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Assessment of a Gravel Nourishment Project Fronting a Seawall at Marina di Pisa, Italy

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ABSTRACT

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A gravel beach was created in winter 2001-2002 seaward of a 330-meter-long seawall at Marina di Pisa, Tuscany, Italy. A monitoring project was performed to evaluate the stability of the new beach and the interaction between the coarse fill and the fine sand comprising the nearshore profile. Bathymetric surveys were conducted in October 2001, before the nourishment operation, in March 2002, two weeks after nourishment, and in January 2003. Topographic surveys were conducted from the backshore to 9 m depth along eleven cross-shore transects spaced every 25 m. Sediment samples were collected on the nearshore surface prior to nourishment and on the nearshore and nourished beach following nourishment. One-meter-deep trenches were dug across the beach in May 2002 and January 2003. Shoreline planform and profile analysis reveals that the beach rotated toward the direction of high energy wave approach, resulting in a narrowing of the berm in one segment that allowed waves to overtop the seawall and deposit gravel landward of it. Sand from the nearshore infiltrated the gravel pore spaces, reducing the permeability and porosity of the gravel beach, and potentially altering its stability. No gravel clasts appeared to move seaward of the beach step during storms. Preliminary results indicate that a gravel beach can protect coastal infrastructure and produce a surface usable for tourist activity.

ADDITIONAL INDEX WORDS: *Beach profiles, gravel fill, nourishment, shore protection, wave overtopping*.

INTRODUCTION

More than 50% of the Italian beaches experience severe erosion which has been addressed by building groins, seawalls, detached breakwaters and artificial islands (AMINTI and PRANZINI, 1993). These modifications to the coastal landscape often shift the erosion problem to the adjoining unprotected sectors, restricting recreational use of the beach. In the early 1980s softer or less obtrusive shore-protection strategies began to be applied, including submerged breakwaters (SILVA and DI GIROLAMO, 1993; GHEZZI *et al*., 1999), submerged groins (AMINTI *et al*., 2003), beach nourishment (HANSON *et al.,* 2002; PRETI and ALBERTAZZI, 2003) and recently beach dewatering (DAMIANI *et al*., 2002). Most of these strategies were applied to previously unprotected beaches or seaward of old protection structures, but not where the water seaward of those structures is now several meters deep and wave energy is not dissipated through shoaling. Here, these "archaeostructures" cannot be replaced by soft protection methods without a huge amount of sediment (and money) for artificial nourishment. Although a rapid conversion from hard to soft shore protection is not possible, a gradual transition can be carried out to begin to restore a more natural profile. This process is being undertaken in Tuscany, with a joint effort by the regional government, local administrations and university researchers (AMINTI *et al*., 1999). Two coastal sectors are presently addressed in this initiative:

1. Marina di Massa, where seawalls, detached breakwaters and groins connected to low-crested breakwaters will be replaced by submerged groins that are presently being tested on the eroding shore downdrift of the structures (AMINTI *et al*., 2003);
2. Marina di Pisa, where 10 detached breakwaters fronting 2,000 m of a 2,330 m-long seawall will be lowered to -0.50 m above mean sea level (msl) and a gravel beach will be constructed seaward of the seawall.

The submerged groin project is evaluated in a previous paper (AMINTI *et al*., 2003). This paper focuses on the first phase of the project at Marina di Pisa, which is the construction of the portion of gravel beach in front of the 330 m long seawall downdrift of the breakwaters (Figure 1). This experiment provides a unique opportunity to study the morphological adjustment of gravel fill placed on a sandy shore to see if the reduction in wave reflectance helps transport sand onshore and see whether an unprotected gravel beach is stable in this coastal sector. Previous studies have identified the advantages of using gravel as fill material or as a dynamic revetment because it has greater stability than sand (EVERTS *et al.,* 2002; US ARMY CORPS OF ENGINEERS, 2002; KOMAR *et al*., 2003). Our study identifies some of the problems and advantages of using gravel as fill where it does not occur naturally.

STUDY AREA

Site Description

Marina di Pisa is located on the southern depositional lobe of the Arno River delta, where the coastline prior to the formation of the lobe was oriented approximately North to South. Dominant waves approach from 240° and the offshore wave energy resultant is 247° with 2371 kW h m^{-1} yr^{-1} with a limited directional dispersion.

