Journal of
Marine Science and Engineering

MDPI

Review

Scour Protections for Offshore Foundations of Marine Energy Harvesting Technologies: A Review

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Abstract: The offshore wind is the sector of marine renewable energy with the highest commercial development at present. The margin to optimise offshore wind foundations is considerable, thus attracting both the scientific and the industrial community. Due to the complexity of the marine environment, the foundation of an offshore wind turbine represents a considerable portion of the overall investment. An important part of the foundation's costs relates to the scour protections, which prevent scour effects that can lead the structure to reach the ultimate and service limit states. Presently, the advances in scour protections design and its optimisation for marine environments face many challenges, and the latest findings are often bounded by stakeholder's strict confidential policies. Therefore, this paper provides a broad overview of the latest improvements acquired on this topic, which would otherwise be difficult to obtain by the scientific and general professional community. In addition, this paper summarises the key challenges and recent advances related to offshore wind turbine scour protections. Knowledge gaps, recent findings and prospective research goals are critically analysed, including the study of potential synergies with other marine renewable energy technologies, as wave and tidal energy. This research shows that scour protections are a field of study quite challenging and still with numerous questions to be answered. Thus, optimisation of scour protections in the marine environment represents a meaningful opportunity to further increase the competitiveness of marine renewable energies.

Keywords: scour; protection; wave energy; tidal energy; offshore wind energy

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Citation: Fazeres-Ferradosa, T.; Chambel, J.; Taveira-Pinto, F.; Rosa-Santos, P.; Taveira-Pinto, F.V.C.; Giannini, G.; Haerens, P. Scour Protections for Offshore Foundations of Marine Energy Harvesting Technologies: A Review. *J. Mar. Sci. Eng.* **2021**, *9*, 297. https://doi.org/10.3390/jmse9030297

Academic Editor: Elisabetta Tedeschi

Received: 4 February 2021
Accepted: 4 March 2021
Published: 8 March 2021

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1. Introduction

Offshore wind energy (OWE) is one of the largest forms of clean energy and a sector in clear expansion over the last decades [1–4]. Europe is the leader in installed offshore wind farms [2], and its growth could be explained, due to the major role that wind energy plays in the achievements of the 20-20-20 targets defined by the European Union (EU) [5]. According to the *Central Scenario* in Reference [6], a 70 GW of offshore cumulative wind energy capacity are expected, producing 888 TWh of electricity, equivalent to 30% of EU's power demand and meeting the 27% renewable energy benchmark established for the beginning of 2030.

Offshore wind is around 50% more expensive than onshore wind, being towers and foundations 350% more costly than the ones used in onshore turbines [7]. The foundations represent, on average, about 30% of the structure's total investment [8,9], with a considerable part being related to scour protections [4]. Therefore, the optimisation of scour protections can have a direct impact on the LCoE—levelised cost of energy—which represents the ratio between the structure lifetime cost's and energy production [10]. This impact can occur via the capital expenditure (CAPEX) or the operational expenditure (OPEX), mainly because such optimisations are often related to the reduction of the stone material and transport costs applied to the initial solution (CAPEX optimisation) or to the reduction of re-filling operations after the occurrence of extreme storm events (OPEX optimisation).

Scour protections are seen as a preferential contribution to lowering the LcoE and have registered major developments in the past 10 to 12 years. It is expected that such developments can, in time, be extended to wave and tidal energy foundations as well.

Key contributions include, for example, the wide-graded and dynamic scour protections or the application of probabilistic design methods [11–13]. However, the field implementation of such concepts and design methodologies still poses challenging knowledge gaps, which are yet to be fully addressed. The offshore wind sector, which sets the pace for many of the optimisations that are then extended to other sectors of marine renewables, has been focused on major trends towards higher profitability, including the repowering of existing foundations [4], the re-adaptation of oil and gas structures to wind energy production, the development of complex foundations [14] or new hybrid foundations with more than one type of energy conversion, e.g., combined wind and waves [15].

Depending on the site conditions, these trends may enhance the use of scour protections, which need to be designed to account for the added complexity of new geometries of the foundation, the disturbance of the flow-fields, due to the presence of energy converters, the extended life-time cycle of already existing foundations, the occurrence of severe damage, among several other aspects, which remain to be fully understood.

The new trends for the development of offshore wind foundations have a direct impact on the design of the protections, due to its influence on the damage in the rubble mound armour layers with complex geometry, i.e., varying thickness and horizontal extension. The damage behaviour of rubble mound armour layers under different loading and design conditions is still to be known in detail, and new studies are now focusing on improving the resulting damage description, e.g., References [16,17].

Furthermore, new fields of Marine Renewable Energy are now rising towards several demonstrations and large scale in situ projects, owing to its large potential to capture the untapped ocean energy resources [18]. However, the design of scour protections for foundations with movable energy converters, whose motion impacts the waves-current profile, is yet to reach a mature state of knowledge.

Unlike other maritime structures, e.g., breakwaters, quay-walls or groins, the knowledge needed to design scour protections is hold by a restrictive number of experts in the industry and academia, which is a result of the harsh confidential policies adopted by the stakeholders of the sector [4]. This results in the absence of enough benchmark data available to explore and solve the existing knowledge gaps, particularly in large-scale studies. Only, more recently, this data has been partially compiled and extended in studies, such as References [13,16].

Given the new trends for offshore foundations and the most recent contributions made, reviewing the research needs, challenges and recent findings associated with scour protections represent an important contribution for a systematic guidance on optimising offshore foundations. Hence, providing opportunities to increase the competitiveness of marine energy harvesting technologies, from the most developed ones, i.e., offshore wind energy, to the ones that are still striving for a mature commercial stage, i.e., wave, tidal and marine currents energy. The challenges arising on this topic are numerous, and a thorough review focused on the latest findings is important to summarise current knowledge and outline future research lines.

Aiming to contribute to a deeper notion on the existing knowledge gaps that contribute for an over-conservative design and high costs of scour protections, the main goal of this article is to summarise and highlight the most recent research on scour protections, with particular emphasis on the dynamic, and wide-graded rip-rap systems.

The present review approaches different optimisation perspectives, from the conceptual improvements to the application of scour protections in complex and hybrid offshore foundations. This research ultimately provides a broad notion on the fields that benefit from the most recently acquired knowledge of the topic and the prospective developments that may also enhance the most recent trends shown in offshore foundations. In addition, synergies between scour and scour protection research and related research fields are also identified and discussed.

The remaining of this paper is organised in the following manner: Section 2 addresses the most recent advances on conceptual optimisations, including recent design methodologies. Sections 3 and 4 focus on two aspects, scarcely addressed in the literature, considered to be crucial to describe the protection's behaviour in the marine environment, the long-term damage evolution and the influence of the relative direction between waves and currents. In Section 5, the methodologies to characterise damage are analysed with a focus on their influence on design methodologies. Sections 6–8 give a broad overview of relevant studies, findings and knowledge gaps on the topics of numerical and physical modelling, and field monitoring studies. Sections 9 and 10 provide a broad analysis of the prospective application and development of scour protections for complex foundations and alternative marine energy harvesting technologies (wave and tidal energy). Finally, Section 11 provides the main conclusions and summarises the knowledge gaps identified in previous sections.

2. Conceptual Optimisations

2.1. Scour Protection Conceptual Designs

Scour protections have an important role in offshore wind turbine design. Rip-rap (rubble mound material) protections are a common type of protection, due to their low cost and material availability [3].

It should be noted, however, that the cost of scour protective measures may vary from one case to another, depending on several factors, as the location or the material stock at nearby regions. In addition, the material stock, transport and installation costs may depend on the required stone size. Therefore, rip-rap scour protections may not always be the most affordable solution. Nevertheless, although the studies performed on different scour countermeasures in the marine environment, e.g., References [19–21], rip-rap scour protections remain as one of the most widely used, hence being the focus of this review. Depending on the stability concept applied, these can be separated into three major groups (also see References [22–24]):

- Static Protections: Stone movement in the armour layer is not allowed;
- Dynamic Protections: Stone movement is allowed if the protection does not fail;
- Wide-graded protections, which consist of an armour layer of wide-graded material without a granular filter. These might be designed to be both statically or dynamically stable.

While static scour protections have been widely employed in commercial offshore wind projects, using dynamic scour protections (wide-graded or not) is yet to be widely applied. However, it is important to mention that often novel and optimised concepts, which may have been successfully implemented in the field, are not extensively announced to the scientific and professional community. This is due to the heavy restrictions posed by non-disclosure agreements between stakeholders.

Therefore, it is hard to assess the actual implementation of such concepts. Nevertheless, the focus on dynamic scour protections started about 12 years ago, with the systematised design proposal made by Reference [25], despite the preliminary studies presented by Reference [26].

Regardless of the lack of data for the commercial application of dynamic scour protections, Reference [1] indicates that these are expected to have a thickness of rubble mound layer generally varying between 0.30 m to 0.40 m, which compares to thicknesses of 0.5 to 1.0 m (sometimes higher) in the traditional static scour protection.

However, such differences in the thickness depend on the optimisation of the median stone size (D_{50}), since its reduction, which can go up to 80% according to Reference [23], may require an increase of the thickness to sustain the acceptable damage level without failure occurrence. Therefore, reducing the stone size too much may require a large increase in the thickness, which may contribute to increasing the costs of the dynamic solution. Moreover, it is important to account for operation and maintenance costs that may arise from the need to refilling the dynamic protection after severe storms. These costs are reduced if a static solution with very large stone sizes is applied. Therefore, the actual optimisation needs to be assessed on a case-to-case basis and always accounting for the CAPEX and OPEX parcels throughout the lifecycle of the foundation (also see Section 2.3).

2.2. Static Scour Protections

Since in static scour protections, the movement of the rubble mound material is not allowed, the design is based on the threshold of motion criterion. This means that the median stone size needs to be such that the wave-and-current-induced shear stress does not surpass the critical shear stress of the protection material [3,27]. Such size can also be varied depending on the density of the rubble material to be used. In Reference [22], it is shown through physical modelling for two stone materials, with densities of 2650 kg/m^3 and 3200 kg/m^3, that the damage of the protection can be reduced if higher stone's densities are used. For the environmental conditions given, the design of a static scour protections consists of defining the critical stone size (D_{cr}), which ensures that no movement occurs at the top layer.

Many formulations were adapted to determine the D_{cr} (m), e.g., a recent comparison of different formulas to obtain D_{cr} in the marine environment is given in Reference [28], which includes the comparison with formulas derived for the fluvial environment only. It was shown that the applicable formulations may lead to very different results in terms of stone sizes and weights. Nevertheless, in common design situations, the wave- and current-induced shear stresses are combined and then compared with the critical shear stress given by Reference [27]:

$$\tau_{cr} = \theta_{cr} g(\rho_s - \rho_w) D_{50} \tag{1}$$

where θ_{cr} is the critical Shields parameter, which for non-cohesive soils and a dimensionless grain size D* larger than 100 (see Reference [27]) corresponds to the asymptotic value of 0.056.

In Reference [22], an alternative way to obtain the maximum wave- and current-induced shear stress is given, and a new quantification of the critical shear stress is proposed. This new shear stress is calculated based on the $D_{67.5}$ instead of D_{50} and θ_{cr} = 0.035.

The reason behind this is that Reference [22] noted that smaller stones in scour protections with narrow graded material tended to move faster than if a wide-graded material was used. It was noted that often these smaller stones could present singular movements without an actual generalised violation of the static stability. In compensation, a smaller value of the critical Shields parameter was used, thus contributing to a conservative estimation of the critical shear stress. In Reference [11], it was shown that the critical shear stress according to Reference [22] was still less conservative than the formulation given by Reference [27], which could eventually reduce the design value D_{cr}.

However, the number of tests used to define the onset of motion, i.e., static stability, in Reference [22] led to a regression formula that combines the wave- and current-induced shear stress, which has a considerable degree of uncertainty. At the end of the day, this poses an important setback to its application instead of Reference [27], which was extensively validated for undisturbed conditions, i.e., without a foundation placed at the seabed.

