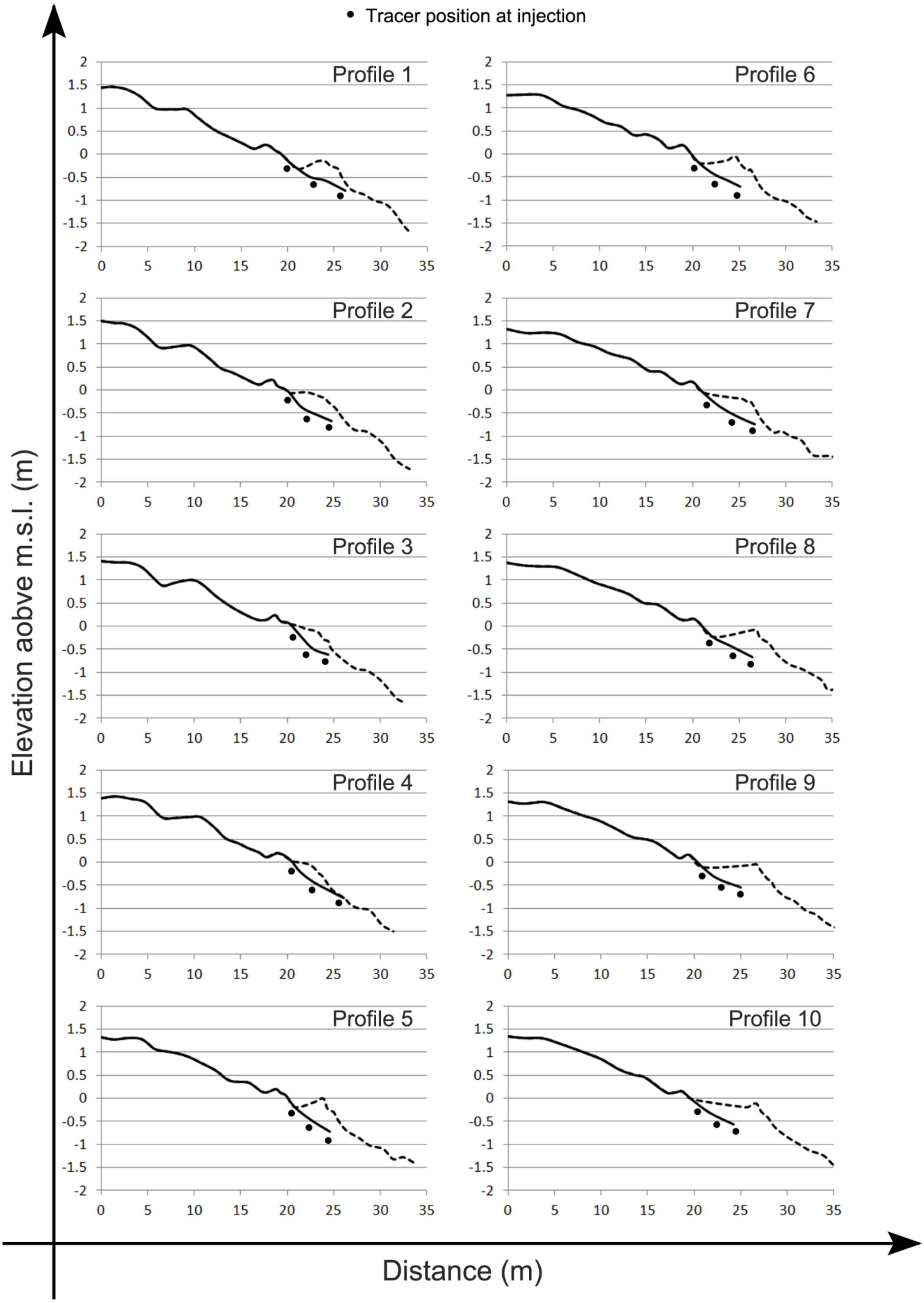
Table 1 - Main statistical indexes and t-test results of the displacement distribution of the two shapes: Mean, Median, Mode, Standard Deviation (SD), Standard Error of the Mean (SEM), number of samples (N) and P value resulted from t-test.

