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A case-history of remedial measures against sand beach erosion preserving its aptitude for bathing

Une étude de cas des mesures correctives contre l'érosion d'une plage de sable préservant son aptitude à la baignade

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ABSTRACT: The maritime and geotechnical engineering aspects of the design of the stabilisation and protection works of the sand beach of S. Alessio Siculo village in Sicily are dealt with in the paper. Severe erosion of the beach was triggered about forty years ago by the construction along the shoreline of an embankment promenade retained on the seaside by a vertical seawall, in lieu of the pre-existing natural sand dune barrier. Subsequently significant lengths of the seawall were undetermined and collapsed, and the beach width reduced by as much as 70 m. To reduce the intensity of the wave attack a submerged breakwater was built, a rock revetment was provided at the toe of the seawall to avoid scour, and finally the beach was restored by filling with sand the space between the submerged breakwater and the seawall. The submerged breakwater option was necessary to preserve the bathing vocation of the village. The preliminary design was evaluated and improved by means of physical model tests and numerical analyses carried by HR Wallingford. The work is now nearing completion; its performance proved to be fully satisfactory even under strong wave attack.

RÉSUMÉ: Le papier traite les aspects techniques de l'ingénierie maritime et géotechnique de la conception des travaux de stabilisation et de protection de la plage de sable de S. Alessio Siculo en Sicile. L'intense érosion de la plage a été provoquée il y a une quarantaine d'années par la construction, le long de la côte, d'une promenade bordée par un mur vertical qui a remplacé le système préexistant de dunes de sable. En conséquence, des longueurs significatives du mur se sont effondrées et la largeur de la plage avait été réduite près de 70 m. Afin de réduire l'intensité de l'attaque des vagues, une récif barriére brise-lames submergé a été construit, un revêtement de roche a été realisé à la base du mur pour prévenir l'affouillement. Enfin, la plage a été reconstituée en remplissant de sable l'espace situé entre la barriére brise-lames submergée et le mur. L'option de la barriére brise-lames submergé était nécessaire pour préserver la vocation balnéare du village. Le projet a été évalué et amélioré par modeles physiques et numériques menées à HR Wallingford. Les travaux sont en cours d'achèvement. Ses performances ont été totalement satisfaisantes même dans le cas de grandes vagues.

Keywords: Erosion; scour; submerged breakwater; beach protection

1 INTRODUCTION

S. Alessio Siculo is a small seaside village located near Taormina in Sicily. Its main touristic attractiveness is the sand beach (about two kilometres long) which stretches from Cape S. Alessio to the mouth of Forza d'Agrò creek, Figure 1. A long row of dwellings, built near the coastline, was once protected against wave actions by a system of sand dunes whose height reached 6m. Regrettably, about forty years ago the dune system was dismantled to make room for an embankment road (promenade) which was retained on the seaside by a vertical reinforced concrete seawall. The effects of this improvident modification soon started to be evidenced by the intense erosion of the beach and the scour and collapse of the seawall (see Figure 2) and also by the damage to dwellings. In 1997 the beach width underwent a reduction up to 70m, and the municipal administration appointed Eng. F. Giordano as designer of remedial works and the senior author as geotechnical consultant.

The adopted stabilisation measures and their performance are reported in the present paper.

2 SUBSOIL CONDITION

The subsoil was explored by means of 9 vertical boreholes (S1-S9, Figure 1) and 6 shallow trenches (T1-T6, Figure 1). The depth of boreholes ranges from 10 to 20 metres; the depth of the trenches varies from 2 to 3 m. The boreholes S1, S2, S4 and S9 and all the trenches T1-T6 are located on the seaside of the promenade, while boreholes S5 and S8 are located on its upstream side. Boreholes S3, S6 and S7 are located at a distance of 50-70m upstream from the promenade.

Typical schematic profiles of the boreholes are shown in Figure 3. The soil found in all exploratory trenches is made prevailingly of gravelly coarse sand.

These data show that the subsoil involved in the engineering problem under discussion is made essentially of dense or very dense sand and gravel and occasional cobbles. The substratum is made of metamorphic rocks.

Standard penetration tests were carried out in all the boreholes; the results, plotted in Figure 3, show that the sands and gravels are dense or very dense.