The delta formed during the last two thousand years as the result of the increased input of river sediment caused by intense deforestation inside the catchment area (PRANZINI, 2001). The town was built in the 19th Century as one of the first coastal tourism settlements in Italy. Delta accretion ceased about the time of construction of the village, and beach erosion showed its first effects (TONIOLO, 1910). Sediment input from the river was more than 5×10^6 m^3 yr^{-1} from 1500 to 1800 but is now less than 2×10^6 m^3 yr^{-1} (BECCHI and PARIS, 1989). This reduction in sediment input from the river is due to mountain reforestation, land reclamation, dam construction and river bed quarrying. This erosion became most pronounced during the 20th century (PRANZINI, 1995). The shoreline on the northern lobe of the delta was not developed and was free to retreat, causing loss of 1300 m of land from 1881 to 1997. The present beach erosion rate there is locally 20 m yr^{-1}.

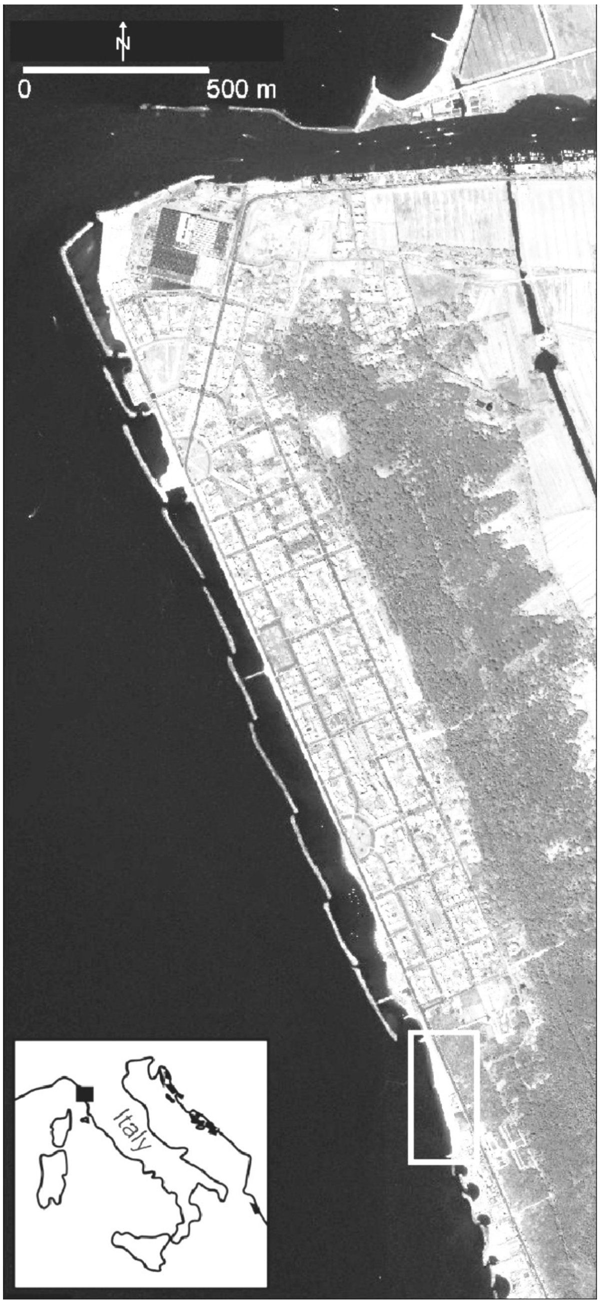

Figure 1. Study area.

The presence of the village on the southern lobe resulted in calls for shore protection. Groins were built in the 19th Century; seawalls were added beginning about the turn of the past century; and detached breakwaters were added after WW II. Structures include 1) the 2.33 km seawall, 2) 10 detached breakwaters, with submerged connections at approximately 1 m below msl built along the first 2 km of the seawall, and 3) 6 groins built between the seawall and the breakwaters (Figure 1). At present, a total length of 4.3 km of hard structures protect 2 linear km of coast (2.15 km km^{-1}). Only small patches of sand now exist along the shore landward of the breakwaters as a result of artificial nourishment using sand provided by dredging at the river mouth.