Elevation	Disks (6 h)	Spheres (6 h)	Disks (24 h)	Spheres (24 h)
Mean	0.04	0.02	0.05	0.04
Median	0.05	-0.01	0.06	-0.02
Mode	0.01	-0.01	0.00	0.00
SD	0.21	0.29	0.26	0.30
SEM	0.04	0.05	0.05	0.06
N	25	28	21	24
t-test (P value)	0.77		0.84	

Table 2 - Main statistical indexes and t-test results of the elevation distribution of the two shapes: Mean, Median, Mode, Standard Deviation (SD), Standard Error of the Mean (SEM) and number of samples (N) and P value resulted from t-test.

4.3 Topographic variation of the swash zone.

According to topographic variation, a new fair-weather berm formed in front of the berm where the tracers were injected 24 hours before (Fig. 7). An increase in elevation in the upper part of the swash zone is also visible from the seaward extension of green-yellow colors of Fig. 4. The maximum thickness reached by this new fair-weather berm was 0.5 m and its crest resulted more distant from the one of the day before going from S to N (Fig. 7). The distance between the two crests went from a minimum value of 4 m in the southeastern zone (see profiles 3 and 4) increasing to a maximum of 9 m at profile 10 (Fig. 7). Furthermore, the crest of the fair-weather berm resulted better developed and sharpener from profile 5 to 10 (northwestern sector of the experiment area), whereas resulted attached to the previous berm, without a well developed crest, at the southeastern zone (especially profiles 2, 3 and 4; Fig. 7). The beachface slope was around 0.11-0.12 and did not change for the whole experiment despite the formation of the new fair-weather berm.



Tracer position at injection
Profile 1
Profile 2
Profile 3
Profile 4
Profile 5
Profile 6
Profile 7
Profile 8
Profile 9
Profile 10
Elevation aobve m.s.l. (m)
Distance (m)

Figure 7 - Topographic variation of the beachface between the injection situation (black continuous line) and the end of the experiment (black dashed line).

5. Discussion

5.1 Experiment considerations

The prevailing longshore component affecting the tracers 6 h after the injection was not observed for the majority of berm-injected tracers. Those tracers remained basically stable at the injection position, especially in the first 6 profiles (Fig. 4), regardless of the shape, as they were neither buried by a layer of other sediments thicker of 40 cm to result undetected nor reached, entrained and displaced by swash action. This was also proved by the new fair-weather berm that basically merged with that already present in profiles 2, 3 and 4 creating an armouring of sediment that prevented those berm tracers from moving (Fig. 7). Swash and step tracers of those profiles were largely displaced northwestwards, as they are easily reached and transported by swash currents, and because of a stronger tendency to move downslope, being injected on steeper beach slopes.

It is remarkable that 50% of disk-shaped tracers injected in the swash zone were not detected after 24 hours (Fig. 5B). That could be explained with the large amount of sediment deposited in the northwestern part of the experiment site, also confirmed by a northwest directed longshore displacement of tracers. Sedimentation in this area exceeded the 40 cm of detection range of RFID antenna. Burial generated by the formation of a new fair-weather berm 50 cm high impeded the recovery of some disk-shaped tracers: this could confirm the lower dynamicity of disk-shaped pebbles already perceived by other authors (Shephard and Young 1961; Kuenen, 1964; Bluck, 1967; Grottoli et al. 2015). Likely, disks are more subjected to imbrication based on their lower mobility (Bluck 1967; Orford et al., 2002; Hayes et al., 2010), and are consequently prone to burial by sediments characterized by higher dynamics and regularly set into saltation like spheres (Isla and

Bujalesky, 1993). This process may create a protecting armouring layer (Isla, 1993) that, in the case of these experiments, hindered disk recovery in the swash zone of the northwestern area.