The application of Reference [27] to monopile foundations, or any other type of foundation, in fact, implies the use of an amplification factor, which accounts for the increase in the wave- and current-induced shear stresses, due to the presence of the foundation. The definition of the amplification factor is often hard, and is very empiric in nature. In monopile foundations, defining the amplification factor could be a simpler task, since classic references as References [29,30] widely address this aspect. In complex geometries, however, the difficulty increases considerably, and the majority of the projects require physical and numerical models to assess the proper amplification factor to be used. The formulation given by Reference [22] does not imply the use of an amplification factor, since it was derived specifically for monopiles. Conversely, its application is rather limited, and the extrapolation for complex geometries of the foundation is not straightforward.

2.3. Dynamic Scour Protections

In 2004, the first proposal of a dynamically stable scour protection was introduced by Reference [26] as a result of the OPTI-PILE project [31]. The OPTI-PILE project, destined to optimise the scour protection design, introduced the so-called stability parameter (stab), to classify protections according to three levels of damage (static, dynamic, failure). It was concluded that dynamic protections could be built using smaller median stone sizes (D_{50}) when compared to the static protections. The stability parameter was defined as the ratio between the maximum dimensionless wave- and current-induced shear stress (θ_{max}) and the dimensionless critical shear stress (θ_{cr}):

$$\text{stab} = \frac{\theta_{max}}{\theta_{cr}} \tag{2}$$

The introduction of the stab parameter marked the beginning of a new design paradigm in scour protections for the offshore marine environment. In this new paradigm, the threshold of motion is no longer the criteria for stability; instead, the rubble mound material is allowed to have a certain degree of movement, as long as the filter layer does not present an exposure area equal to, or larger, than $4{D_{50}}^2$—i.e., an equivalent square with a size equal to two stones with size D_{50} by D_{50}.

The following states of stability/failure were defined in Reference [26]:

- Static stability: stab < 0.4155;
- Dynamic stability: 0.4155 ≤ stab ≤ 0.460;
- Failure: stab > 0.460.

In this type of protection, the development of scour pits is allowed to develop until their equilibrium stage [26], then a two layers protection is placed (granular filter and rubble mound top layer). According to Reference [26], dynamic scour protections reshape the armour layer, i.e., stones previously moved may return to the initial position, for example, when currents reverse. Since static protections have proven to be conservative driven, the possibility of having movement of stones without failure allows for a smaller stone diameter to be used—thus lowering the costs at offshore wind foundations, namely, the ones related to transportation, installation and rubble material acquisition. However, the possibility of reshaping may imply regular monitoring of the protection's damage after storm events, to ensure no excessive exposure of the filter layer has occurred. Thus, in practical cases, it is often common to compare the CAPEX and OPEX parcels of both static and dynamic scour protections, to ensure that the maintenance of a dynamic solution is not overcoming the savings made in CAPEX parcel when compared to a static solution. Still, an important aspect is that often static scour protections fail and require further expenditures on the OPEX parcel as well; this has been addressed by Reference [32], with field surveys in known protected offshore wind turbines, e.g., in Egmond aan Zee (NLD) and Horns Rev (DEN) offshore wind farms.

The stability parameter is also, in a certain way, dependent on the amplified bed shear stress, due to the presence of an offshore foundation. Later on, in 2008, a key breakthrough was introduced by Reference [25], also presented in 2012 by Reference [23], which provided an alternative design for dynamic scour protections based on the damage parameter. Based on extensive physical modelling activities, following a Froude similitude and a geometric scale of 1:50, Reference [25] noted that the stab parameter failed to predict the onset of motion for scour protections tested under different hydrodynamic conditions.

Hence, looking for a simplified design procedure, the damage number (S_{3D}) was introduced. The S_{3D} was not directly dependent on the critical shear stress, thus surpassing some of the limitations of calculating the critical shear stress and the maximum shear stress induced by local conditions. In fact, the damage number finds its resemblance in Van der Meer's damage number developed for breakwaters [33], which also show the ability to develop a stable profile under dynamic conditions of the armour layer material.

For design purposes, Reference [23] proposes the following formula to quantify the damage number of scour protections:

$$\frac{S_{3D}}{N^{b0}} = a_0 \frac{U_m^3 T_{m-1,0}^2}{\sqrt{gd}(s-1)^{3/2} D_{n50}^2} + a_1 \left(a_2 + a_3 \frac{(U_c/w_s)^2 (U_c + a_4 U_m)^2 \sqrt{d}}{g D_{n50}^{3/2}} \right) \quad (3)$$

where N is the number of waves, g (m^2/s) is the acceleration of gravity, d is the water depth, s is the ratio between the density of the rock material (ρ_s) and the water density (ρ_w), U_m (m/s) is the orbital bottom velocity, U_c (m/s) is the depth-average velocity and the regressions coefficients a_0, a_2, a_3 and b_0 are equal to 0.00076, −0.022, 0.0079 and 0.243, respectively [23]. The settling velocity (w_s) and the coefficients a_1 and a_4 are also defined in Reference [23]. Similarly, to Reference [26], the failure criteria used by References [23,25] was also the exposure of the filter layer to an area equal to $4D_{50}^2$. The following limits for the damage number were defined:

- Static stability: $S_{3D} < 0.25$;
- Dynamic stability: $0.25 < S_{3D} < 1$;
- Failure: $S_{3D} \geq 1$.

While the damage number, does not require the quantification of the amplification factor, other uncertainties can be found in its definition, namely, the limited conditions for which it was initially developed. For example, although being a result of a considerably large number of scour protection tests (85 tests), the range of water depths and armour layer thicknesses tested was rather reduced.

Other studies, e.g., References [34–36] tried to extend the testing conditions of the formula, all these reaching the conclusion that the limits established for the stability of the scour protection showed overlapping situations, thus the failure of a dynamic scour protection could occur for values above 1.00. This was also initially noted by Reference [23], which proposed a suitable limit within a conservative design perspective. Still, the space for improvement of the present formula's accuracy exists and is an important aspect of ensuring that dynamic scour protections reach a similar level of maturity as the static design. Moreover, the damage number was specifically developed for monopiles, and its application to other complex structures is also not straight forward, since there are regression coefficients to be adjusted in the prediction formula.

2.4. Wide-Graded Protections

Rip-rap scour protections are regularly designed with two layers, first granular material is applied and then a rubble mound layer is placed on top. However, in line with the laboratory observations made by References [12,24,37,38], formally introduced and developed the wide-graded protection optimisation, which used a single layer with a very extensive granulometric curve, whose stability was expected to be increased in comparison to narrow graded protections. This assumption was based on the fact that in wide-graded materials, smaller stones could find better shelter among the largest ones, with the voids of the protection being reduced, thus contributing to the stability of the overall. Reference [12] showed that for wide-graded mixtures, the washout of finer particles was less likely to occur.

Reference [12] tested wide-graded protections under waves and currents. Reference [12] determined fractional critical shear stresses through velocity measurements and noted the occurrence of highly selective incipient motion of individual fractions under steady current conditions. The selective mobility of this wide-graded material could not be expressed by the Shields approach. A stable and almost immobile protection surface was observed under the currents, indicating a provisional static armour layer. Whereas, under waves, wide-graded armour layers tend to be quite stable. The scour pattern observed around the monopile had a maximum depth at the protection almost identical both in front and at the back of the monopile. However, after 9000 waves, a final equilibrium scour depth was not reached at a distance of $1.5D_p$ from the centre of the monopile. The use of 9000 waves, as a reference for testing wide-graded materials, was not previously used in the tests that led to the development of dynamic scour protections, e.g., References [25,26] and remaining ones. This poses an interesting question in terms of results comparison, and a clear indication is given by Reference [4], which states that results referring to long-duration tests, i.e., above 5000 waves, are still needed in larger numbers in the literature.

Reference [39] performed 46 scour tests, using a singular graded scour protection, and concluded that for wide-graded protections, at the top of the protection singular layer, the finer fractions are removed, by an armouring process, and mainly due to the action of the horseshoe vortex, leading to a partial settlement of the surface layer. Beneath the top, the material properties remain, revealing that scour from the top reaches an apparent equilibrium. The observed equilibrium scour was about $2D_{50}$, whereas the settlement was about $1D_{50}$. The studies performed in References [12,24,37–39] provide strong indications on the feasibility of static and dynamic scour protections made out of a single wide-graded layer, which may contribute to lower costs of installation and material preparation, since no granular filter is needed. More recently, two large-scale scour protection tests are also analysed in Reference [13]. However, the most recent analysis of such data set, made by Reference [13], was more focused on the behaviour of two-layered dynamic protections, thus the literature still shows a lack of data and results discussion in terms of wide-graded scour protections, particularly in situ and in large scale models. Additionally, it is important to note that the dynamic design based on the damage number, relates to the exposure of the filter layer, which is not applicable to wide-graded protections. Eventually, the damage number associated with failure could be defined for the exposure of the actual sand bed. Nevertheless, a detailed discussion of the stability and failure boundaries for wide-graded protections is yet to be fully addressed in the literature.

Another interesting aspect of rip-rap scour protection relates to the pore pressure registered inside and beneath the protection layer, which may lead to the sinking failure mode as a consequence of the suction of the material placed as a filter or the actual sand-bed sediments [40]. In wide-graded scour protections, the volume of voids might be considerably smaller than in a narrow-graded protection and scour protections with two layers. Therefore, the hydraulic gradient is different, which in turn affects the potential for material to be washed out and transported away from the protection. Recently, Reference [41] provided insights on the onset of motion beneath scour protections made of rubble mound material. However, the effects of the grading were not investigated in detail. Still, important outcomes were derived for waves and currents combined and acting alone. It was found that the onset of motion of the sediment underneath the scour protection was dependent on the sediment properties and the thickness of the scour protection (among other variables). This clearly indicates that it is worth further investigate the pore pressure on wide-graded materials, which have a tendency for sort out finer fractions on top of the protection, but that can remain intact at lower levels of the protection's thickness, as mentioned by Reference [39].

The literature shows a lack of reported field applications of wide-graded scour protections. Still from the design point of view, they are faced as an interesting alternative, since the stability of the protection has been shown to benefit from the wide gradation. In addition, from the installation point of view, the no need for a filter layer placement is also an appealing detail. In practical terms, installing these protections, typically made with fall pipe vessels, needs to be considered, since the act of dropping the wide-graded material in offshore conditions, even in good weather windows, may always lead to a loss of the finer fractions. This occurs because the fall velocity is not the same for all fractions, and some of them are more prone to be dragged away during the settlement process than others, before reaching the sea bottom. Hence, the installation process may influence the performance of this solution and also represents a relevant aspect for future applied research.

2.5. Challenges on Conceptual Optimisations

While the concept of statically stable scour protections is at a mature state of the application in several commercial projects of offshore wind energy, the design concepts of dynamic stability and wide-graded protections are yet to reach the same level of application, at least from what it can be judged from the reported field cases. It is although natural that some applications may exist, but under such restrict confidential policies, it is hard to assess their success in practical cases. Reference [1] reports that dynamic scour protections have been successfully applied in Scroby Sands (UK) and Princess Amalia (UK) offshore wind farms. Nevertheless, there is a sufficient number of research studies to look at these alternatives as interesting contributions to enhance a cheaper exploitation of marine renewables, with a particular emphasis on the offshore wind sector.

Conversely, there are still important challenges to be addressed before wide implementation of these optimisations. Firstly, as identified in Reference [28], the available methodologies for design, including the shear-stress and damage quantification, are not large in number and present considerable disparities in terms of the outcomes for design variables, such as the median stone size (D_{50}).

Secondly, some of these methodologies, e.g., Reference [26], depending on factors, such as the wave and the current friction coefficients or the amplification factor, which are remarkably empirical in their nature and often hard to be defined in a forthright manner. Such factors are also present for statically stable design, e.g., as discussed in Reference [4] regarding the amplification factor, which varies depending on the hydrodynamics and the foundation's geometry, among other aspects. Others, as References [22,23], have been derived from extensive physical modelling data sets, but they have limitations on their range of applicability, namely, the fact they have been developed specifically for monopile foundations. Albeit being the most widely used foundation, this causes uncertainty when designing optimised protections to other foundations, such as gravity-based ones, jackets, tripods, or even bottom founded tidal turbines and wave energy converters (WECs). In fact, submerged energy converters alter the flow conditions and the turbulence structures, such the horseshoe and lee-wake vortices, which in turn affects the amplification factor, the shear stresses, the pore pressure and other hydrodynamic and soil-fluid interaction parameters, ultimately influencing the design of the protection (see Sections 9 and 10).

