SCOUR PROTECTION AROUND A SINGLE SLENDER PILE EXPOSED TO WAVES

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The study of the scour around a monopile foundation and, in particular, the evaluation of the performance of alternative scour protection systems made of geotextile sand containers (GSCs) are here presented. Different configurations of the scour protection system were experimentally analyzed. The scour protection efficiency has been tested with both regular and random waves. A design dynamic formula for the scour protections is developed based on the stability of the GSC and, hence, on the evaluation of the weight of the geotextile sand container by means of the stability number. A damage level has been defined and related with the modified stability number. The paper provides useful information for the design of the scour protections made of geotextile sand containers, for the evaluation of the performance of such systems in terms of scour reduction, sinking and damage level of the scour protections.

INTRODUCTION

During the last years, the development of renewable energies led to the growth of wind farms and offshore platforms over the main seas. The majority of wind farm foundation is made of monopile anchored in the seabed. The interaction of waves with structures leads to erosion at the base of the pile. Therefore, there is substantial risk for the stability of the structure and solutions must be found to minimize the effects of seabed scouring at the foundation. In this perspective, laboratory experiments were carried out to investigate the emergence and development of the scour at the base of a slender monopile immersed within an erodible granular bed and exposed to waves. Whitehouse et al. (2011) analyzed the scour and its protections from several offshore wind farms and other piled foundations. Petersen at al. (2015) investigated also on the edge scour occurring alongside the protection. A typical protection system is made with armour rocks. Nevertheless, in the last years, the development of permeable and resistant materials as geotextile increased its diffusion in different fields such as the maritime environment. Recio e Oumeraci (2009) studied intensively the effect of waves over different geotextile sand container (GSC) configurations for shore protection structures.

Very few empirical design methods are available to design the resisting element for the scour protection around a monopile foundation (Sumer and Fredsøe, 2002). In the literature, standard methods adopt a static protection where the top layer of armour is designed to resist hydraulically. A static approach based on the criteria of threshold motion is generally used (e.g. Kirkergaard et al., 1998; De Vos et al., 2011) for which the damage is defined as the displacement of the top layer resisting element. In De Vos et al. (2012) a dynamic design formula is provided that allows some displacement of the top layer stones which corresponds to an expected damage level. In similarity with the study of De Vos et al. (2012), a new practical dynamic design formula has been developed which describes the stability of the innovative scour protection systems made of GSCs (Corvaro et al. 2014). Damage was characterized by the dimensionless damage parameter and different damage levels were defined. In order to develop a design formula for the determination of the GSC's weight, the stability number N_s has been used, according to the well–known empirical formula of Hudson (1959). However, during the years it has been noted that such a formula does not include the wave period, the number of waves and does not take into account of random waves. Ahrens (1975) showed the importance of the wave period on the stability of a maritime structure. In the formula of Van der Meer (1998), the type of breaker, the permeability parameter, the number of waves and irregular waves have been taken into account.

The aim of this work is the study of the effectiveness of the scour protections made of geotextile sand containers to protect a single slender pile exposed to the wave action in terms of scour reduction, stability of the elements and damage level.

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EXPERIMENTAL SETUP

The experiments were carried out at the wave flume of the Università Politecnica delle Marche (Ancona, Italy) that is 50m long, 1m wide and 1.3m high (Fig. 1). At the end of the flume is placed a dissipative gravel beach with a slope of 1:20. Regular and random waves were run in the flume and forced by a piston type wavemaker to propagate over the physical model. The cylinder is characterized by a nominal diameter D of 100mm. In Table 1 were reported the wave characteristics, were H and H_s are, respectively, the wave height for regular and irregular waves, Re_D is the Reynolds number in the range $3\text{x}10^4 \div 7\text{x}10^4$ ($Re_D = UD/\upsilon$, U is the is the maximum value of the undisturbed orbital velocity at the seabed, υ is the kinematic viscosity of water), the Keulegan Carpenter $KC = UT/D$ is in the range $8 \div 16$ for regular waves (T is the wave period) and $KC_{rms} = 2\pi a_{rms}/D \sinh(k_p h)$ is in the range of $8 \div 10$ for irregular waves (k_p is the wave number corresponding to the peak period T_p, $a_{rms} = \sqrt{2}\sigma_\eta$ and $\sigma_\eta = \int_0^\infty S_\eta(f) df$ where $S_\eta(f)$ is the wave spectrum of the free surface elevation $\eta(t)$). The water level over the physical model h was of 50cm.
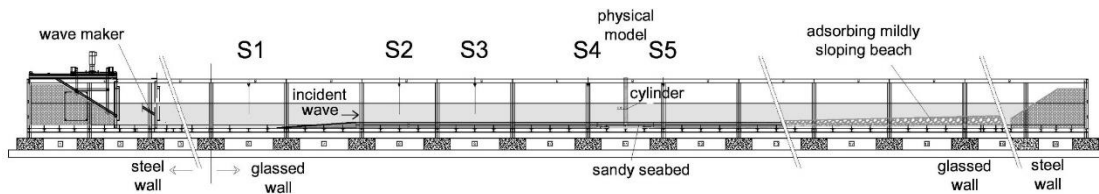