The importance of the once-fashionable village has declined, and bathing activities and structures built to support beach use have shifted southward. Many small protection structures are built along 1.6 km of sandy coast south of the 330 m of seawall not protected by breakwaters. Most of these structures were built by the bathing establishment owners without a master plan and frequently without authorisation.

Although the coastline seaward of the village was stabilized by the breakwaters and seawall, erosion was still active in the nearshore, and the bottom is now 7 m deep at the outer base of the detached breakwaters. No bar system develops here and a convex profile has formed due to erosion at the base of the structures.

The sediment budget is expected to increase in the future due to restrictions on river bed quarrying and to a more sustainable management of the river basin due to creation of basin authorities in 1994, that are required to consider the sediment budget to the coast that is due to stream flow (AUTORITA' DI BACINO DEL FIUME ARNO, 1994). The coast at Marina di Pisa may not benefit from this increase in sediment input, because sediment may not pass the protection structures. Accordingly, nourishment is required to restore the beach.

The experimental nourishment was carried out seaward of the southern part of the seawall, where no offshore structures are present and no beach existed prior to the project (Figure 2 a).

The beach profile decreased from -2 or 3 m just seaward of the seawall to the -10 m isobath at a mean slope of approximately 6°. From October 2001 to February 2002, 28,000 m^3 (about 93 m^3 m^{-1} of coast) of fragments 40 to 200 mm in mean size derived from marble processing operations were placed seaward of the seawall (Figure 2 b). Some of the clasts were not fragments of original bedrock blasted from cliffs but tabular waste materials left over after slabs were cut into sheets. The sediments had been previously discarded in a stream near the processing operations, and many of the clasts were rounded by prior fluvial transport. Others were flat, sharp-edged slabs that revealed little reworking. Sediments were placed in front of the seawall to form an approximately 20 m wide platform at 2 m above msl. Three 30-m-long groins were built to prevent longshore sediment losses; two were built at the extremities of the project area and a flatter one was built in the center, creating two segments. Each groin has a 10-m-long submerged extension (Figure 3). The gravel fill was placed on a sandy nearshore where the water depth was about 3 m below msl. The nourished beach was reworked by waves within 6 months of emplacement, forming a high berm. The berm was mechanically graded seaward two months after placement to displace the swash zone seaward and allow waves to rework the sharp-edged grains to cause them to become more rounded.

Figure 2. Study site looking north on September, 2001 prior to nourishment (a) and on May, 2002 following nourishment (b).

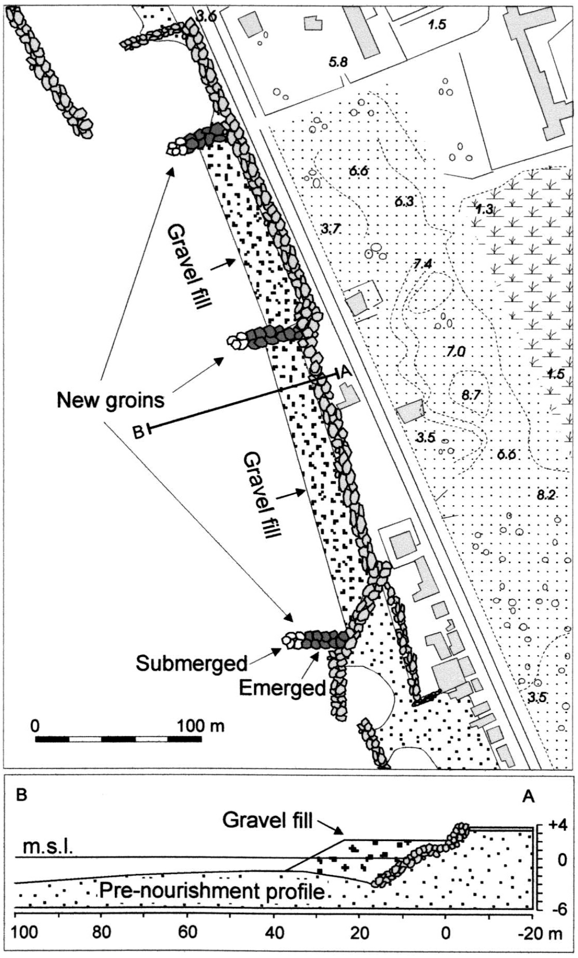

Figure 3. Design of beach nourishment project in 330 m study site (A-B profile vertical exaggeration 1:2).