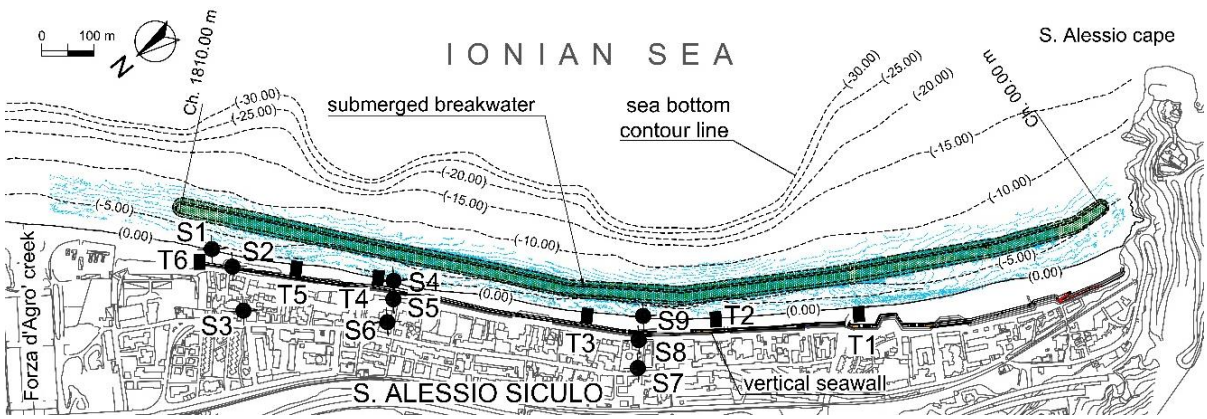

Figure 1 Plan of the site, submerged breakwater, boreholes S and exploratory trenches T. Elevations in metres (m) referred to mean sea level.

Figure 2 Typical rupture patterns of the seawall and the promenade.

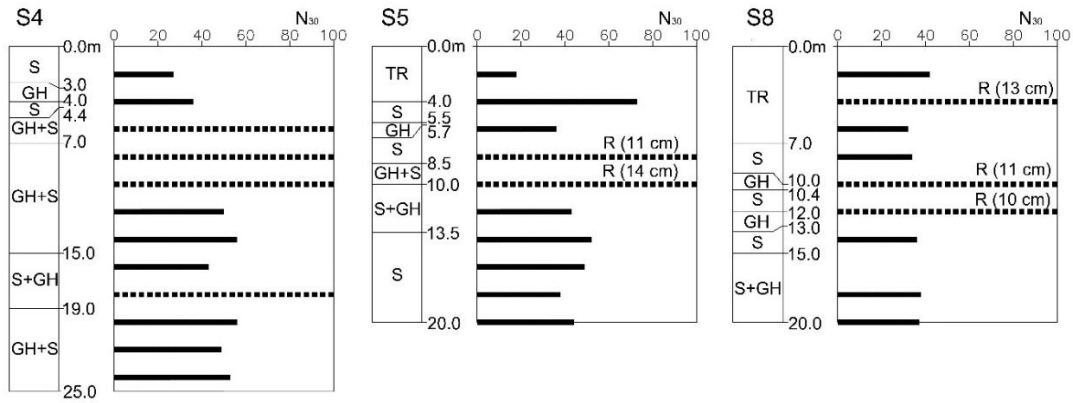

Figure 3 Typical schematic profiles of the boreholes S4, S5 and S8 and results of standard penetration tests. Key: TR: embankment material made of sand and gravel mixed with subangular rock blocks; S: graded gray sand; GH: polygenic gravel. R: "refusal" when the penetration depth is lower than 30cm at 100 blows of the hammer.

3 GEOTECHNICAL PROPERTIES OF SOILS

Sand is the main component of the beach and of the underlying soil. The sand fraction ranges from 77 to 87%; the gravel fraction varies from 11 to 20%. A typical grain-size distribution of the sand is shown in Figure 4. Rather thin layers of gravel have been found at different depths; they are evidenced by very high or refusal values of the N_{30} index of the standard penetration tests (see, Figure 3). The specific weight γ_s varies from 26.5 to 26.8 kN/m^3. The saturated unit weight γ_{sat} varies from 20.5 to 21.5 kN/m^3. N_{30} values of sands of the upper 15m thick layer ranges from 20 to 60. According to the De Mello (1971) correlation the peak angles of shear strength φ' range from 40° to 50°. The relative density D_R ranges from 70% to 90%, according to the Gibbs and Holtz (1957) correlation. The sands are dense or very dense. In the upper layers in which the effective stress level is very low the peak angle of shearing strength can reach values higher than 50° (Sture et al., 1998; Valore and Ziccarelli, 2009; Chakraborty and Salgado, 2010; Celauro et al., 2014; Valore and Ziccarelli, 2015; Ziccarelli, 2016; Valore et al., 2017; Ziccarelli et al., 2017).