Moreover, the design procedures proposed for different optimisations present differences in the assumptions considered to develop the design methodologies. For example, the dynamic scour protections studied by Reference [26] are levelled with the seabed, whereas Reference [25] uses protections above the bed level. Despite the gentle slope used by the latter, the edge scour will always be considerably larger than the one presented in a levelled scour protection. This can be a partial reason for the differences shown in the comparisons between the stability parameter and the damage number.

According to Reference [36], in dynamic stability, the transitions between some movement and failure are gradational, thus limits proposed must be seen as conservative values indicated for design purposes. It is difficult to define a sharp limit for each stability category and leads to the need for further validation of the referred methodologies and, sometimes, a case-to-case calibration, which is the case of the stability parameter. Thus, improving the accuracy of the design formulas is another important challenge, which needs to be tackled using novel laboratory experiments and field monitoring campaigns.

To account for the design uncertainty applicable to both static and optimised scour protections, Reference [11] proposes a probabilistic design approach based on Monte-Carlo simulations. The approach allows for a design based on the probability of failure of a scour protection and has been applied to Horns Rev 3 (DEN) offshore wind farm, concluding that dynamic and static scour protections can be designed to yield the equivalent levels of safety. However, the method is yet to be extended to wide-graded scour protections and other failure modes than the erosion of the top layer, e.g., edge scour, sinking failure. The novel damage characterisation proposed in Reference [16] contributes with additional insights on the statistics of damage at scour protections, thus representing an opportunity to improve the probabilistic design methods.

3. Long-Term Damage

The definition of acceptable damage for scour protections is not consensual [36], and it is crucial for the reliability analysis and risk evaluation of scour protections [4]. In addition to that, there is a lack of knowledge about the capacity of dynamic protection to recover from that damage that has occurred during a specific storm or sequences of storm events, which may or may not be alternated with mild conditions [4].

Independently of a consensus on the acceptable damage number, the analysis and evaluation of a scour protection's efficiency over long-term periods implies a broad understanding of the long-term behaviour of damage and its potential recovery if a dynamic design is being adopted. Experimental tests and studies were developed to determine and measure damage or to understand the behaviour of the protections through different and severe conditions. Studies have been performed for 3000 to 5000 or even 7000 waves [34,35]. Reference [12] reached the 9000 waves for a reduced data set. The dynamic design approach from Reference [23] has been based on tests with 3000 to 5000 waves. The literature clearly shows that scour protection tests longer than 5000 waves, are still scarce. Thus, the knowledge of the damage time-scale and equilibrium stage is still limited. In addition, the studies reported focus sets of 3000 to 5000 waves under the same wave spectra, whereas there are no studies reported for sequences of different wave trains.

The importance of increasing the existent data sets for large wave series is mainly related to the need for understanding the ability of scour protections to recover from previous induced damage, eventually shaping into an equilibrium profile. This becomes particularly important in dynamic protections, which are supposed to backfill, if the local hydrodynamic conditions allow for it, as it is the case of many locations with cyclic reversing of tidal currents or opposing dominant directions of waves and currents depending on the weather season.

For static scour protections the number of waves is not considered in design formulas, since they are based on the threshold of motion criteria [22], solely. However, in dynamic scour protections the number of waves directly affects the estimation of the damage number. Like in a regular scour case, the erosion of the rubble mound top layer cannot occur indefinitely. An equilibrium profile will be reached, until new hydrodynamic conditions act on the offshore foundation. Reference [34]'s scour protection tests indicated that damage at the top layer of dynamic protections could still occur after 5000 waves, but the scour increasing rate drops considerably after 1000 waves and from 3000 to 5000 waves the increase is already very small. However, the prediction formula for S_{3D} presented by Reference [23] suggests that under the same hydrodynamic conditions, if the number of waves tends to infinite, then the damage number will tend to infinite as well.

Since the damage number formula given by Reference [23] is not able to represent an equilibrium situation, Reference [42], suggested the inclusion of the characteristic number of waves (N_{charac}), by altering the left side of the damage number equation (see also Equation (3)):

$$\frac{S_{3D}}{N^{b0}} \approx \left(\frac{S_{3D}}{b_1 \left[1 - \exp\left(-\frac{N}{N_{charac}} \right) \right]} \right) \tag{4}$$

$$b_1 = 7.6 \text{ for } N_{charac} = 855 \text{ waves} \tag{5}$$

Reference [42] formula gives rather similar results to References [23,25], between 1000 and 5000 waves. The use of b_1 = 7.6 is recommended by the author, but it is stated that for such value, the increase in damage will hardly be noticed after 2500–3000 waves, thus meaning that equilibrium could be reached after one storm and that a more severe one would be required to reshape the scour protection into a different pattern.

For dynamic scour protections, most physical model studies reveal that the damage increases until 3000 waves and then starts to slow down (although for 5000 waves, damage was still developing. Reference [34] reported that for 3000 waves could not be sufficient to achieve an equilibrium profile, although after that damage rate decreases significantly. Reference [34] also performed a test where for 7000, waves scour holes were formed, then filled at the same time that other holes started to occur in other locations. Despite such results, it is recognised that one test was not enough to form a conclusion on the long-term evolution of damage. For 9000 waves, Reference [12] concluded that dynamically stable profiles are reached from 5000 waves forward. Nevertheless, a common factor between these data sets is that tests are performed with a small range of hydrodynamic condition, which makes generalisations difficult. Therefore, a relevant step forward on this matter would be to create larger data sets on this topic, while also comparing the existing ones with a detailed analysis on potential differences arising from model setups and different scales used.

At present, state-of-the-art, long-term evolution of damage, particularly on dynamic scour protections and wide-graded scour protections, faces two key knowledge gaps that might be primarily addressed by proper physical modelling activities: (i) Understand if the equilibrium of the protection is indeed reached up to 5000 waves and what systematically happens if longer durations are used, (ii) understand what is the effect of sequential storm events, which may not be as high as the design event, but that may produce a considerable amount of accumulated damage over time. To address these two aspects, future physical modelling tests should consider durations at least above the 7000 waves, preferably with waves combined with currents. In addition, it is also important to perform scour tests that can combine sequences of "operational sea states" alternated with storm events, to analyse damage evolution under accumulated effects of different sea-states.

4. Effects of Waves and Currents

The simultaneous reproduction of waves and currents and their combined effect is important to replicate offshore conditions as accurately as possible. The most common approaches used to describe the interaction between waves and currents are the ones proposed by References [27,43]. Moreover, the shear stress equations, proposed by Reference [24], consider the different directions of propagation of both currents and waves.

However, these equations have only been used to design static protections, which account for the threshold of motion. In the case of dynamic protections, the methodologies to calculate the damage number only consider co-linear waves following or opposing currents [23].

Since flow characteristics affect both the wave height and period, the calculation of the damage number should include these influences. References [23,25] state that the protections' damage number is larger in waves opposing currents than in waves following currents—for the same conditions of significant wave height (H_s), peak wave period (T_p) and depth-average current velocity (U_c). Subsequently, if the damage number formula is not created to consider different waves and currents directions, the actual damage predictions may not be accurate for locations, where the wave-current field is not aligned [4].

When waves and currents act in the same direction, the wavelength may increase, leading to longer wave troughs, which last longer than wave crests. Although the trough velocity is smaller than the crest velocity, it lasts longer, so the duration of the bed shear stress during troughs persists longer [25]. As detailed by Reference [25], the movement of the rock material that composes the scour protection is not only dependent on the magnitude of the bed shear stress, but also on the duration of that same acting shear stress. On the contrary, waves and currents acting in opposite directions cause the wavelength and the wave period to decrease, increasing the wave height, thus increasing the bed shear stress induced by waves.

Very recently, Reference [44] studied the scour effect caused by waves spreading under combined waves and oblique currents on a monopile foundations. This study provided ground-breaking contributions, since very few studies can be found on non-collinear waves and currents. Reference [44] concluded that for wave-only conditions, final scour depths have been measured in unidirectional waves that were on average 33% larger than those in directionally spread waves for comparable values of KC number. Furthermore, final scour depths decreased with increasing wave spreading and displayed a growing dependency on KC numbers with increasing wave spreading. Scour protections were not analysed, however the conclusions derived on scour physics provided insights on future critical damage locations at protected structures under similar hydrodynamic conditions.

The quantification of the wave-currents relative direction in the damage behaviour and the design scenarios that lead to the ultimate limit state of the protections is not straightforward. Further research-oriented to enlarge the data sets for different relative directions is of utmost importance to clarify this aspect, namely, the observations made by References [23,25], which led to a formula that provides larger damage numbers for waves opposing currents. This could be addressed in a first step by extending the study presented in Reference [44] to protected foundations.

5. Characterisation of Damage

Another important aspect of improving the design of scour protections lies in the accuracy of the existing formulas. Reference [36] compared the results from References [34,35] with the ones from Reference [23]. The predictions' root square mean error increased from the original value of 0.114 to 0.756 when using the damage number formula of Reference [22]. Additionally, if considered the fact that research performed by Reference [25] also identifies values of the damage number for the transition between dynamic protections and failure, i.e., above $S_{3D} = 1$, it can be recognised that the predictive formula can be improved particularly outside its original range of tested conditions [4].

Nevertheless, as mentioned in Reference [4], the referred design formula is on the conservative side, for most of the tests presented in the literature. The improvement of the existing formula, or the appearance of improved ones, is much dependent on the quantification and measurement of damage in laboratory tests.

Key aspects of this topic and their potential influence were raised and discussed in Reference [4], which proposed an alternative way of quantifying the damage of a scour protection tested in the physical model. The alternative corresponded to the analysis of overlapping regions of the protection, instead of looking at fixed regions, the so-called sub-areas, as proposed in Reference [23]. Details on the sub-areas and calculations of the measured damage number are given in Reference [23]. Figure 1 provides a scheme of the sub-areas division used in Reference [23].

The method suggested in Reference [4] was recently materialised in the novel method proposed by Reference [16] to characterise damage of the rubble mound protections. The new method allowed for the analysis of both the maximum damage number, and the statistical characterisation of damage using the cumulative distribution function of damage.

According to Reference [23], the damage number of each sub-area—which has an equal area to the monopile cross-section—is determined by the ratio between the respective eroded volume (V_e) and the monopile's cross-section area (D_p). The representative damage number of protection corresponds to the maximum damage number of all sub-areas.

$$S_{3Dsub} = \frac{V_e}{D_{n50}\pi\left(D_p^2/4\right)} \tag{5}$$

$$S_{3D} = \max_{i=1 \text{ to number of sub-areas}} \left(S_{3Dsub,i}\right) \tag{6}$$

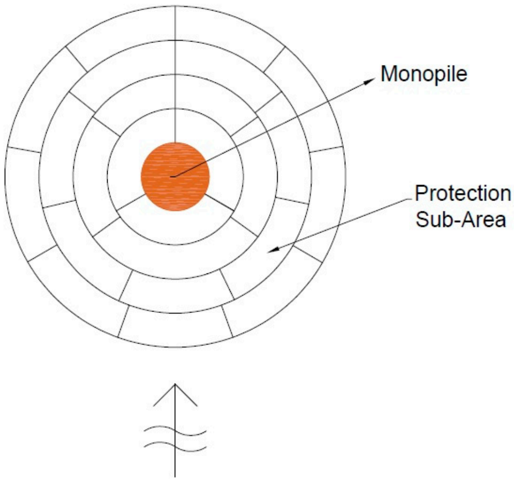

Figure 1. Scheme of the sub-area divisions used in Reference [23].

In Reference [4], two theoretical examples are presented to address situations for which the maximum damage might not be enough to describe the protection's proneness to failure. These are then explored in detail in Reference [16] using the large-scale tests provided described in Reference [13]. The first example concerns the maximum damage number as the most representative S_{3D} value of the protection. The second example discusses the cumulative effect of damage in different sub-areas locations.