METHODOLOGY

Nearshore morphology seaward of the seawall was surveyed in October 2001, prior to the nourishment. Surveying was repeated in March 2002, two weeks after the nourishment was completed, and in January 2003. Topographic surveys were conducted from the backshore to a depth of 9 m along eleven cross-shore transects, spaced every 25 m (Figure 4). Accuracy of depth measurements is considered +/- 50 mm. These data permitted comparison of shoreline position and cross-sectional profile change. Twenty-six sediment samples were collected on the pre-nourished nearshore during the October 2001 bathymetric survey. Forty-one sediment samples from the swash zone to approximately -6 m were collected in March 2002. Repeat sampling was done during the last bathymetric survey in January 2003. Trenches about 1 m deep were dug across the profile in May 2002 and January 2003 using earth-moving equipment. Trenches dug in May 2002 were discontinuous, whereas in January 2003 they extended from the swash-zone to the berm crest.

The results of sediment analysis are not discussed in detail in this paper, but preliminary information on the onshore migration of sand and its incorporation into the gravel are given. Topographic data were processed by Autocad 2002 and Surfer rel. 7 to produce beach profiles, bathymetric maps, 3D models and height-variation maps. Visual observations of the effectiveness of the fill were made during and just after a major storm occurring 4-5 October 2003.

RESULTS AND DISCUSSION

Shoreline Change

The project shape in profile and in plan (Figure 3) was never achieved because of the storms that reshaped the beach before completion of the work. The beach became realigned, with sediment displacement to the south (Figure 4), substantiating the need for the two groins to hold sediment within the nourishment site. Two weeks after the end of the construction work, the shoreline faced 240°, closer to the direction of high incident wave energy. This alignment caused the shoreline to intercept the seawall a few tens of meters from the northern groin (Figure 4).

Wave breaking on the seawall was not prevented near the groin, and the beach in the northern segment is not stable. Mean shoreline retreat was approximately 2 m from March 2002 to January 2003 along the 116 m length of this segment. The southern segment, where a full beach profile could develop without intercepting the seawall, accreted slightly (+0.35 m) due to the addition of sediment passing the low central groin.

Beach Profile Changes

Representative pre-construction profiles (Figure 5) show a trough just seaward of the seawall. Profiles surveyed at the end of the following winter season show a sharp connection between the new gravel beach and the sea floor. The trough that once bordered the seawall is filled (e.g. Profile A).

The nearshore has a discontinuous bar system (Figure 6). The bar system is not present north of the study area, where the depth is more than 6 m offshore of the detached breakwaters, but it is well developed south of the study area, where coastal structures are smaller and interrupted. The landward bar is farther offshore after the nourishment, but its average distance from the shoreline (now the gravel beach) is the same. The second bar, where present on the profile, is shifted offshore about the same distance.

A sharp and high berm crest was reformed by storm waves

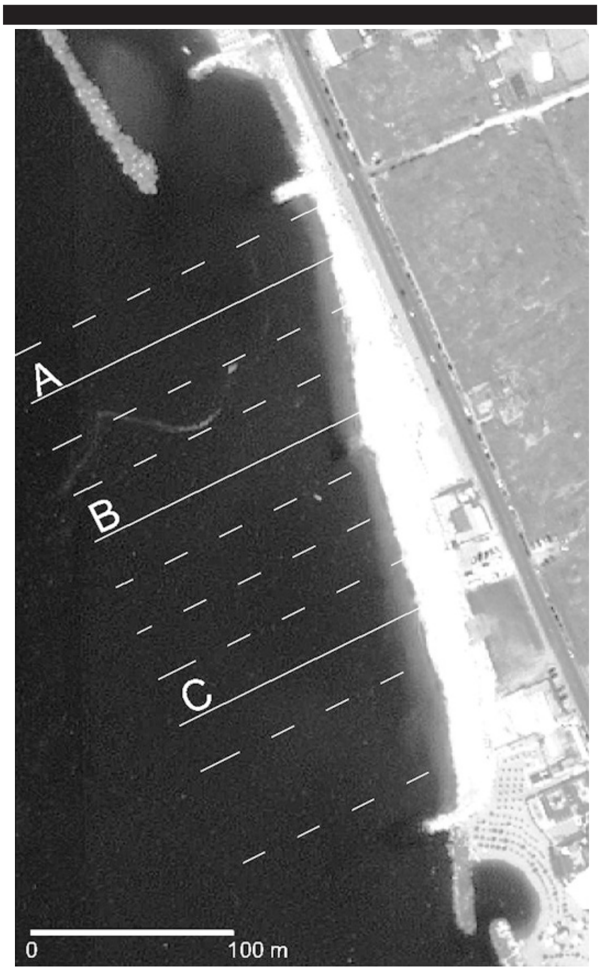

Figure 4. Study site (June 15th, 2002) showing locations of topographic transects.