Figure 1. The wave flume and the physical model.

| Table 1. Wave characteristics for regular and random waves.					
Wave	h (m)	H (m)	T (s)	KC (-)	Re_D (x10^4)
R1	0.5	0.14	2.74	8.1	3.0
R2	0.5	0.21	2.74	11.7	4.3
R3	0.5	0.28	2.74	15.7	5.7
R4	0.5	0.35	2.74	19.6	7.1
R5	0.5	0.20	1.83	6.7	3.7
R6	0.5	0.25	1.83	8.0	4.4
R7	0.5	0.16	1.83	5.2	2.9
R8	0.5	0.16	2.19	6.8	3.1
R9	0.5	0.19	2.19	8.1	3.7
R10	0.5	0.23	2.19	9.9	4.5
R15	0.5	0.17	2.74	9.8	3.6
R17	0.5	0.19	2.74	10.6	3.9
Wave	h (m)	H_s (m)	T_p (s)	KC_{rms} (-)	Re_D (x10^4)
NR2	0.5	0.17	2.74	8.0	3.0
NR3	0.5	0.19	2.74	10.1	3.7
NR9	0.5	0.20	2.19	7.7	3.7

Two different experimental campaigns were carried out. In the former one the physical model is made of a mobile seabed, consisted in a sandy bed (characteristic diameter 0.6mm) with a length of 1.5 m, width of 1 m and thickness of 0.13 m. In the latter one the physical model is a rigid bed.

The scour protection around the pile has been realized by Geotextile Sand Containers (GSCs) composed of a specific non-woven geotextile, filled with a median grain size sand and 80% fill ratio with different configurations: without any protection S0, a circular configuration S1, two square configurations S2 (S2a and S2b with a different orientation of the containers), as shown in Fig. 2. Each container is about 8 cm long (*l*), 6 cm wide and 2 cm high (in the prototype corresponds to containers of weight *W*=1t). In the configuration S2a the long side of the containers is placed along the direction of the wave propagation, while in the configuration S2b the long side of the containers is placed perpendicular to direction of the wave propagation. In each configuration the containers were displaced in two layers. An additional random configuration S3 has been realized in order to study the behaviour of an easier scour protection installation.

The advantages of the evaluation of the scour protection performance placed over the mobile

seabed are the similarity with the real filed conditions and the possibility of the evaluation of the sinking of the scour protection; the disadvantage is the scale effects of the seabed forms that could alter the performance of the protection system (see Corvaro et al., 2018). Therefore, as above reported, a second experimental campaign with fixed-bed conditions is analyzed. The scour protection around the pile is made of the same geotextile sand containers. In such second experimental campaign only two configurations were analyzed: the square configuration S2a and the random configuration S3. In addition, in this second experimental campaign, it has been also analyzed a water depth of 75cm (for waves R2, R3, R4, R9, R10 and R12).