As sphere-shaped pebbles need just mild forces to be displaced, they are less affected to burial generated by sediments piling up. As already highlighted by Isla (1993), spheres and rounded pebbles continue to overpass (i.e. capability to roll over) other sediment, usually comprised of disks (Isla and Bujalesky, 1993), which are more easily trapped within the bed surface. Quite obviously the swash tracers were the most dynamic ones during the experiment and this was also confirmed by the topographic variations occurred on the swash zone (Fig. 7). As explained by Orford et al. (2002), the lack of an effective surf zone on coarse grained beaches, due to steep angle foreshores, means that hydrodynamic activity, especially on low energy beaches, is concentrated on the swash zone and the actor playing the main role on sediment transport is the asymmetry of flow between uprush and backwash (Kemp, 1975; Kirk, 1975; Masselink and Hughes, 1998). Despite elevation variations in positioning were limited both among spheres and disks, it was interesting to realize that spheres after 24 hours showed lower elevation changes, but travelled longer distances compared to disks. This might also be explained with the easier capability of spheres to roll over the swash zone driven by the uprush and backwash fluxes of "swash grazing" (Sherman and Nordstrom, 1985), which resulted in a northwestward longshore transport being generated by easterly waves. The capability to roll over the beach surface keeps the spheres always in movement, whereas disks, once displaced, tend to be less dynamic and to maintain a more stable position on the beach profile (Ciavola and Castiglione, 2009; Grottoli et al., 2015). This capability to roll by spheres can be confirmed also by the dynamics of step tracers, since 30% of them were able to climb the beachface and reach the berm position after 24 hours. On the other hand, only half of the disk-shaped tracers injected on the step were able to reach the swash zone and the remaining half basically did not move from the step zone (Fig. 4 and 5). This means that higher wave energy would be required to slide disks up towards the berm.

5.2 Considerations for local nourishments

This study aimed at improving the understanding of the influence of pebble shape on its transport, ultimately providing suggestions for a better production of fill material for nourishment projects. Sediment characteristics of pebbles are very important, especially when nourishment projects, contemplating coarse material, have to respect specific requirements to reproduce a fill material as similar as possible to the native beach sediment. Little attention is usually spent by nourishment designers on gravel shape of fill material. One should remember that shape can represent a crucial characteristic: for example when natural coarse-grained beaches are highly crowded by tourists or when high environmental values have to be preserved. Those requirements have surely to be respected in the case of Portonovo, as the beach is part of a natural reserve and committees of local beach users claiming for respecting the natural beach characteristics are currently active. Consideration can be also expressed about the right choice of shape for fill material for gravel nourishment both locally and elsewhere.

According to medium term monitoring and the proved pocket beach behavior of Portonovo highlighted by Grottoli et al. (2017), it seems that there is no loss of material outside the beach system. Grottoli et al. (2017) showed that consistent displacement of sediment associated to shoreline rotation occur in response to storm direction but despite the high dynamicity the system seems to be in equilibrium. Recent studies on native pebble transport on this beach reveals that every pebble size is largely dynamic if located in the swash zone: under low energy conditions (0.2-0.3 m of significant wave height) very large pebbles and cobbles (mean diameter between 48-96 mm), with any shape distinction, if reached by wave run-up and swash processes are mainly dragged down slope towards the step zone (Bertoni et al., 2013) or are not able to slide up back to the fair-weather berm if located on the step (Grottoli et al., 2015). On the other hand, smaller pebbles (mean diameter between 24-48 mm) are able to "climb" the beachface and disks in particular preferentially reach more stable position on the back of the fair-weather berm or at the step. Spheres, being more dynamic, roll all over the swash zone continuously. Despite the high dynamicity showed by Portonovo beach both under low (Bertoni et al., 2013; Grottoli et al., 2015) and stormy energy conditions (Grottoli et al., 2017), the beach, being largely exposed to the effects of a bimodal and opposite direction of storms (NE and SE) and being limited by defense structures at its longshore edges, can quickly recover from a storm (Grottoli et al., 2017). In this perspective the choice of sphere-shaped pebbles, given their higher dynamicity which is compatible to the high dynamicity of the system, should be preferred for potential fill material production in the future. Based on local studies produced so far, the beach in Portonovo does not seem to require any sediment refill in the near future: to confirm this opinion further studies should be made on long term monitoring of sediment transport coupled to analyses on abrasion rate, in order to investigate how shape and size actually evolve over time through continuative high energy conditions. Furthermore, as already occurred at the gravel nourished beach of Nice (Anthony et al., 2011), the chance to lose material offshore has to be avoided. Being Portonovo a unique "artificial" pocket beach, these considerations are very site specific: as highlighted by Sammut et al. (2017) pocket beaches should be analyzed as individual coastal settings, since each beach has unique characteristics related to coastal configuration, geology and exposure to incoming waves. For example, Pikelj et al. (2018) on an artificial gravel beach of Croatia (Dugi Rat) highlighted continuous sediment losses over 1.5 years of monitoring, despite beach re-nourishment repeated on an almost yearly basis. On the other hand, the same authors noted how a natural gravel beach (Brseč) rapidly responds to waves generated by the prevailing north-easterly and south-easterly winds of Adriatic Sea, changing its rotation and generating sediment losses and gains.