Reference [4] alerts to the fact that the eroded height is being averaged per sub-area. Therefore, being difficult to understand if several adjacent sub-areas display similarly large values of S_{3D}. Several adjacent sub-areas and/or sectors' intersection with $S_{3D} > 1$ might be more prone to filter exposure than dispersed sub-areas with larger values of S_{3D} [4], and this is not considered if only the maximum value is being analysed (Figure 2). Additionally, severe damage occurring in the inner regions of the protection, closer to the foundation, may have a more immediate influence on the structure's safety, whereas damage occurring at the edges of the protection has an influence that is expressed in the long run, after the damage propagation to the inner regions occurs, resulting in the loss of the protection's functionality. Reference [4] discussed a different way to analyse the damage being measured at the laboratory tests. It consisted in the creation of a mesh of overlapping circles placed in concentric rings, centred at the monopile, with a certain overlapping distance, angle (α) and resolution—according to the accuracy required (Figure 3). The size of each element of the mesh is defined as a multiple of the nominal median stone diameter of the protection.

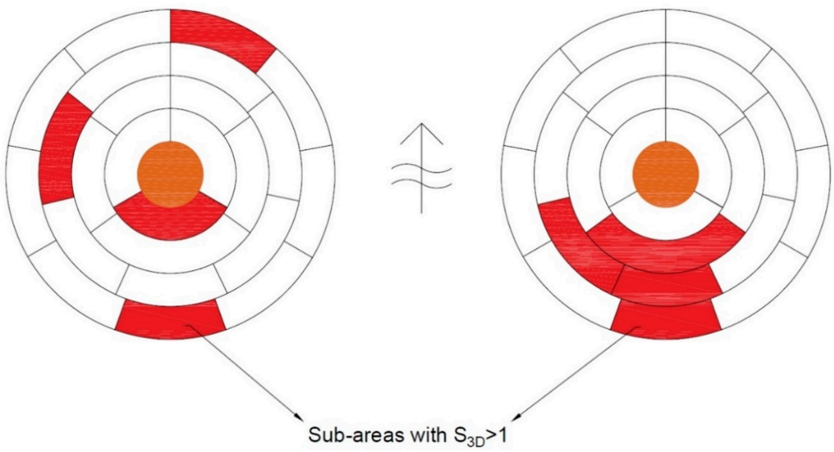

Figure 2. Example of different scour exposures for the same S_{3D} > 1.00—left Protection: Less prone to filter exposure; right Protection: More prone to filter exposure, because the damage is gathered in the same region, adapted from Reference [4].

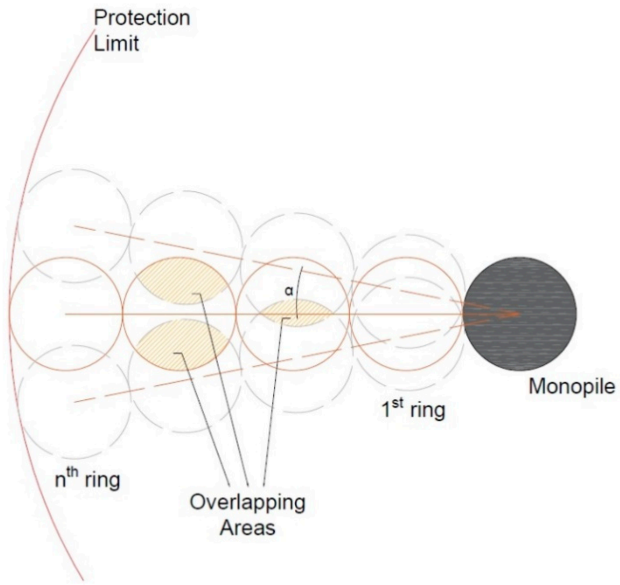

Figure 3. Overlapping circle mesh concept, according to Reference [4].

The alternative methodology [4], divides the V_e by the area of the overlapping circles:

$$S_{3Dsub,i} = \frac{V_e}{D_{n50}\pi(nD_{n50})^2} \tag{7}$$

This ratio is divided by D_{n50} so that the S_{3D} value can correspond to a scour depth expressed as a function of the number of armour layers units that are being used in the protection.

This approach was later implemented in Reference [16], including an extension of the overlapping areas for both circles and ring-shaped sections similar to the ones in References [23,25].

The concept of overlapping sub-areas prevents an excessive lowering of damage, due to the averaging of the scour depth over larger sub-areas. With the combination of these two steps, a mesh is created that reduces deceptive damage interpretations. In addition, this method also presents the advantage of being independent from direction of the flow [16].

The methodology developed and implemented in Reference [16] enabled a much large population of damage numbers quantified over the scour protection's area, thus allowing for the statistical analysis of damage as well. This unlocked the possibility of describing failure with additional parameters than the maximum damage number. In Reference [16], the standard deviation and the 95th quantile of the damage number are shown to be useful to mathematically describe the exposure of the filter layer associated with failure ($4D_{50}^2$) and formerly introduced in Reference [26]. In addition, overlapping sub-areas has the advantage that the damage calculation no longer remains dependent on the cross-section of the protection, the type of foundation and the angle between waves and currents [16]. This becomes quite handy, particularly, when focusing on another important literature gap, which is the damage of scour protections for complex foundations (see Section 9).

Note that the new method uses the median nominal stone diameter as reference, allowing to compare tests with different grain sizes and foundation cross-sections.

An aspect left to be solved by Reference [16] relates to the fact that under the new overlapping method, the acceptable damage number for dynamic protections needs to be re-defined, implying the analysis of broader data sets. At the present state, the method did not present specific guidance for design values of the damage number, thus, Reference [23] remains as the practical design methodology that can be used to derive the protection's stone size. However, Reference [16] provides an interesting prospective on further updates to the damage number formula given by Reference [23] and the reliability analysis developed in Reference [11], since it provides useful information on the damage quantiles. Future research on this topic should focus on the analysis of the new damage number scale obtained with Reference [16], as doing it may enable the development of new and potentially more accurate equations to be used for design purposes.

6. Physical Modelling Research

Scour protection's research and optimisation has mainly resulted from the knowledge acquired through physical modelling activities. Albeit the fact that many physical modelling studies have been reported in the literature for the fluvial environment and marine static scour protections, the studies related to optimised protections in the marine environment, e.g., dynamic and wide-graded ones, have not produced the same amount of data and knowledge.

Table 1 compiles the most recent studies performed on optimised scour protections. It is shown that most of the tests have been performed at rather small geometric scales, mainly close to 1:50. The scale (and model) effects on scour protection tests are widely discussed in References [45,46], and they represent a relevant source of uncertainty in the comparison between the studies performed so far. The detailed description of all scale effects lies outside the scope of the present review. However, there is one in particular that has considerable importance on the development of design methodologies for optimised protections. Reference [13] noted that in large scale tests, the threshold of motion, i.e., the critical shear stress, is larger than in previous small scale studies for equivalent median stone sizes. Reference [13] also included repeated tests from the data set from References [22,23], and the threshold of motion was only occurring for larger values of critical shear stress. Thus, meaning that small scales tend to be conservative with regard to the incipient motion of rubble mound material.

Table 1. Physical modelling studies on optimised scour protections (model conditions).

	[10]	[12]	[13]	[22]	[23]	[26]	[34]
Type Protection	Dynamic	Wide-graded	Static Dynamic	Static	Dynamic	Static Dynamic	Static Dynamic
Scale	1:50	1:4	1:16.67 1:8.33	1:50	1:50	1:47.25	1:50
T_p (s)	[1.50–1.62]	8	[2.00–3.50]	[1.13–1.70]	[1.13–1.70]	[1.29–1.40]	[1.52–1.55]
U (m/s)	[0.13–0.15]	[0.51–0.96]	[0.25–0.57]	[0–0.30]	[0.00–0.30]	[0.15–0.3]	[0.15–0.23]
Wave-current (direction)	Following	Waves	Following Opposite	Following Opposite	Following Opposite	Following	Following
H (m)	[0.10–0.11]	[0.70, 1.00, 1.30]	[0.19–0.56]	[0.05–0.17]	[0.05–0.17]	[0.14–0.18]	[0.80–0.14]
d (m)	0.36	5	[0.9–1.8]	[0.20–0.40]	[0.20–0.40]	0.51	[0.24–0.50]
Waves	Irregular	Irregular	Regular Irregular	Regular	Irregular	-	Irregular
N (–)	[5000–9000]	9000 [3 × 3000]	3000	50	[1000–5000]	-	[1000–7000]
D_p (m)	0.10	1	0.3 0.6	0.10	0.10	0.09	0.10
$D_{n50/}$ (mm)	4.24	12	[6.75–13.5]	[3.45–7.14]	[3.5–7.2]	[5–600] kg (prototype rock grading)	[2.7–7.5]
ρ_s (kg/m^3)	2630	-	2650	2650	[2650–3200]	-	[2564–2600]

Table 1. *Cont.*

	[10]	[12]	[13]	[22]	[23]	[26]	[34]
Armour Thickness	$3D_{n50}$	0.50 m	[2.5 to 9] D_{n50}	$3D_{n50}$	[2.5 to 3] D_{n50}	$3D_{n50}$	[2 to 8] D_{n50}
Armour Extent	$5D_p$	$11D_p$	$5D_p$	$5D_p$	$5D_p$	$5D_p$	$5D_p$
Filter Type	Geotextile	No Filter	Geotextile	Geotextile	No filter Granular Geotextile	Granular Wide-Graded	Granular

If on one hand, this is rather satisfying, because it implies that design according to the stab parameter or the damage number is on the safe side; on the other hand, it may also imply that existing design methodologies can overestimate the beginning of motion (and damage) at the protection. The generalisation of the observation made by Reference [13] is of utmost priority when it comes to future challenges that need to be addressed in terms of physical modelling studies on both dynamic and wide-graded scour protections. Furthermore, because there is no consensus on the literature with respect to the tendency for such a conservative tendency. In this aspect, using large-scale facilities, e.g., the Fast Flow Facilities at HR Wallingford, as in References [13,47], enables the validation of former conclusions obtained from small-scale setups. Therefore, it is important that the scientific community continues striving to extend the large-scale benchmark data sets as a way to acquire further realistic insights on scour protections.

Table 1 and general literature also indicate the need to enlarge the range of tested conditions, namely, in terms of stones' density, diameter, wave-current relative direction and protection's thickness. This need had already been identified in Reference [4] as a shortcoming that prevented the acquisition of generalised conclusions regarding the damage behaviour of dynamic protections (see also the discussion of Section 2.4). This can also be extended to the case of wide-graded scour protections, whose reported number of studies is also considerably reduced. An extensive review on scale and model effects can also be seen in References [3,30].

The limited range of testing conditions is also applicable to the water depths analysed in each study. The water depth to monopile diameter ratio plays an important role in scour phenomena [30]. The analysis performed in Reference [36] presented cases outside the original testing conditions of Reference [23], for which the damage number formula, under waves following currents, tended to overestimate the protection's damage in the deep-water conditions ($d/D_p = 5$), whereas underestimations were noticed for shallow water conditions ($d/D_p = 2.4$). For intermedium water depths, with $d/D_p = 3.6$, the predictions matched the measured damage without significant deviations. Albeit the reduced number of tests analysed, Reference [36] highlighted that future studies need to enlarge the available data sets to new testing conditions.

The studies presented in Table 1 also show an evident lack of testing considering structures with complex geometries, and as mentioned before, non-collinear wave-current's direction. Recently, Reference [48] tested an unprotected jacket structure under orthogonal waves and currents and similarly to Reference [44], the work enabled a better understanding of the differences between the cases of aligned and non-aligned waves and currents. It was seen that scour patterns were dependent on the velocity ratio ($U_{cw} = U_c/(U_c + U_m)$), with the sediments' transport ripples being more aligned with the currents for increasing values of such ratio. This highlights the need to look into both complex hydrodynamic conditions and geometries as their effect on scour phenomena is evident, which, in turn, means that scour protections must be adjusted for such cases, since their damage and sand bed exposure may occur in different locations than the ones identified in the studies compiled in Table 1. Many other aspects could still be referred to as challenges to be tackled with respect to the improvement of physical modelling of scour protections and their optimised configurations. The ones addressed in this section are viewed as some of the most important considering the common knowledge gaps of the latest studies conducted and the connection with the remaining challenges addressed in this work, particularly, in Sections 2, 8 and 9. For further details on this complex topic, the reading of References [3,4] is recommended.