Melville and Coleman (2000) advised to place the top of the scour protection at the same level of the surrounding bed. However, as observed by Oud (2002) the scour protection placed above the seabed is the most economical solution. De Vos et al. (2011) argued that the higher location of the scour protection induces a very limited increase in the wave load and that the influence is mainly restricted to the edge effects. Therefore, the scour protection was placed over the seabed in two overlapped layers. The diameter of the scour protection (length and width for the configurations S2) is about five times the pile diameter *D*.
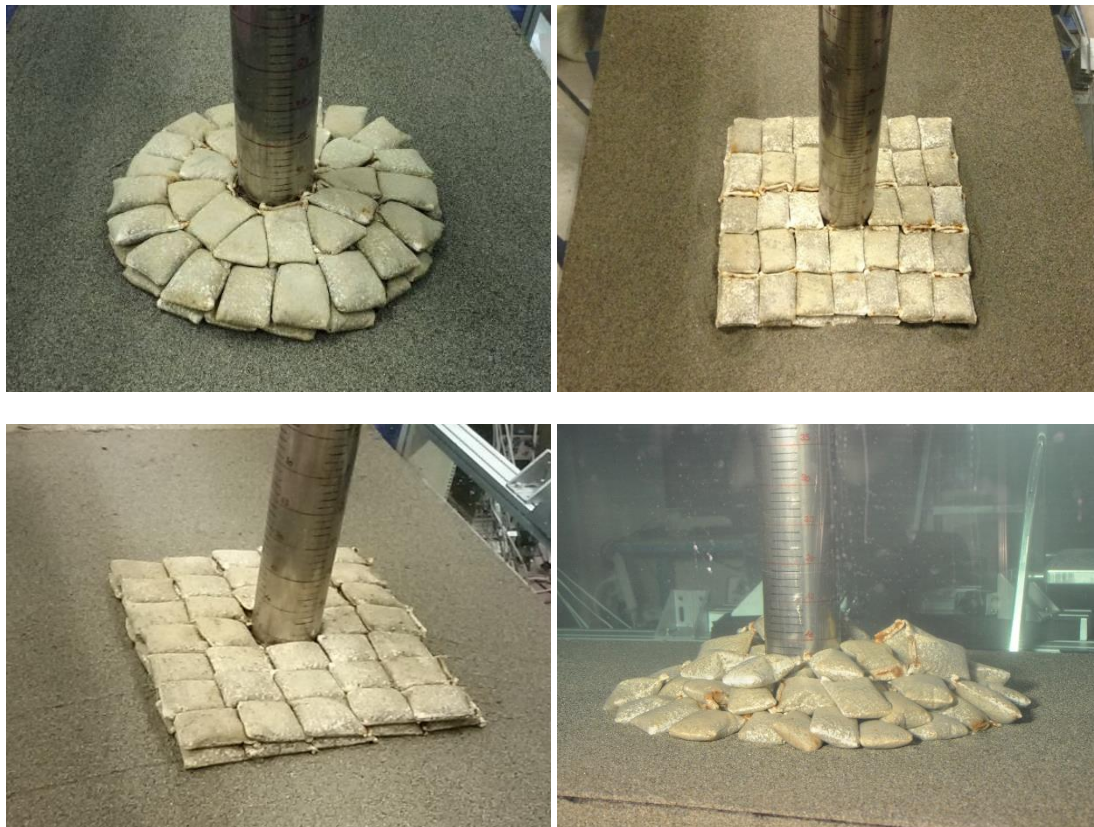
Figure 2. Different configurations of the scour protection systems made of geotextile sand containers (GSCs): circular configuration S1 (upper left panel); square configuration S2a (upper right panel); square configuration S2b (lower left panel) and random configuration S3 (lower right panel).

The analysis of the scour, the morphodynamics and the sediment transport for the configuration S0 is reported in Corvaro et al. (2018) and Miozzi et al. (2018). A tridimensional graphical reconstruction has been used in order to evaluate the performance of the different scour protection systems. Elevation gauges along the wave flume were used in both the experimental campaign. Pressure transducers were placed between the sand containers both in the upward and downward zone and both in the first and second circular crown (for the circle configuration S1 over the mobile seabed).

SCOUR PROTECTION SYSTEM'S STABILITY

In this section the scour protection stability is studied.

The wave loads on the protection systems can be defined as the Drag force F_D, the Inertia force F_I,

the Lift force F_L:

$$F_D = 0.5 C_D \rho A_s u^2 \tag{1}$$

$$F_I = C_M \rho V \frac{\partial u}{\partial t} \tag{2}$$

$$F_L = 0.5 C_L \rho A_T u^2 \tag{3}$$

where ρ is the water density, C_D, C_M, C_L are empirical force coefficients, u is the wave-induced horizontal particle velocity, $\partial u / \partial t$ is the associated horizontal particle acceleration, V is the volume of the container, A_s is the vertical projected area of the container while A_T is the horizontal projected area.

The observed GSC failure modes are two: sliding and overturning. The sliding occurs when the resisting force, given by the weight of containers under buoyancy W' and lift force F_L, multiplied by the friction coefficient μ, is equal or smaller than the mobilizing force given by the Drag force F_D and the inertia force F_I. The stability against the sliding is given by:

$$\mu(W' - F_L) \geq F_D + F_I \tag{4}$$

The stability against the overturning can be described as:

$$W'r \geq (F_D + F_I)\, b + \, F_L\, r \tag{5}$$

where r and b are, respectively, the horizontal and vertical projections of the distance between the center of gravity of the container and the rotation point that is located at the edge of the contact area of the container opposite to the acting of the flow.