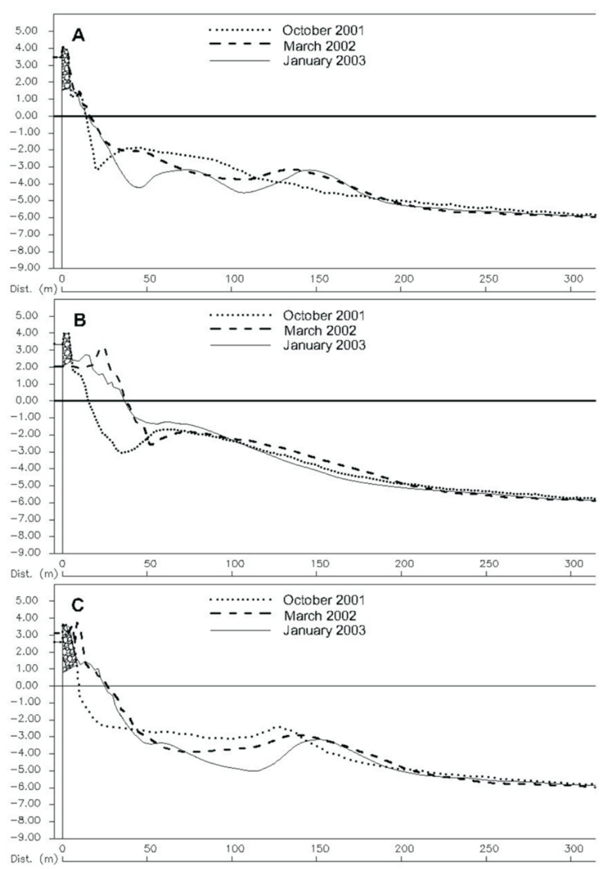

Figure 5. Topographic profiles taken along the transects put in evidence in Figure 4.

after reshaping by earth moving equipment. The elevation of the berm crest is higher than the seawall in places (Profile C, Figure 5), reaching 4 m above msl. Where the berm is narrower, the crest intercepts the seawall at the same top elevation, and some clasts are transported over the seawall and onto the street during storms (Figure 7). Where the available material is sufficient to develop a backshore (Profile B, Figure 5), the storm crest is far from the seawall and this problem does not occur. Traffic was prevented from passing the study areas twice in a year on average prior to the project because of waves passing over the seawall. After deposit of fill traffic was not prevented, even during the severe storm of 4-5 October 2003 (Figure 7).

In January 2003, mean slope from the berm crest to the shoreline varied from 20% to 25%, but values of 50% were reached on some segments of the storm berm slope. Steepness is characteristic of coarse-grained beaches and can reach 15% on cobble beaches (KOMAR, 1999) but measured values at the field site are higher. Beachface slope is a function of rates of swash infiltration and permeability that is controlled, in part, by sediment size and sorting (MCLEAN and KIRK, 1969). Swash infiltration and deposition is enhanced higher on the profile where the interstices of the gravel matrix are not filled with sand. The tabular shape of many of the clasts at the field site increases the likelihood for onshore transport in the swash uprush (particularly during storms) increasing the elevation of the berm crest (LORANG, 2002) and the slope of the foreshore above msl. When sand occupies the interstices of the gravel matrix permeability can be lowered and result in lower beachface gradients (MASON and COATES, 2001; MCLEAN and KIRK, 1969) which is the case lower on the beachface at the field site.