7. Numerical Modelling Research

While most of the works performed on scour protections consist of physical model studies, the literature shows a clear lack of research based on numerical models of scour protections in the marine environment. The numerical modelling of scour phenomena is, nowadays, widely spread across the scientific and professional community, with solid results which provide additional insights on physical-data, e.g., Reference [49] extensively reviews this topic.

When it comes to the numerical modelling of scour protections for the marine environment, there are important aspects that contribute to the complexity of the modelling activities, thus, contributing to the reduced number of works presented.

A key aspect of modelling the failure of scour protections lies in the added difficulty of modelling each stone unit belonging to the top layer of the protection. To define the failure of a scour protection as in References [23,25,26], one needs to look to a rather small domain, about of a square of four missing stones, with a median size D_{n50}. Establishing models that can deal with such small domains is both expensive and time consuming. In addition, for scour protections with two layers, there will be the need to model the filter layer and its interaction with the rubble mound material, not to mention the need to account for seabed mobility. If one moves to even more complex configurations, as in layered or mixed soils, along with wide-graded protections, the full interaction between the finer fractions of the soil and the larger ones provides further difficulties in the implementation of numerical models. Often the seabed is faced as a wall boundary condition, which does not allow for the analysis of important effects, such as edge scour, that can be more easily quantified in physical models. The complex soil-structure-fluid interaction contributes to the challenging task of numerically modelling scour protections at offshore foundations, while in other marine structures, e.g., breakwaters or groins, the acquired knowledge is by far more mature.

Still, the numerical models provide a very useful alternative to assess governing scour variables, as the pore pressure, the shear stresses, and the flow velocity within the scour protection. Often these variables are hard to be properly measured in physical models, as they imply the use of submerged load cells and other intrusive equipment, which can interfere with the physics of scour depths and sediment dynamics inside and in the protection's vicinity.

In Reference [50], a combined physical and numerical model is implemented to assess the flow, and bed shear stresses beneath scour protections. Albeit addressing currents only, this work provided a solid contribution in terms of the numerical modelling of scour protections, with a particular focus on testing the hypothesis of sinking failure caused by the motion of sediments in the protection, due to a strong enough horseshoe vortex. The numerical model was mounted on Flow 3D, a Computational Fluid Dynamics (CFD) code solving the fully 3D transient Navier–Stokes equations, which uses the volume-finite-difference method in a fixed Eulerian grid. In this research, the obstacles inside the flow domain are modelled through a method similar to the immersed boundary method (IBM)—which, according to the authors, enabled the easy setup of complex structures and multiple discrete elements. Reference [50] also mentions that a mesh resolving all the stones geometries could be used, however sounding an ideal approach, it becomes rather impractical when dealing with complex, layered systems as scour protections.

The difficulties and time consumption associated with scour protection's modelling is well expressed in Reference [50]. In the simulation domain, Reference [50] placed layers of spheres with similar size characteristics to the stones used in the physical setup, concluding that using spherical elements provides reasonable and economic approximations in comparison to the modelling of the real geometry of the individual stones. Still using spheres, in order of hundreds at least, still requires a considerable computation effort. Thus, the authors experimented with a volume average approach where the macroscopic effect of the porous media is integrated into the governing Navier–Stokes equations as an extra forcing term. The porous media approach implied that the bulk of the scour protection layers were modelled as a porous media with their own porosity and hydraulic conductivity. From the numerical point of view, this research analysed three setups: (i) Spheres arranged in regular patterns; (ii) porous media; and (iii) a hybrid approach that combines the porous media with spheres placed in the regions where the precise calculations of velocities were required. It is concluded that option (iii) gives a good compromise between the accuracy of setup (i) and the quickness from setup (ii). An interesting advantage of the hybrid approach with spheres and porous media is the possibility of addressing relatively thick scour protections in a simpler but reasonably accurate manner. This is shown in Reference [13] for a scour protection with four layers, and comes in handy if one is interested in the numerical analysis of the armour layer thickness effect of dynamic and wide-graded scour protections, e.g., in a similar physical model as the one adopted in Reference [34]. The use of spheres in intermediate layers of the total thickness of the protection might be important, for example, to analyse the effect of the secondary horseshoe vortex described in Reference [51], which is stated to appear only for relatively thick protections.

The results derived from Reference [50] showed that hybrid models (porous media combined sphere elements) were found suitable to determine the bed shear stresses underneath the scour protection, the same occurs for the porous media approach, which unlike the previous setup, may require model calibration for porosity and hydraulic conductivity.

The former research has not addressed the combined effect of waves and currents, which is indeed a key knowledge gap when looking at the numerical modelling of protections to be placed at sea. In a similar manner to References [50,52], modelled scour protections under currents effects, looking for a further expansion to waves action, are yet to be implemented in the literature. In this case, a porous media approach was adopted in an OpenFOAM framework. Moreover, in this case, the numerical model was mainly used to assess the shear stresses within the protection and the sinking failure mode. The porous media approach is implemented with a hexahedral mesh—which, according to Reference [52], provided high-level accuracy to the numerical results and smaller numerical dissipation in the free surface region than a tetrahedral grid. The applied grid had different levels of refinement, with the centre of the scour protection corresponding to the zone with the most detailed discretisation. Reference [52] highlighted the need to address the impacts of the mesh size in the results' accuracy. An aspect that was not analysed in detail in Reference [50] as well.

The simulations of Reference [52] allowed for identifying the streamlines' tendency to penetrate the scour protection on the upstream side of the pile and to a fully turbulent behaviour of the flow at the wake side of the monopile. In Reference [50], a scour protection with four layers was also used, and the simulations were compared with Reference [52]. The numerical velocity results showed a good agreement with Reference [50]'s numerical results for the upper part of the protection (roughly top half of the thickness 8 cm to 16 cm above the seabed), whereas deviations occurred for the bottom half (0 cm to 8 cm above the seabed). The numerically assessed velocities of Reference [52] also compared reasonably with the physical measurements provided in Reference [50].

The application of porous media approaches and the knowledge of flow's behaviour in the interstitial voids in other coastal structures is in a more mature state, e.g., References [53,54], a literature gap is perceived when it comes to the application of such knowledge on scour protections. Thus, in the near to mid-term future, it is expected that the numerical modelling of scour protections benefits from the works and synergies already developed for other maritime structures. For example, in Reference [52], the formulation proposed in Reference [55] for the inclusion of the extended Darcy–Forchheimer equation in the Navier Stokes equations is followed.

Physical modelling is still considered by the industry's stakeholders as the most accurate way to analyse the behaviour of a scour protection, thus numerical models are yet to be improved before they reach a high level of maturity. In addition, this is augmented by the considerable portion that a scour protection represents in the overall costs of the foundation. However, combining physical and numerical modelling activities in scour research is of great importance, given the fact that physical models are often expensive and time-consuming.

Future research based on numerical modelling should also look to the novel methodologies applied in the characterisation of damage, e.g., Reference [16], whose refined characterisation of damage may help to define the numerical setup for optimised protections, namely, concerning the definition of the regions of the mesh that may require a higher level of discretisation.

Once the establishment of numerical models for scour protections' behaviour reaches a more developed stage, new opportunities arise from their application to foundations with complex geometries and other similarly complex problems that remain to deeply studied and understood (see Sections 9 and 10).

Another rather recent field of research on the numerical modelling of the protection's effect on the soil stiffness around the foundation. It is known that scour has a crucial influence on the momentum bearing capacity of an offshore structure and its natural vibration, thus contributing to fatigue and eventual resonance collapse, e.g., References [56–58]. Scour effects on the vibration of very slender structures, such as offshore wind turbines, or bottom-fixed foundations with movable parts of a considerable size, such as WECs or tidal turbines, gain particular importance, since many of these structures are designed to have their natural frequency within restricted bounds.

Given the importance of scour for design purposes and the operational lifecycle of offshore structures, a lot of research has been made on this topic. However, the numerical modelling of protected structures is by far less studied. One may ask, if scour protections avoid excessive scour depths, why is it also important to study protected structures? Firstly, the exposure of the sand bed near the foundation might be related to the instability of the rubble mound material that may be influenced by the actual motion of the foundation, e.g., as it could be the case of the Arklow Bank offshore wind farm reported in Reference [32]. Currently, the actual effect of the structural vibration on the scour protection's performance is yet to be clearly demonstrated. Secondly, the presence of a scour protection, particularly the very wide and thick ones, may represent an increase in the soil's stiffness at the interface between the soil and the unburied part of the foundation. This can also impact the structural behaviour of the foundation, with the impacts being different for static scour protections with larger stone sizes than in dynamic or wide graded scour protections, unless much larger thicknesses are used in the latter. Recently, the works of References [59–61] shed light on the structure-protection interaction, scour effects were also analysed.

The majority of the works focus on scour effects by artificially simulating the scour holes and removing layers of soil around the structure, e.g., Reference [62]. However, Reference [60] provides a comprehensive physical model at a considerably large geometric scale, 1:20, which allowed for a realistic simulation of local and global scour around monopiles, which is then used as input to perform the numerical modelling of the monopile-tower system.

Reference [60] also addresses the use of three different scour protections, pre-installed rock armour, remedial rock fill and remedial tyre-filled nets. The research showed the tendency, in some cases, for the increase of the natural frequency after the rock fill material had been placed. As discussed in other physical models, e.g., Reference [34], the protection's efficiency is much dependent on its thickness. Reference [60] noted that for thin protections with a limited extent, the consequent global scour produced substantial further reductions in the observed natural frequency. Tyred-filled nets and pre-installed rock armour scour protection were observed to also produce small increases in the foundation stiffness, sometimes neglectable in the case of tyred-filled nets. Additionally, for all systems, sand accretion at the protection was able to provide a useful enhancement of performance in terms of the systems' dynamics, and was also associated with a potential stiffness increase. However, the authors note that it is unclear to what extent the sand accretion observed could also occur in field situations. Moreover, the sand accumulation on the protection's matrix and the further enhancement of the stiffness contribution is diminished if extreme global scour leads to the instability of the protection. The numerical work presented in Reference [59] used a one-dimensional (1D) finite element model developed for the analysis of natural frequencies for monopile-supported turbines with scour and scour protection. The numerical modelling produced consistent results with data from the flume experiments and with the case study of Rigg Offshore Wind Farm, proving that scour protections do influence the soil stiffness and that the choice on the type of scour protection needs to account for such effects.

The numerical modelling of the structural behaviour of protected foundations is yet to be widely extended to other complex structures and to optimised protections in offshore monopiles. Additionally, the numerical modelling of the protection itself has registered a very small number of studies, as seen in References [50,52], which do not yet account for waves and currents combined. Therefore, the development of numerical studies for scour protected offshore structures remains a key challenge to improve the knowledge of the topic and walk towards cheaper and more reliable foundations.

8. Field Monitoring of Scour Protections

This section addresses the contents of some of the most recent and relevant monitoring and field data studies; however, for an extensive review on monitoring techniques, Reference [63] is recommended. Once a scour protection is in place, or even if it has not been applied, it is common to monitor the scour at the foundation. While field studies on scour depths at offshore foundations are extensively reported, e.g., References [32,64], in scour protections, the available information is much scarcer. Practical cases of scour protections are commonly reported in dispersed isolated cases, rather than systematically reviewed and discussed, e.g., References [65–67]. The compilation of different cases is rare and remains a key knowledge gap in the literature, with Reference [32] likely being one of the most remarkable contributions, given the number of cases analysed, with interesting monitoring time-windows for different offshore wind farms. Table 2 provides examples of recent monitoring and field data studies concerning scour protected offshore wind foundations and brief observations on the added value of each study.

Table 2. Examples of recent case studies reported with monitoring and field data concerning scour protected offshore wind foundations.