In the experiments we observed that the main mechanism of GSC's failure is the overturning, as shown in the temporal sequence of Fig. 3. The container at the lee-side of the cylinder begins to destabilize due to the overturning (see the upper panels), during the passage of the wave trough the container comes back to its initial position (middle left and middle center panels) and after the wave crest phase (during the reversal flow) it is again destabilized due to the overturning, until it is completely displaced from its initial position (lower panels).

In order to provide useful information for the design of the scour protection, a novel practical design formula for the geotextile sand container applied as a scour protection system is here proposed. The design formula is derived by the well-known empirical formula of Hudson (1959).

The GSC stability is proportional to the ratio between the mobilizing (F_D, F_I, F_L) and the resisting forces (W'). By assuming that when the mobilization of the GSC occurs the inertia force can be neglected, the stability number can be evaluated as $(F_D + F_L)/W'$, leading to equation (6):

$$\frac{\text{Mobilizing force}}{\text{resisting force}} = \frac{u^2}{\Delta\, g\, l} \tag{6}$$

$$l = \left(\frac{W}{k_W \gamma_s}\right)^{1/3} \tag{7}$$

where $\Delta = \left(\frac{\rho_s}{\rho} - 1\right)$, ρ_s is the mass density of the geotextile sand container, W is the weight of the geotextile sand container GSC, l is the length of GSC (l is the design parameter as reported in eq. (7)), k_W is the container volume factor ($k_W = V/l^3$).
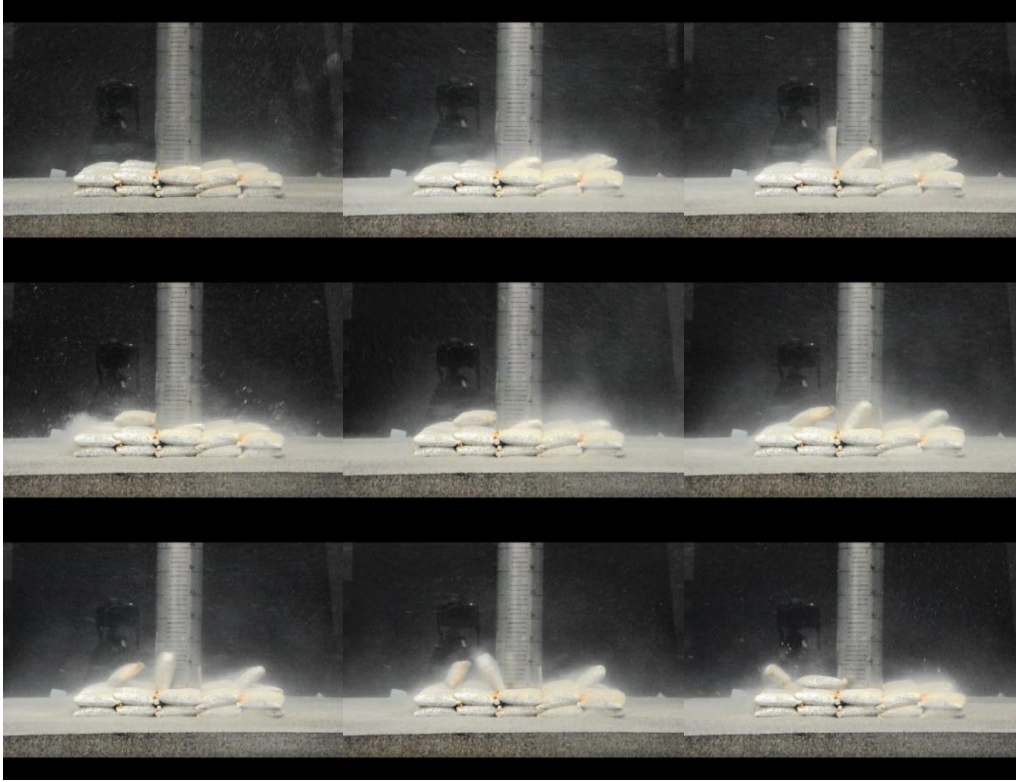
Figure3. Temporal sequence of the geotextile sand container movement under the action of Wave R3. The failure mode is the overturning.