5.3 Consideration on fill material for gravel nourishments

Hanson et al. (2002) made a comprehensive review on nourishment practices in European countries: the study compares several parameters taken into account by each country for nourishment project, but no mention is made about the sediment shape of fill material. The high dynamicity showed by pebbles even with low energy conditions means that fill material used for gravel nourishment has to be precisely defined in all its characteristics. Recent studies about pebble abrasion demonstrated that the latter can be consistent, bringing to 61 % of mass loss (Bertoni et al. 2016) or 41% of weight loss (Matthews, 1983) already after one year. Pebble abrasion not always depends on mineral characteristics of fill material, but strongly depends on geometric aspects of pebble surface leading to shape changes (Novák-Szabó et al., 2018). Gravel is usually not a popular beach material because it is hard to walk on and uncomfortable for sunbathe, but fill material usually has a size larger than or at least equal to the native beach sediment, so knowing how the sediment particle will transform its shape and size by abrasion and transport processes is essential. In this perspective is very important to better understand how gravel fill material evolves over time when deployed on a native sandy beach surface. Several project have been made choosing gravel as nourishment material to counteract erosion processes on native sandy beaches (Takagi et al., 2001;Cammelli et al., 2004; Kumada et al., 2010; Bertoni and Sarti, 2011; Ishikawa et al., 2012), but no considerations are made on shape nor shape evolution of fill material. The real issue of gravel nourishment is the supply of coarse gravel (pebbles and cobbles), thus many coastal managers chose to replenish using fine gravel or sand-gravel mixes (Williams, 2005; Moses and Williams, 2008). For this reason attempt to achieve a specific shape is not an easy task and surely could represent an extra expense within the project budget. Further studies are needed to better establish the lifetime of gravel nourishments in comparison with sand or mixed sand and gravel ones. Understanding how coarse gravel shape can positively influence the durability of nourishments in order to make this solution more sustainable is also needed since beach recharge are naturally short-term fix solutions that have to be regularly repeated (Moses and Williams, 2008).

6. Conclusions

The study presents an original contribution to the understanding of the role of pebble shape on controlling sediment transport in a short timespan. The transport of sphere and disk-shaped pebbles was analyzed and compared as it has profound implications for the right choice of fill material for gravel nourishments. Under low energy conditions all shapes move in the swash zone with a predominant longshore component and remarkable displacements. Even though from this experiment emerged that there is no statistical relationship between the shape of the pebbles and their displacements, shape can be a discriminant factor for pebble transportation, at least under low energy condition. Spheres resulted more dynamic than disks thanks to their capability to roll over the swash surface. Spheres are always kept in movement by swash fluxes and taking advantage of their capability to roll over the beachface can easily climb and be dragged down all over it. Disks, being less dynamic, are more subject to imbrication and once displaced towards a more stable position can be easily buried by other sediments. Nourishment schemes should prefer a spherical shape for fill material especially on dynamic beaches (e.g. pocket beaches) where the equilibrium is represented by a regular shifting of sediment in response to a bimodal wave direction.

Understanding how the sediment particle will transform its shape and size by abrasion and transport processes is essential, especially nowadays that gravel is often preferred to sand as recharge material also on native sandy shores. The precise characterization of gravel fill material is also crucial given the lack of natural sources exploitable. Studies on particle shape are needed to better establish the lifetime of gravel nourishments as these practices are short-term solutions that have to be regularly repeated.

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