Reference	Reported Cases	Observations
[8]	North Hoyle Egmond ann Zee (NLD) Thornton Bank (Be) Horns Rev (Den) Scroby Sands (UK) Arklow Bank (UK)	Reference [8] compiles a set of field and monitored data from References [32,68], which are then coupled with details on the characteristics of each scour protection. This research includes the common cases of monopiles, but also the gravity-based foundations (GBF) type of foundation.
[32]	Horns Rev 1 (Den) Scroby Sands (UK) Arklow Bank (UK)	Reference [32] provides a very broad review of field data, coupled with scour depths monitoring at several protected and unprotected offshore wind foundations. An extensive analysis of scour development is given over the time span after installing the foundation, which includes the time-windows between this installation and the protection's placement.
[60]	Robin Rigg (UK)	Reference [60] couples the field data analysis concerning the scour phenomena, and the scour protection damage with the natural frequency of the monopile foundations. Although the effects of scour in the foundation's frequency are reported in the literature using numerical and physical model studies, the cases reporting field data are very scarce in this matter.

Table 2. *Cont.*

Reference	Reported Cases	Observations
[65]	Thornton Bank (Be)	Reference [65] provides detailed monitoring of the first C-Power Offshore Wind Farm, which has the particularity of consisting of six GBF foundations.
[67]	Egmond ann Zee (NLD)	Both References [67,68] address one of the most widely reported cases in the literature. The interest of these studies lies mostly in a considerable amount of time covered by the monitoring data. With surveys starting around 2006, the analysis goes up to surveys from 2013.
[68]		

Monitoring scour is crucial to understand if scour is reaching an alarming level for operation and structural safety. Moreover, if a protection was applied, monitoring activities will identify the failure and need for further refilling operations. Notwithstanding the confidential policies, a reduced number of monitoring campaigns has been reported. In Reference [68] (see also Reference [42]), monitoring results at Egmond ann Zee's protection showed that edge scour has occurred at some of the foundations. Edge scour contributed to decreasing the radial extent of the protections during "normal" weather conditions; thus, an increase of damage for storm events was expected.

The review of monitoring results presented in Reference [32] includes the analysis of the scour protections placed at Horns Rev 1, Scroby Sands and Arklow Bank. For Horns Rev 1, Reference [32] found that some loss of filter material had occurred, as well as the lowering/sinking of the armour layer. The sinking depth reached $0.35D_p$, i.e., close to 1.5 m [32]. In Scroby Sands, it is reported that the protection had clearly contributed to avoid the increase of scour depths. However, it was noted that secondary scour occurred in the seabed around the rock dump. Nevertheless, no failure occurrence, due to the flow slide mechanism, was reported. Regarding Arklow Bank, Reference [32] shows that diver surveys indicated an exposure of sand or gravel at the protection, thus meaning that voids in the armour layer were existent. Even though the protection was supposed to be statically stable, the absence of marine fouling on the wall of the monopile indicated that the bed level was likely to have fallen, or it was a sign of sediment mobility with gravel abrasion on the monopile.

Following the data presented in References [32,67,68], provided data for Egmond aan Zee between 2006 and 2013, at the latest survey taken, it was noted that the scour protection still met design requirements. However, it is also noted that a gradual degradation of the protection ever year was accounted for in the design, thus meaning that damage at the protection was expected to occur. Differences in the armour layer thickness between radial sectors, due to the materialising falling apron effect, which corroborates the importance of the constructive methodologies in the final reliability of the protection. In this case, edge scour was also noted to increase to a maximum of roughly about $0.6D_p$, at least up to 2500 days after installation (approx. 6 years and 9 months).

More recently, Reference [60] addressed the Robin Rigg offshore wind farm (UK), showing that even after an installation of a scour protection, scour occurrence was still noticed, although already being expected according to the dynamic stability as defined in Reference [26]. The data presented by Reference [60] poses a very interesting case, since the monitoring data is also combined with the natural frequency assessment of the monopile foundation, for the unprotected and the protected case (with the latter being a quite rare case reported in the literature—see also Section 7—with potential effects on the soil stiffness at the base of the monopile, due to the protection's presence). Moreover, this case addresses site conditions, which report to sandy layers of soils combined with layers of clay. Albeit the scour studies under sandy layered and mixed soils reported in Reference [69], there is a lack of knowledge of the behaviour of scour and scour protections in cohesive and non-cohesive layers of soils.

A final note should also be given on the importance of the field installation technique used to place the scour protection. Typically, rubble-mound protections are placed with fall-pipe vessels. However, the uncertainty in the stones' placement may contribute to a not so uniform protection thickness, which in turn can lead to regions of the armour layer which are more prone to failure than others. This aspect is not yet discussed in the literature and, particularly, to the authors knowledge, no physical modelling studies have been addressing the influence of the installation technique or other building details, e.g., the cables laying of the J-tubes, in the damage occurrence at the protection. For further details on the foundation's installation techniques and different scour protection systems, the reading of References [70] or [71] are suggested.

As mentioned, access to real scour data is often difficult to obtain, not only due to the costs of the monitoring campaigns, but also due to the confidential policies and non-disclosure agreements. Therefore, if the failure of a scour protection occurs, the event often remains unknown to the general public. Nevertheless, as demonstrated from the previous monitoring campaigns either using the exposure of the sand bed, by sinking or due to edge scour, protections can indeed fail. The scarce field data available highlights the uncertainty related to state-of-the-art design and the importance of further investment in open-source field data that contributes to the improvement of optimised design and knowledge on full-scale behaviour of protections.

9. Scour at Complex Structures

Aiming at the competitiveness of Marine Renewable Energy (MRE) investments, the industry is looking for the potential use of hybrid structures, which accommodate more than one harvesting technology, e.g., offshore wind and WECs. Hybrid structures imply the use of foundations with complex geometry, such as monopiles coupled with energy converters, jackets, tripods and others. However, in these foundations, scour remains a potential cause of instability. Scour protections tend to avoid further fatigue and differential settlements related problems in the foundation and upper-structure, which in the presence of movable parts, such as a WEC or similar, may be enhanced, due to the cyclic motion of the converter. On the other side, the dissipation of the wave energy or the disturbance of the marine flow, when reaching a WEC or a tidal turbine, may reduce the orbital velocity, and thus, have a positive effect on reducing the shear stresses acting on top of the protection placed at the foundation. In addition to hybrid structures, the reconversion of former oil and gas platforms to exploit marine renewables, e.g., Reference [72] is also a market motivator to develop novel studies on scour protections for complex foundations.

Currently, and as discussed previously, most of the past research has addressed monopile foundations only, and in practical cases, the very same methodologies for scour protection design are applied to such foundations. Although the design methodologies should be validated with physical and numerical modelling approaches, the resulting design is often over-conservative, due to differences caused by the foundation's shape in the overall development of local and global scour, as clearly identified in Reference [73].

9.1. Jacket Foundations

One of the most used offshore foundations is the Jacket structure, particularly applied in intermediate water depths, typically above the ones used in monopiles (above 30 m). In the literature, not many scour studies have been performed for the jacket type foundations under currents and waves. Reference [74] studied scour depths for jacket types of the Thornton bank and found that the scour depth (S/D) had an average of 0.65 and a maximum of 1.2, only 2.5 months after pre-pilling. Six months after the installation S/D was equal to 1.35 [74]. A comparison between estimated scour, using existing formulas for local and global scour for monopiles, and measured scour depths revealed significant differences in Reference [73], which highlighted the importance of further investigations regarding this topic, noting that the damage spatial distribution and magnitude in complex geometries differs from monopiles, which in turn may affect the damage behaviour of static, dynamic and wide-graded scour protections.

In jacket foundations, the additional braces near the seabed cause the flow to contract, leading to the increase of flow velocity and bed shear stress at the bottom. Moreover, vortices on the lee side of the structure braces are generated, thus increasing the erosive potential. Other structure characteristics, such as the distance, angle and diameter of the braces, the blockage effect and the ratio of the extent of the structure to the diameter of the main piles, influence the scour development [73]. Therefore, the layout variables of the protection, e.g., the armour thickness, the horizontal extent and perimeter shape, may differ from the common values reported in the literature, namely, the ones in Table 2.

There are little to no studies reported for scour protected jackets. This might be caused by the fact that often in practical studies, the need for a scour protection in a jacket structure is assessed to be less relevant than in a monopile, e.g., as reported by Reference [75] for the Vineyard Wind Project. However, as seen in Reference [74], scour at jacket foundations can indeed reach considerable values, which may require the same use of rip-rap protection as a monopile would.

Recently, Reference [76] performed a physical model study on a 1:30 geometric scale of a protected three-legged jacket foundation with both front mats and rip-rap protection around each jacket pile. The case study concerns the East Anglia One offshore wind farm currently under construction by ScottishPower. In this case, the rip-rap protection of each pile included high-density rocks and a circular shaped extent. The experimental tests included waves only and waves combined with currents for reference values associated with 1 to 50 years return periods. Moreover, the study analysed different storm sequences with increasing, decreasing and random sequences of severity in the hydrodynamic conditions. In this limited set of tests, the descending sequence was the one leading to larger erosion. It was concluded that if the higher sea state appears at the beginning of the foundation life cycle, the cumulative damage is worse. It was also concluded that the damage monitoring needed to be adjusted depending on the applied scour countermeasure, since the front mats interact with the hydrodynamics in a different manner than the rip-rap protections. As in many other studies published in the literature related to existing or planned offshore wind farms, due to confidential policies, this study is also very limited on the reported values for the magnitude of damage on the protection, it still showed that the preventive measures were important to reduce scour phenomena in this case with complex geometry.

In Reference [77] a study is introduced concerning the testing of a scour protection for a four-legged structure concerning the two Offshore High Voltage Stations of Hollandse Kust Zuid (HZK) Offshore Wind Farm, HZK Alpha and Beta. In this study, different configurations were considered, with the main difference between them being the distribution of the rock material, as seen in Figure 4. Configuration c was found to be the most unfavourable for the armour layer stability. The results presented were similar to the ones provided by Reference [78] for the Borssele Wind Farm stations, Borssele Alpha and Beta. In both the Borsselle and the HZK cases, it was found that the proposed concepts for scour protection registered some occasional mobility of the rubble mound material, while still maintaining their efficiency in reducing the scour depths at the foundation. Moreover, it was also noted that for the two layers system, the filter played an important role in the protections' performance. These observations and the reproduction of similar studies may represent an opportunity to extend the concepts of dynamic and wide-graded scour protections to complex foundations.

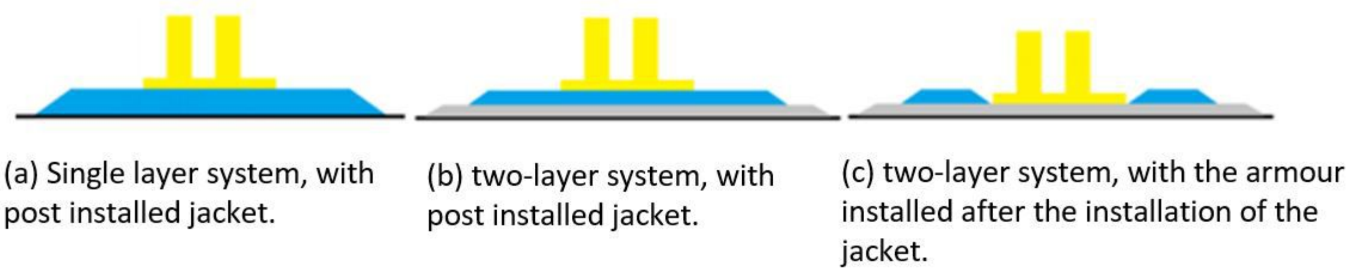

Figure 4. Configurations studied in physical modelling of Reference [77] for 4-legged structure at Hollandse Kust Zuid (HZK) Offshore wind farm.

In complex foundations, such as jackets, tripods or gravity-based ones, the occurrence of global scour is also of relevant importance to the overall scour depths registered, which are a result of the global and local scour phenomena. In these cases, the use of a scour protection levelled with the seabed, as in Reference [26], may come in handy as it helps to reduce the edge scour, which results from the sudden difference in the roughness of the seabed to the protection's rubble mound material. For complex foundations with large footprints, the edge scour will occur in the area where the global scour tends to appear. Reference [79] adopted the levelled configuration and performed physical model tests with a scale of 1:36 for a jacket type foundation. The levelled scour protection as compared to a soft scour countermeasure consisting of a cage net aquaculture facility. The comparison investigates the potential to integrate coastal aquaculture facilities with offshore wind farm foundations, thus enhancing synergies between both sectors. The model included current, induced scour and combined waves and current, and it showed that both countermeasures could result in a considerable reduction of scour depths at the foundation. Reference [79] showed that there is an interesting perspective on the integration of aquaculture cages in offshore wind foundations, since they may yield a positive impact in reducing the effects of scour.