The very high values of D_R and φ' do not prevent the erosion of the sands to occur under wave attak since they are not cemented.

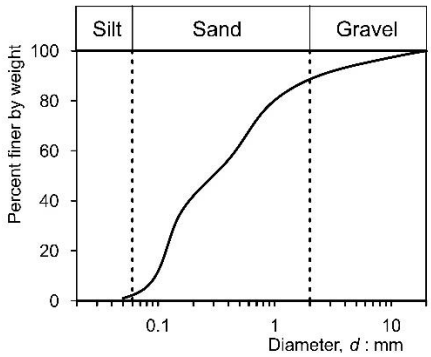

Figure 4 Typical grain size distribution of sandy soil.

4 CAUSES OF THE EROSION AND SCOUR PROCESSES

Two main causes of the beach erosion and of the scour of the seawall have been identified. The first and most important one is the reflection of waves off the vertical seawall; it brought about the erosion and the offshore transport of the sand of the beach. It was also responsible for the scouring of the sand on which the seawall was founded; as a consequence the wall settled disuniformly, overturned and broke apart. The retained embankment material was washed out and breaches were opened in the promenade through which sea waves passed and reached the existing houses. This kind of processes are well-known in Coastal Engineering (e.g. Silvester and Hsu, 1997; CIRIA et al., 2007). The second cause was the reduction of longshore solid transport that was no longer fed by the Forza d'Agrò creek because of the implentation of hydraulic taming works built in the eighties of past century.

5 REMEDIAL MEASURES

The fundamental aims of the remediation works were identified soon after the start of the study in 1997, namely (i) to protect existing houses and the promenade, (ii) to restore the beach to its former configuration or at least to its full functionality for bathing; (iii) to avoid spoiling the attractiveness of the site associated to barriers rising out of the water. The selected solution, shown schematically in Figure 5, consists of:

- a submerged breakwater, 1810 m long (see Figure 1), with the crest at 1.5-1.8 m below mean sea level and a layer of sacrificial stones on the seaside, and an internal geotexile sheet as a filter to prevent the sand of the beach from passing through the breakwater and being lost in the open sea;
- a layer of coarse gravel and cobbles overlain by a layer of sandy fine gravel to nourish the depleted coast (Figures 5 and 6);
- a rock revetment adjacent to the seawall (rebuilt where necessary) to stabilise and protect it from scouring processes (Figure 7). Staircases were built in the revetment to permit people to access the beach from the promenade.

The stones of the breakwater were numbered, surveyed and weighted and precisely laid down one by one with the assistance of a diver.

Works started in 2003 and were carried out in three different stages, and are now nearing completion; in particular 1716 m out of 1810 m of the submerged breakwater have been already built.

The validity of the preliminary design was confirmed through physical and numerical model studies carried out by HR Wallingford (Albanese et al., 2003). This study permitted to refine and optimise the design.

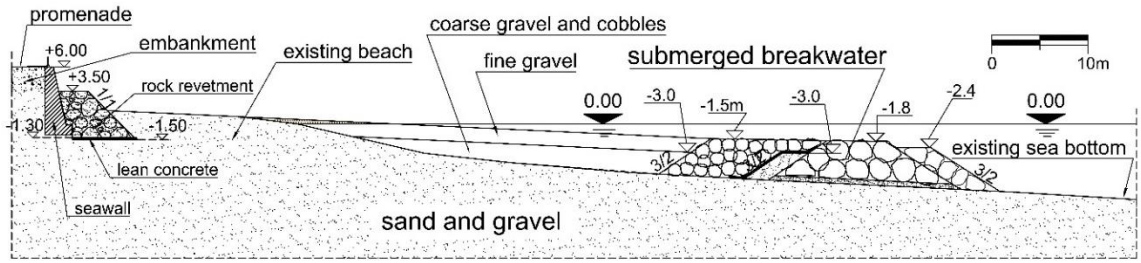

Figure 5 Schematic cross section of the beach and stabilisation works. Elevation in metres above mean sea level. Revetment made of stones d=500-700mm "bonded" by concrete.