In January 2003, the overall shapes of the profiles on the lower foreshore were similar to March 2002, but the upper foreshore and nearshore profiles showed conspicuous change. Up to 2.5 m of lowering was measured relative to the pre-construction profile. Deepening occurred close to the beach face on some profiles (Profile A, Figure 5), but it is not clear whether the deepening occurred due to bar migration or wave reflection at the base of the steep gravel beach. Conspicuous changes occurred about 100 m from the shore (Profiles A and C) and appear to be due to alterations to the bar. Changes about 40 to 50 m from the shore occurred at different times on many of the profiles. These changes may be due to wave reflection at the base of the foreshore or possibly to an increase in backwash velocity associated with the reduced permeability of the beach caused by infiltration of sand into the gravel deposit. The permeability of a gravel beach decreases as the sand content increases, inducing an increase in the backwash (CARTER and ORFORD, 1984; BLANCO *et al*., 2003).

The groins may have introduced more conspicuous morphology in the nearshore. Deposition occurred seaward of the groins, and the March 2002 digital terrain model (Figure 6) shows that the beach planform shape was cuspate, with the groins centered at the horns. Reflectivity of the beachface within the groin segments may not be significantly lower than reflectivity of the seawall. The steep beachface may result in increased backwash velocities at the centre of the groin segments.

Deposition occurred on the dry beach in the southern sector, with the growth of the storm berm crest that was wider in January 2003 than in March 2002. This greater width was a result of longshore transport within the fill area as the shoreline became realigned to the direction of high incident wave energy.

Sedimentology

Field observations of the beachface and data collected from trenches dug into the berm allow interpretation of sedimentological changes. As on other sand and gravel beaches (MASON and COATES, 2001), the nourished beach has its surface covered by coarse sizes, but patches of a few square meters of sand occur near the shoreline (Figure 8) or beneath the gravel layer.

The trenches dug in May 2002, two months after the nourishment, reveal that fine sand infiltrated the gravel and created an interstitial sand-matrix in the gravel deposit, but

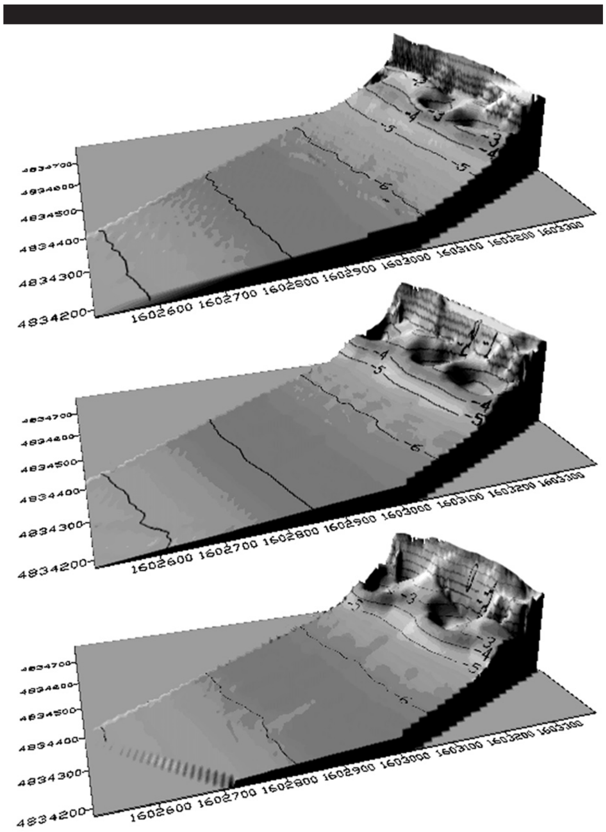

Figure 6. Topographic profiles taken along the transects put in evidence in Figure 3.

Figure 7. Waves breaking over seawall during the high-intensity storm occurring 6 October 2003.

there was no sand within the top meter of gravel on the berm crest. Those trenches were not continuous, so it was not possible to identify changes in the thickness of the mixed layer across the beach. Inspection of the trench dug in January 2003 revealed that the gravel and sand layer ranged from a few centimetres to half a meter thick, with the thickness of the coarse layer increasing with beach elevation. The berm crest was still composed of pure gravel down to at least the 1-m depth of the trench. Nearshore sediment collected in March 2002 and January 2003 indicate that gravel was not transported offshore, and the contact between sand and gravel was pronounced despite the movement of sand into the gravel matrix.