The horizontal velocity on the breakwater slope can be assumed proportional to the water depth and, hence, by assuming that $H/h=1$ on the structure, it leads to $\sqrt{gh} \cong \sqrt{gH}$. For the design of a scour protection the horizontal velocity cannot be evaluated in a such a way, as made for the design of the breakwater armour layer. Therefore, the horizontal velocity has been evaluated at the seabed, by using the first order linear theory as expressed by equation (8), being small the discrepancy between the measured and predicted horizontal velocity over impermeable beds (see Corvaro et al. 2014 and Miozzi et al. 2015).

$$u = \frac{H\sigma}{2\sinh(kh)} = \frac{H\pi}{T\sinh(kh)} \qquad (8)$$

$$u^2 = \sqrt{\frac{H^2\sigma^2}{4\sinh^2(kh)}} = \sqrt{\frac{H^2 gk\tanh(kh)}{4\sinh^2(kh)}} = \sqrt{\frac{H}{4}\frac{H}{h}g\frac{2kh}{\sinh(2kh)}} \qquad (9)$$

By using the same expression defined by Tanimoto (1982) for $k_1 = 2kh/\sinh(2kh)$, (k is the wave number) and substituting equation (9) in equation (6), it leads to the expression of the modified stability number N_s^*:

$$N_s^* = \frac{u^2}{\Delta g l} = \frac{H k_1}{\Delta l}\frac{H}{h} = N_s k_1 \frac{H}{h} \qquad (10)$$

where $N_s = H/\Delta l$ is the traditional stability number formula defined by Hudson (1959), in which the characteristic size of the resisting element is the length of the container l instead of the mean rock diameter D_{50}.

Note that the function k_1 increases with the wave period and with the water depth.

Finally, as usually done in the literature, the damage was characterized by a dimensionless damage parameter S_d defined as the ratio between the area of removed geobags A_e with respect to the horizontal area of the container A_T:

$$S_d = \frac{A_e}{A_T} \tag{11}$$

For the analysis of the level of damage, a tridimensional graphical reconstruction has been used in order to evaluated the eroded area A_e. In analogy with the works of De Vos et al. (2012) and Whitehouse et al. (2014), the damage levels are defined as:

- Damage 0: no movements of GSCs
- Damage 1: movement of GSCs in Area B
- Damage 2: relevant movement of GSCs (Area A and Area B)
- Damage 3: failure of the protection

The failure of the scour protection is considered when a larger number of geotextile sand containers were removed in the Area A, being such area closer to the pile (see Fig.4).
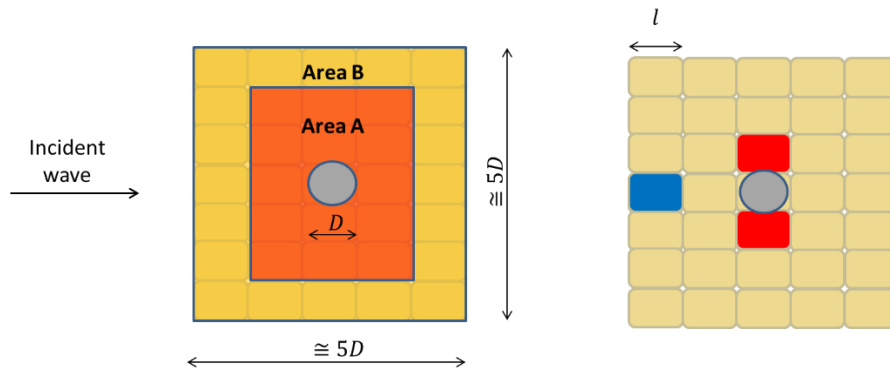

Figure 4. Sketch of the scour protection with the definition of Area A and Area B.

An evaluation of the evolution of the damage with the number of waves N has been also investigated, finding that for regular waves the scour protection achieved a steady stable condition after about 500 waves, while for random waves the steady state condition is achieved after about 1500 waves. In the following section the results are reported by assuming that the steady stability state conditions were reached.

RESULTS

In this section the results about the efficiency of the alternative scour protection made of GSCs around a monopile is divided into subsection: damage, stability and sinking of the scour protections.

The scour protections made of GSCs seems to be a good protection system, for the waves here tested (non-breaking waves). The global failure is never observed. The damage 2 were found for the waves characterized by a larger wave period and wave height.