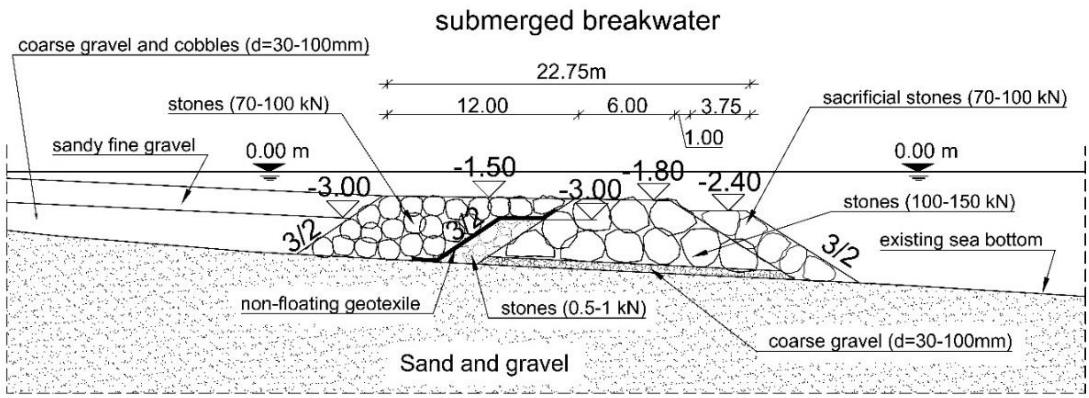

Figure 6 Details of submerged breakwater (cross section).

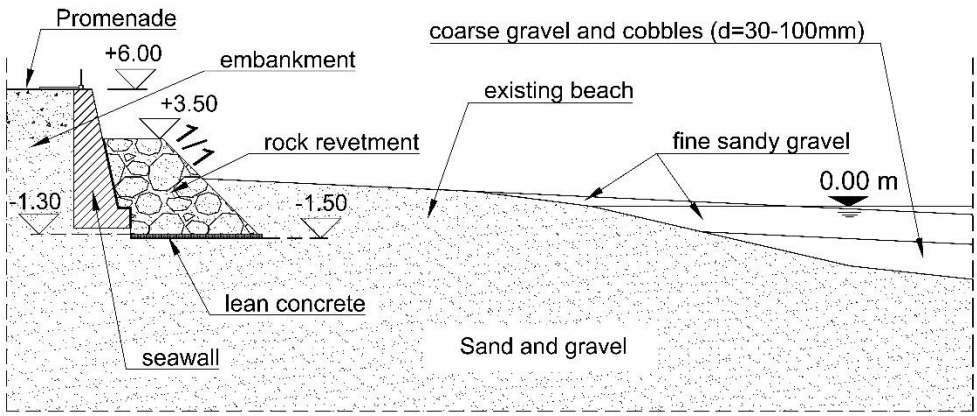

Figure 7 Details of seawall and rock revetment (cross section).

6 OBSERVED BEHAVIOUR AND CONCLUSIONS

In situ inspections were carried out, especially after storms. They proved that the selected coastal defence system is fully effective. In fact, the promenade and the adjacent houses have not suffered damages during rough sea. During violent storms only some sand drift, coming from the beach located above sea level, reached the promenade. Bathimetric surveys of the submerged breakwater revealed that its seaside slope underwent settlements as high as one metre at the toe of the sacrificial layer. These settlements originated from localised scour of the sand around the lowermost sacrificial stones that progressively sank into the foundation sand, as expected according to results of physical model tests. It must be noted that this kind of settlements cannot be predicted by the usual geotechnical methods. The above sinking process is self-stabilising; however, refurbishment of the breakwater is advisable and was foreseen.