A gross estimate of the amount of sand that infiltrated into the pure gravel fill indicates that a volume representing about 30% of the fill moved from the nearshore to the foreshore. This sediment did not increase the overall size of the fill, so the reduction in volume of sand offshore of the foreshore can be considered a temporary loss in the coastal sediment budget. This loss is not nearly as great as the loss depicted on the nearshore profiles that results from the migration of the bar forms.

The addition of sand to the gravel will change the hydraulic conductivity of the beach and its responsiveness to waves and swash (MASON and COATES, 2001; BLANCO *et al.,* 2003). Changes in responsiveness to waves could be a problem if they occurred across the entire profile and vertically throughout the beach, but the upper layer is still gravel and remains highly permeable and a high barrier to overtopping. Some beaches now nourished with gravel have become primarily sand (CAPUTO *et al.*, 1993). Conversion to a primarily sandy beach may not occur at the study site because there is limited sand in the sediment budget, and new fill material updrift will be gravel.

The basic shape of the original sediment particles was maintained but the edges became rounder causing a minor volume reduction. This process made the beach more usable for tourism, and bather density on this gravel beach in summer was not different from that of the sandy beaches to the south.

Beaches composed of sand and gravel can vary from 1) composite beaches, consisting of a steep gravel berm fronted by a low angle sandy intertidal terrace where spilling waves are responsible for storm beach modification; to 2) mixed beaches where sand and gravel are mixed throughout the entire profile and storm waves break near a single point due to the controlling effect of the step (JENNINGS and SHULMEISTER, 2002). The clear contact between the sand surface and the toe of the gravel fill does not appear to be similar to the intertidal terrace of composite beaches because of its relatively great depth, at 2 m below msl, and the sand on the upper beach is not mixed throughout the entire profile. The amount of sand in the beach does not appear to be sufficient to result in either of the two major categories of beach identified by JENNINGS and SHULMEISTER (2002), but the low-angle layer of pure sand extending landward within the gravel matrix is similar to the sand layer observed by BLUCK (1967) on beaches in south Wales, indicating that this feature is not unusual. The low tidal range or relatively low wave energy regime could prevent the sorting or mixing that leads to development of the more classic sand and gravel beach types.

Beach Use

The gravel beach was designed primarily as a defense structure, so the local administration did not lease space to bathing establishments and did not allow restaurant and bar owners to plant the umbrellas that are a conspicuous component of sandy beaches in Italy. No lifeguards were provided and no beach cleaning was conducted. Nevertheless, the gravel beach is intensively used during the summer season (Figure 8) and on warm days during the rest of the year when people walk or rest in this area or scavenge the beach for well rounded marble pebbles to place in their gardens. Marina di Pisa has a beach again after many decades without one, and many of the local people are now re-using the area, although it is located at the extremity of the developed portion of the village. Gross estimates of beach value have been made for the Italian coast, considering the direct and indirect income to local populations. These estimates reveal values ranging between 1,000 and 5,000 Euro per square meter (BRAMBATI, 2003). Assuming an average figure of 2,500 Euro per square meter, the new beach, with a surface of 6,243 m^{-2} has a value of 15,600,000 Euro, which compares favorably with a construction cost of 750,000 Euro.

CONCLUSIONS

Some preliminary conclusions of this study of the use of processed marble gravel to protect a seawall and provide a beach on an eroding, developed, sandy shore are:

1. A gravel beach can protect coastal infrastructure and produce a surface usable for tourist activity.
2. The beach may become re-oriented toward the direction of high-energy wave approach, resulting in a narrowing of the berm in one segment, causing waves to overtop the seawall and deposit gravel landward of it.
3. Sand may move from the nearshore and infiltrate the gravel pore spaces.
4. Sand infiltration may reduce permeability and porosity, and the beach eventually may behave as a mixed beach, which may be less stable than the original gravel beach.
5. The efficiency of the beach as a protection structure may be reduced by the volume loss due to sand infiltrating the gravel.
6. Profile deepening in sandy substrate seaward of the gravel beach may occur from wave reflection or strong backwash.
7. Offshore effects of gravel nourishment may be obscured by greater morphologic changes caused by movement of bar systems, where present.
8. The movement of gravel offshore is not likely.
9. Bar systems close to the foreshore may be stabilised by the presence of groins.

Figure 8. Recreational use of the beach at the fill site in summer of 2003.

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