Damage of the scour protection systems for regular waves

A comparative analysis between the different configuration of the scour protection system allows us to identify which configurations are more efficient in terms of stability. A smaller number of removed containers has been found for the square configuration S2a with respect to the circular configuration S1 (see Fig.5). For example for Wave R3 the number of displaced containers in the case of circular configuration (S1) is 10 and 7 for overturning and sliding, respectively, while for the square configuration (S2a) the removed containers becomes 6 and 7. However, by analyzing the behaviour of the square configuration S2b with the containers arranged trasversally with respect to the wave direction, an opposite result is observed: 15 and 7 containers were displaced, respectively, for overturning and sliding. Therefore, the square configuration S2 seems to be very influenced by the direction of the wave propagation with respect to the container orientation, hence, a circular orientation S1 of the containers represents a better solution for the scour protection configuration in terms of performance, although such configuration requires a more demanding installation. In the site where the main wave direction is well defined, the configuration S2a could be the best solution.

The efficiency of the random configuration S3 has been evaluated by means of an imaging tools based on the comparison of the container displacement after different number of wave attacks. After

only one wave attack (test R3) a quasi-stable configuration is achieved, demonstrating that the significant initial displacement is only due to the random arrangement.

The number of displaced containers is larger during the first experimental campaign, due to the influence of the seabed forms. The seabed forms and the scour pattern typologies were extensively studied in Corvaro et al. 2018.
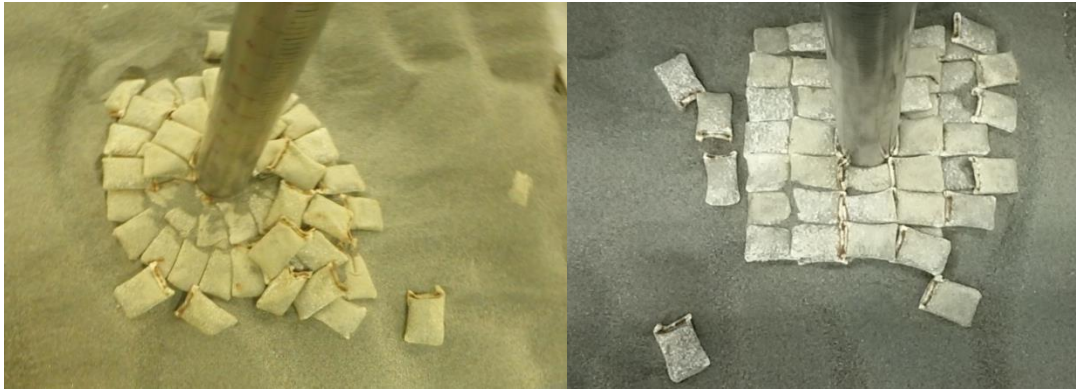

Figure 5. GSC displacement after test R3. Configuration S1 (left panel), configuration S2a (right panel)

The level of damage has been evaluated by means of equation (11) for all the regular waves. The results for Wave R3 with KC=16 is shown in Fig. 6. The displacement of the containers also affects area A, hence the damage level is equal to 2, while the evaluated damage parameter S_d is equal to 7.0. For the configuration S3 characterized by the elements arranged in a random way, larger values of the damage parameter have been found, because the initial condition is less stable with respect to the other configurations where the containers are arranged in a ordered way. Therefore, such result is strongly influenced by the initial arrangement. If the damage parameter was calculated by comparing the final arrangement with the arrangement reached after few wave attacks (where the most displacement occurs), the damage parameter S_d would be reduced.
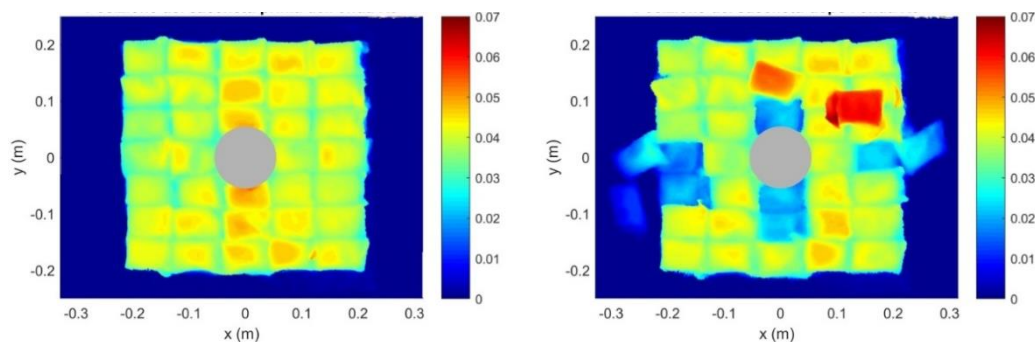

Figure 6. Tridimensional graphical reconstruction of the scour protection system (Configuration S2a) for the regular wave R3

Damage of the scour protection systems for irregular waves

The performance of the scour protection under irregular waves has been evaluated by means of a bidimensional imaging tool (mobile seabed tests) and a tridimensional graphical reconstruction (rigid seabed).