The importance of the sequence of construction of the different parts of the defence system is clearly shown by the comparison of figures 8a and 8b. Figure 8a refers to a beach stretch where the submerged breakwater has been already completed when a sea storm occurred: it may be seen that there did not occur any scour at the base of the rock revetment on the contrary of what happened in another stretch of the same beach, Figure 8b, where the revetment underwent scour and breaching because the corresponding submerged breakwater was not yet built at the time of the storm. Figure 9 shows the breaking of sea waves on the submerged barrier during a storm, and the strong attenuation of the wave effects on the beach. Figure 10 portrays the initial part of S. Alessio beach during the summer season after the completion of the defence works; it may be observed that the sand beach is preserved and fit for recreational activities.

The submerged breakwater has not caused any inconvenient to the bathing activity. Moreover, it now houses a new marine ecosystem of resident fish species.

In conclusion, this case-history demonstrates that the integrated use of the principles of coastal and geotechnical engineering as well as physical model tests helps to find effective solutions to multifaceted problems.

Figure 8 a) The submerged breakwater has been already built: the beach is protected during sea storms against erosion, and the revetment does not suffer scour. b) The submerged breakwater has not been built yet in the zone facing the rock revetment that undergoes scouring and breaching.

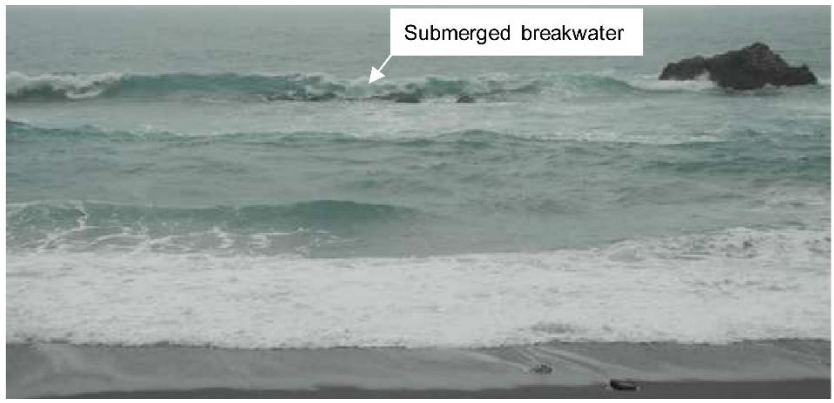

Figure 9 Sea waves break on the submerged barrier and do not damage the beach nor compromise bathing activities. (Photo taken from the promenade).

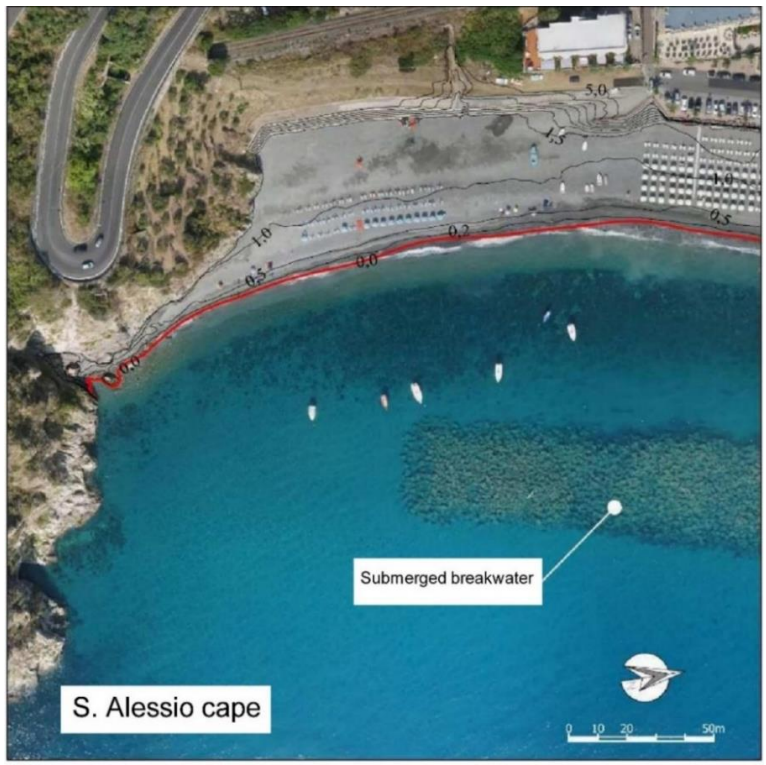

Figure 10 A stretch of beach returned to bathing and recreational activities after the completion of remedial works.

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