9.2. Gravity-Based Foundations

A very interesting example of a dynamic scour protection applied to a complex geometry foundation is the one given for the offshore power converter platform Dolwin Beta given by Reference [80]. This work provides a rectangular-shaped foundation with two main supporting beams and three transversal horizontal braces close to the sand bed. A rectangular scour protection was tested with five different layouts and considering its pre-installation and lowering of the actual foundation. A rather novel approach was applied by using a non-uniform thickness, i.e., more material was placed at critical regions of the protection, and less volume of material was applied in the sheltered zones, namely, in the region directly placed at the centre of the structure's footprint. The work achieved an optimised layout where dynamic stability was evident for the range of tested conditions, albeit only 2000 waves were used. Reference [80] also noted that failure would occur if the minimum thickness of two stone layers was respected. The research given by Reference [80] represents one of the first, if not the first, incursions on the extension of the dynamic stability concept to complex foundations. Nevertheless, no damage number or stability parameter analysis was applied, thus not being possible to compare the damage magnitude with the former works of References [23,26].

Other cases of complex geometry are often related to the application of scour protection to gravity-based foundations (GBFs), e.g., as in Thornton Bank offshore wind farm [81]. An interesting review on scour and scour protections around offshore GBFs is provided in Reference [82], which provides a guideline for scour management plans to intergrate the life cycle management of the GBF. The research outlined in Reference [82] highlights that in GBF foundations there are critical places more prone to scour occurrence, i.e., the corners for non-cylindrical foundations, the leading skirt edge and around the templates and pipelines outside the foundations. Such observation implies that scour protections, including dynamically stable ones, require a proper tunning of the thickness to account for critical regions. Eventually, a non-uniform thickness could be applied as in Reference [80]. Many of the studies performed on such optimisations and layout adjustments are often related to commercial projects, which makes the amount of data available on this topic very scarce, thus it is shown that the literature requires further benchmark data on GBFs' scour protections, with a particular emphasis on optimised ones. The need for further improvements on this topic is proven by the Christchurch Bay tower case study, whose scour protection was installed with two common solutions, a sand filter plus coarse gravel and sand-bags and grout. In this case, according to Reference [81], neither the methods were proven to be successful as long-lasting remediation.

Another important aspect lies in the differences between the time-scale for scour around complex geometries and monopiles. Since scour development occurs at different rates depending on the geometry of the foundation, this implies that the damage in the armour layer of the scour protection may also stabilise for different durations than the ones previously mentioned. While Reference [34] indicated that the scour rate tends to significantly reduce after the first 1000 to 3000 waves, the duration for such reduction to occur in GBFs, jackets or any other complex foundation, is yet to be fully known.

A broad and recent study on scour protections for GBFs is also given in Reference [83]. Among several findings that enabled a better understanding of scour and scour protections for these foundations, Reference [83] proved through scour protection tests that under wave-dominated conditions the amplification factor for GBFs did not exceed the value of 2. This is remarkably important as it provides a clear reference value for novel design approaches based on the threshold of motion. In addition, it was revealed that the long-term persistence of flow conditions that just lead to incipient motion of the scour protection material could eventually lead to complete failure of the scour protection. While Reference [83] provides an updated Shields type diagram, which enables the appropriate selection of the stone size for a rip-rap scour protection system, eventually, with a potential cost reduction, the methodologies related to the damage number and dynamic stability are yet to be developed for GBFs. Nevertheless, the latest research on scour protections shows improvements in the applications for gravity-based foundations, which are still not as developed as in monopile foundations.

9.3. Tripod Foundations

The literature shows that research on scour protections, optimised or not, applied to tripod foundations is even scarcer than in GBFs, jackets and similar offshore foundations. Again, this is also the case of a foundation, whose scour process considerably differs from the monopile case.

Reference [84] provided a uniquely combined monitoring, numerical and physical modelling study on scour occurring in tripod foundations, where similarly to jackets, it was noted that scour affected the piles, but also an extent of the foundation's vicinity, thus implying that scour protections horizontal extent also needs to account for such area, which includes the footprint at the bottom of the main column of the foundation, as also noted in Reference [85] for the case study of Alpha Ventus offshore wind farm (GER). Still, on the nature of scour phenomena, Reference [84] concluded that local and global scour development were considerably dependable on the wave direction. The local scour depths at the pile(s) behind the structure proved to be higher compared to the front pile(s) [84]. The formed ripples proved to influence the scour depths in different areas of the footprint. The variation of scour magnitude in different places of the tripod also highlights the potential of approaches, such as the one formerly discussed in Reference [80], which uses a non-uniform thickness to account for the locations more prone to damage.

Another interesting aspect is that Reference [86] observed that local scour depths for a 1:12 geometrically scaled model were 50% higher than in the ones verified at the 1:40 model tests. Albeit these tests relate to scour phenomena and not the protection's behaviour, this highlights the need to check the matters related to the scale effects and the threshold of motion noticed in Reference [13], as there is an apparent contradiction between findings (see also Section 6). A clarification of this aspect is of utmost importance to understand if current design methodologies for scour protections are providing conservative values or not, as previously discussed. In spite of the lack of studies regarding the scour protections' damage behaviour and design for tripod foundations, the literature on scour research shows that the spatial variation of damage and the different hydrodynamics from the monopile cases are common problems that tripods have to other complex foundations. Therefore, the developments of scour protection design adapted for complex geometries may also benefit this type of foundation, commonly applied in offshore wind farms as in Trianel Windpark Borkum (GER), Global Tech I (GER) or the Bard Offshore 1 (GER).

10. Scour Protections for Wave and Tidal Energy Converters

Scour Protections for hybrid foundations, such as the ones that associate offshore wind energy with wave or tidal energy converters, are still an unexplored subject in the literature. In part, this is due to the primary focus of the literature on the converters' efficiency or the structural and hydrodynamic performance of the converters or their foundations, whereas the scour phenomena and its countermeasures tend to be a matter of study in downstream stages closer to commercialisation, i.e., when the converters are at higher technology readiness levels.

Nevertheless, the study of scour protections for wave and tidal energy converters represents an important field of future research, since the full development of these marine renewable energy sources requires a proper implementation in field conditions, and like in offshore wind, scour may be a hazard to the equipment itself, the foundation, and in turn, a factor of cost increase in the overall project.

An interesting aspect yet to be clarified is the influence that cyclic moving bodies as wave or tidal energy converters may have on the performance of a scour protection. On the one hand, it is known that WECs absorb the wave field energy and alter the waves' characteristics and the orbital velocity at the foundation; on the other hand, converters with oblique or vertical motion may increase the down-pressure of the flow, eventually influencing the horseshoe and lee-wake vortices, which are primary mechanisms of scour under waves and currents combined. In addition, the complex geometry of the converter and foundation system plays an important role in the hydrodynamics, which affects the scour pattern as well.

10.1. Scour Protections and Wave Energy Converters

A key aspect concerning scour phenomena and protections relates to the added challenge of dealing with the fluid-soil-structure interaction in the presence of a moving converter, which may increase or change both the flow and the natural frequency of the structural system in a manner that is different from an offshore wind turbine.

In offshore wind turbines, scour countermeasures might differ in stone size, horizontal extent and thickness, but apart from such features, they correspond to a rather standard solution. However, WECs may vary in their working principles and degrees of freedom, as well as in the frequency and range of their oscillatory motion. This means that both the scour pattern and the corresponding countermeasures will show a particular behaviour, depending on the converters' functioning and layout. This implies that standard solutions (e.g., static, dynamic or wide-graded) need to be adjusted in particular to each harvesting technology.

An interesting example of the influence of the cyclic motion is given by the CECO wave energy converter. For details on the CECO converter, the reader is referred to Reference [86]. In certain configurations, for which CECO is mounted on a bottom-fixed foundation, a scour protection might be required. However, given the upwards and downwards inclined motion of the power take-off system (PTO), a cyclic increase and decrease of the flow velocities and pressure near the horseshoe vortex region might be expected, as well as changes in the uplifting forces acting on the rubble material (Figure 5).

On the other side, the diffraction occurring on the lee-wake side of the pile may also disturb the lee-wake vortices, which affects the scour behind the foundation. As can be seen in Figure 6, a simplified numerical model shows that wave heights are reduced on the lee-wake side of the system. Eventually, this could have a positive impact on the scour severity behind the foundation. Moreover, if the cyclic motion of the converter leads to excessive vibration of the monopile, then the rubble mound material at the interface between the protection and the pile may also get looser, eventually contributing to a similar sand bed exposure as the one described by Reference [32] for Arklow Bank Offshore Wind farm near the monopile's wall.

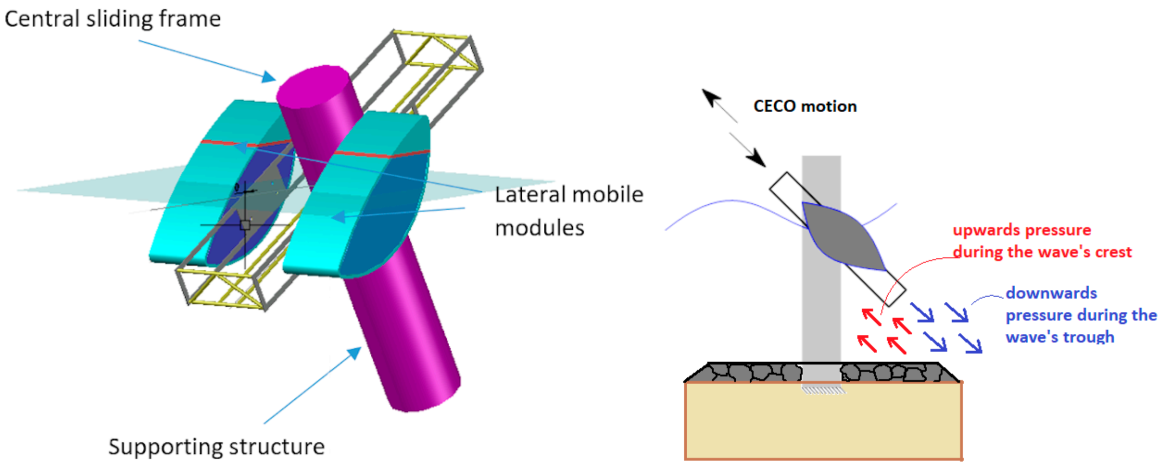

Figure 5. (**Left**): Scheme of CECO device on an oblique monopile support. (**Right**): Scheme of expected upwards and downwards pressure acting on the top layer of the protection.

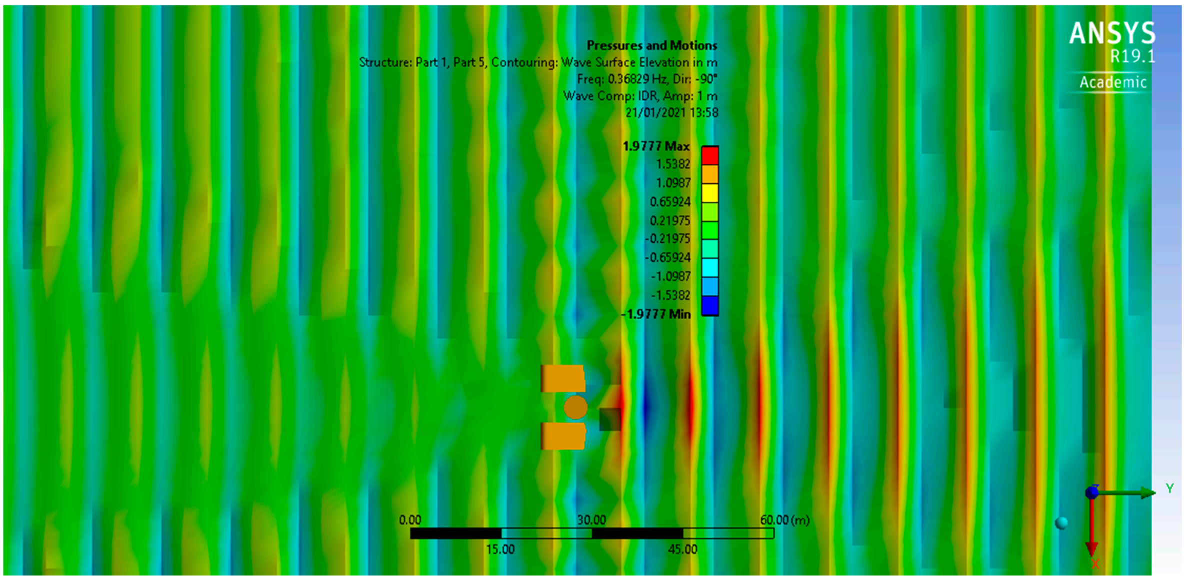

Figure 6. Example of CECO's disturbance of the lee-wake flow, with the incident wave height being reduced, due to wave absorption by the power take-off system (PTO) (waves from right to left).