The results obtained by the bidimensional imaging tool are summarized here: after test NR2 the containers are almost stable, while after test NR3 about 11 containers were displaced.

In analogy with the analysis made for regular waves, the damage parameter has been evaluated by means of the tridimensional graphical reconstruction of the scour protection performance after the wave attack. The level of damage has been evaluated by means of equation (11). The results for Wave NR3 with KC_{rms}=8, is shown in Fig. 7 which corresponds to a damage level 1 (the displacement of the container affects only area B) while the damage parameter S_d is equal to 5.3.
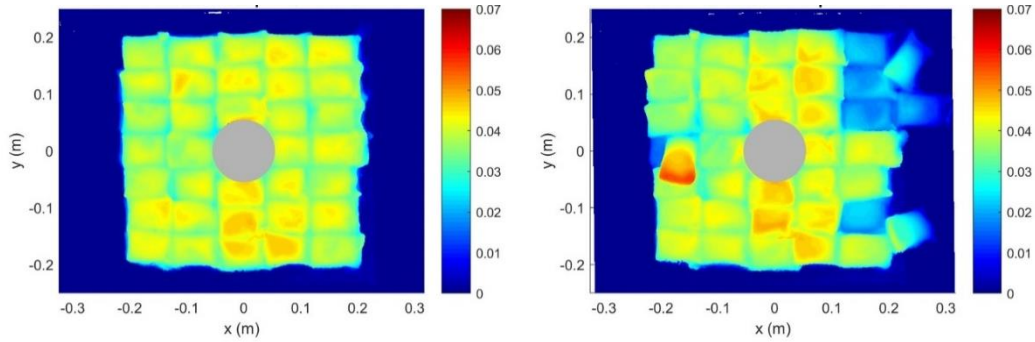
Figure 7. Tridimensional graphical reconstruction of the scour protection system (Configuration S2a) for random wave NR3.

Modified stability number vs the damage parameter

In this section the damage parameter S_d has been related to the modified stability number defined in equation (10). Different damage levels have been obtained for the wave tests. In Fig. 8 the result about the stability number obtained for the scour protection made with GSCs is shown. The green data correspond to the tests where no movement of the container is observed (Damage 0). The orange data correspond to the tests where the container were removed only in the Area B, while the red data correspond to the tests where also the containers close to the cylinder were displaced (Area A). In particular, it is found that the red highlighted containers (see Fig. 4) were removed for larger critical velocity condition with respect to those in blue, hence, the container within area B were subjected to the first displacement, mainly the containers at the first line due to the wave impact. It is also observed that the removed containers in Area A are those in the lee-side of the cylinder. The authors believe that in such area the increase of the bottom shear stress due to the contraction of the streamlines is responsible of the movement of such GSCs, but a larger critical velocity is needed to remove such containers (damage level 2).

Fig. 8 reveals the dependence of the stability number with the term k_1H/h (k_1 increase with the wave period and water depth).
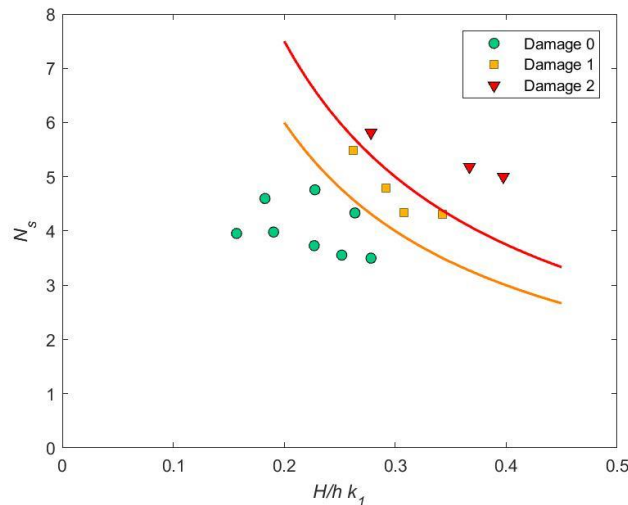

Figure 8. The stability number and the damage levels curve (orange line for $N_s^* = 1.2$, red line for $N_s^* = 1.5$).

The modified stability number, expressed by the equation (10), can be related to the damage level, as shown in Fig. 8, where the orange line corresponds to $N_s^* = 1.2$, while the red line corresponds to $N_s^* = 1.5$. Therefore, the scour protections made of GSCs is stable for a modified hydraulic stability number $N_s^* < 1.2$, that corresponds to the threshold of the damage level equal to 1. Assuming that a

larger level of damage (damage level 1) could be acceptable for the design of a scour protection system made of GSCs, the modified hydraulic stability number N_s^* can reach a value of 1.5, such value corresponds to the threshold of the damage level equal to 2. Once defined the design damage level, a value of the modified hydraulic stability number N_s^* can be found, from which the characteristic length l of the container can be obtained, being $N_s^* = N_s k_1 H/h = k_1 H^2/\Delta l\, h$.

In conclusions, the stability of geotextile sand containers (GSCs) seems to be good, no failure conditions have been observed even for waves characterized by larger wave heights and periods with nonbreaking conditions. For the tests characterized by a damage level equal to 2, the displacement of the containers occurs also for those located in Area A, closer to the cylinder. It is found that the removed containers are those in the lee-side of the cylinder and they at most were 4. The containers in the lower layer of the scour protection in Area A were never displaced, no failure condition were achieved for the nonbreaking waves here tested.

Sinking

The scour protection efficiency has been also evaluated by measuring the sinking of the GSC layers (mobile bed tests). Such values are compared with the scour depths obtained when no protection is used (S0). Both protection configurations S1 and S2 reduce significantly the scour depth around the pile (see Corvaro et al. 2018), as showed in Table 2. However, even if the protection system seems efficient in terms of scour depth reduction and sinking (Nielsen et al, 2015), Fig. 3 shows that some containers were removed from their initial position depending on the intensity of the flow (wave characteristics) and on the GSC orientation (different drag/lift forces between different configurations).

Table 2. Wave characteristics and the comparison between the scour and the sinking of scour protection systems					
Wave	*KC* (-)	S0 (cm)	S1 (cm)	S2a (cm)	S2b (cm)
R1	8.1	1.4	0.0	0.0	-
R2	11.7	2.6	0.2	0.0	-
R3	15.7	3.3	0.2	0.1	0.0
R15	9.8	1.7	0.0	0.1	-
R17	10.6	1.8	0.1	0.1	-

CONCLUSIONS

Experimental tests with regular and irregular waves were carried out in order to evaluate the performance of scour protections made of geotextile sand containers. Several configurations were analyzed finding that the square configuration S2a seems to be the most stable configuration, however the elements arranged transversally with respect to the direction of wave propagation (configuration S2b) show the lowest efficiency. Therefore, the square configuration S2 seems to be very influenced by the wave direction with respect to the container orientation, hence, a circular configuration S1 of the containers represents a better solution for the scour protection in terms of performance. However, the authors believe that for the site where the main direction of waves is well known and defined, a square configuration S2a, with the length of the containers arranged in the same direction of the incident wave, could be the best solution, even because such a configuration needs a lower demanding installation with respect to the circular configuration S1. An additional configuration S3 with sandbags arranged in a random way has been realized in order to study the behavior of an easier scour protection installation. Larger displacements occurred for the configuration S3, hence, larger values of the damage parameter S_d were obtained. However, a significant displacement is observed only at the beginning, after only few wave attacks. Such result is due to the initial random arrangement that surely it is less stable with respect to the configuration with the containers arranged in an ordered way. Therefore, even if the damage parameter of configuration S3 is larger with respect to the other configurations, that the performance of a random arranged configuration (S3) is anyway acceptable.

The damage parameter has been defined in order to classified the level of risk of the scour protections. The conclusion is that the scour protection made of GSCs is stable for a modified hydraulic stability number $N_s^*<1.2$, that corresponds to the threshold of the damage level equal to 1. Assuming that a larger level of damage (damage level equal to 1) could be acceptable for the design of a scour protection system made of GSCs, the modified hydraulic stability number N_s^* can reach a value of 1.5,

such value corresponds to the threshold of the damage level equal to 2. Since the design damage level of the scour protection is defined, the weight W (or the length l) of the container can be calculated by means of the modified hydraulic stability number N_s^*.

In general, no failure conditions have been observed for all the configurations here studied, even for waves characterized by larger wave heights and periods (nonbreaking conditions). The size of the containers corresponds in prototype to a weight of about 1t, that is an available commercial size. Moreover the cost of such protections is comparable with those made of rocks.

Finally, the scour protection efficiency has been also evaluated by measuring the sinking of the scour protections made of GSCs. Such values are compared with the scour depths obtained when no protection is used (see Corvaro et al., 2018). The scour protection configurations reduce significantly the scour depth around the pile, hence, the protection system is efficient in terms of both scour depth reduction and sinking.

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