In other cases, the WEC's working principle resembles already existing scour countermeasures. It is the case of the WaveRoller studied, for example, in Reference [87] and the countermeasure presented by Reference [88], which consists of a panel attached to a geotextile mattress placed on the seabed (as in Figure 7). In these cases, converter's working energy converter might have a positive impact in reducing scour at the nearby structure, which might be a jacket, a pipeline or a monopile of an offshore wind turbine. This will be, of course, dependent on the other characteristics, as the WEC size and motion frequency, among other factors. This aspect should be looked into, given its potential for expenditures reduction in a broad spectrum of marine renewable energy projects. In the case of the WaveRoller there might be no need for a specific scour protection measure, as the scour may not be as significant as in other concepts, since it presents a similar behaviour to the system of Reference [88].

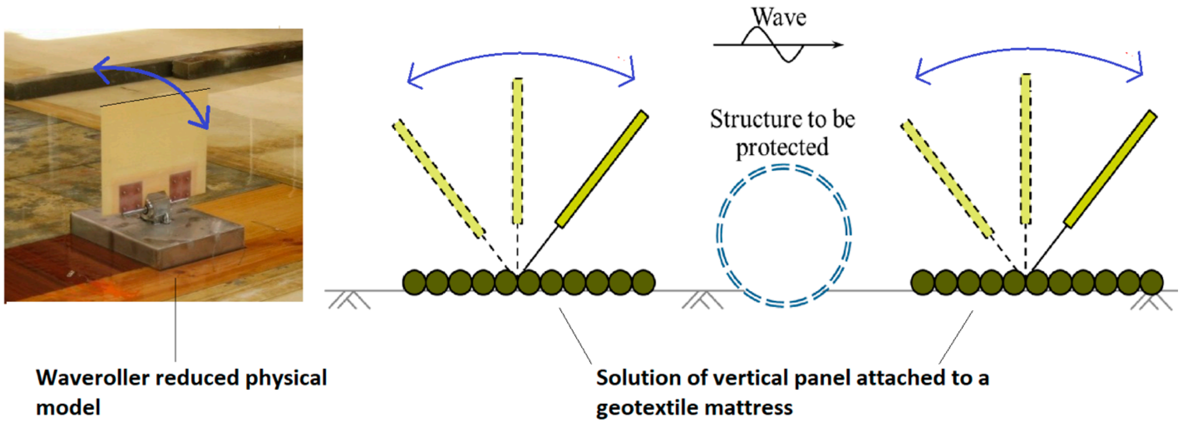

Figure 7. Scheme of the similar principle between the wave energy converter (WEC) WaveRoller from Reference [88] (**left**) and a vertical panel combined with geotextile mattresses from Reference [88] (**right**).

The inclusion of WECs in other maritime structures, such as breakwaters, groins or harbour structures, is also an important topic where the knowledge of the scour phenomena, and the need to protect the sections where the converter is embedded in these structures is scarce. In Reference [89], a broad review is presented on such converters. In Reference [89], it is seen that often vertical caisson breakwaters may require scour protections at the toe, due to wave reflection and considerable breaking and splashing of waves; the same is noted for other common types of breakwaters.

Often the works about WECs integration on breakwaters and similar coastal structures do not report any scour related findings. However, a very interesting case that includes scour analysis is presented in Reference [90]. This research addresses the integration of a hybrid WEC in the rubble-mound structure proposed for the extension of the North breakwater of the Port of Leixões (PT). Reference [90] gives a physical modelling study at a geometric scale of 1:50 of a combined overtopping and oscillating water column-based energy converter (Figure 8).

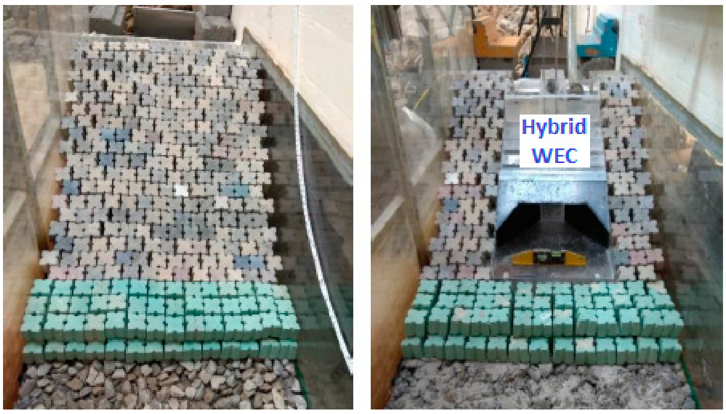

Figure 8. Photographic record of integrated hybrid WEC in a breakwater, 2D physical model without WEC on the **left** and with WEC on the **right**.

The stability of the breakwater is then analysed under a wide range of extreme sea states, and the scour phenomena at the toe is monitored in front of the breakwater. Albeit being only a 2D physical model, the results showed movements of the Antifer blocks on the bottom of the breakwater. However, no scour after 6000 waves was noted, as indicated in Figure 9, which shows side profiles of the central section of the breakwater and the WEC in place. Still, the research highlighted the importance of looking to potentially enhanced scour phenomena at altered cross-sections of these structures, due to the inclusion of WECs. In such cases, the optimisation of the rubble mound material placed at the toe, based on the wide-graded or dynamic stability concepts, requires further detailed study, since these structures are most commonly designed to have statically stable materials, namely, at the bottom. In addition, it is also important to address if the WECs presence may require the increase of both the thickness and extent of the rubble foundation near the toe berm.

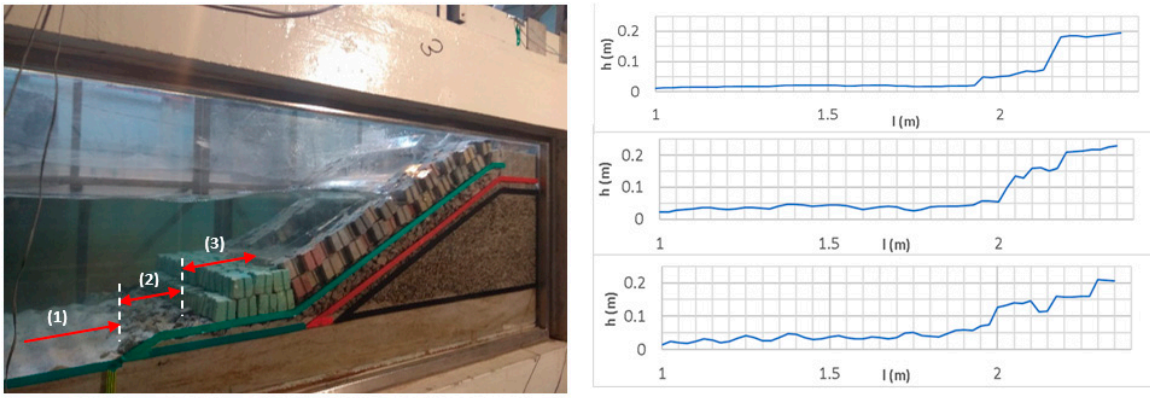

Figure 9. Sideview of the integrated WEC into the breakwater and central cross-section profiles.

In Reference [91], the 3D study of an oscillating water column converter was analysed, and research clearly indicated that the WEC functioning may have implications on the overall scour development, differential settlement and structural integrity of the device. Thus, the need for scour protections is recognised as a key component of the overall system. However, a proper assessment of the negative or positive effects that WECs and the associated absorption and dissipation of the wave energy have on the scour severity is yet to be fully understood and widely dependent on the characteristics of the device itself.

Reference [91] performed research for a model of an OWC WEC at King Island, Australia. Fifteen scour tests were performed with irregular waves for a typical OWC WEC. The device was subjected to different wave incident angles (90° and 70°), by rotating the device.

With normal incident waves, scour holes were formed a few minutes after the beginning of the test, at the four corners of the rectangular-shaped structure. A small scour hole was also formed at the front face of the structure. An equilibrium scour depth was reached within 10 to 30 min of the wave test; however, the extent of those same scour holes increased at a slower pace, reaching only the equilibrium stage 60 to 90 min into the wave test [91]. The results have shown good symmetry in the front corners, opposite to what occurs in the back corners, which were shown to be steeper than the front ones. This could be caused by the turbulence related to the lee-wake vortices, which assumes higher importance under wave-dominated conditions.

For oblique waves, well developed scour holes were noticed in the corners of the diagonal parallel to the flow, whereas the upstream corner developed a smaller scour hole—being the scour on the downstream corner almost negligible [91]. The changes in the scour pattern for different angles between the WEC and the waves' direction highlighted the fact that future scour countermeasures need to consider the complex geometry of the device in a similar manner to what it was reviewed for other foundations with complex geometry, such as jackets, tripods or GBFs.

Furthermore, Reference [91] also noted that the inflow and outflow of the WEC could contribute to an increase of the bottom shear stress and sediment transport in the vicinity of the structure; thus, meaning that scour protections for WECs need to account for such amplifications of the bed shear stress in design stages, to ensure their proper efficiency.

Despite the lack of studies concerning scour protections for WECs, the literature shows that scour countermeasures for these cases need to be properly tuned to account for the specific characteristics of the device and its particular interaction with the mobile seabed. Nevertheless, the literature shows that while some concepts may enhance scour effects, others may, in fact, contribute to the decrease in erosion at the system's foundation. Hence, the need for scour protection needs to be judged on a case-by-case basis.

For WECs, given the relatively high costs of wave energy, when compared with wind energy, for instance, the importance of optimised scour protections is even higher, since additional costs may pose further pressure on the competitiveness of the investment. This becomes particularly evident if maintenance and re-filling operations of the protection are expected to occur during the life cycle of the investment.

10.2. Scour Protections and Tidal and Marine Current Turbines

Similarly, to offshore wind turbines, a considerable share of the tidal energy and marine current turbines is founded using monopile foundations. However, the presence of the tidal current underwater turbines contributes to a considerably more complex flow pattern around the monopile and may also produce considerable scour, particularly in shallow water depths. A broad review on how to estimate scour around marine current turbines is given in Reference [92], which shows that scour at these systems is enhanced by the rotor and its wake effect.

Given the scour induced by the turbine-foundation system, scour protections may also be required to ensure structural stability and optimal service conditions. The potential need for scour protection in these cases is clearly recognised in Reference [93], which highlights the importance of understanding the scour mechanisms under the presence of the turbine to further proceed with the protection's efficient design and implementation.

Once again, state-of-the-art indicates that scour protections applied to tidal turbines remains as a knowledge gap, as no studies have been found. Moreover, the studies performed on the scour phenomena without protection are also limited in number [92]. Commonly, scour at these structures is mainly faced based on the experience accumulated in offshore wind projects. However, as mentioned, the hydrodynamics of the whole system may lead to different morphodynamics; thus, different scour patterns, which need to be accounted for when dealing with the definition of the countermeasures. Additionally, the natural frequency of the foundation is different from the ones in offshore wind turbines; this implies that for muddy and sandy beds with very fine materials, a detailed scour monitoring and management plan has to be considered, since the excessive vibration of the foundation may also induce the seabed liquefaction. Details on soil liquefaction are given in Reference [30].

One of the most important aspects to consider is that tidal energy and marine current turbines are often placed in locations with much higher flow velocities than the places where the offshore wind foundations are typically placed. According to Reference [94], these velocities are typically above 2.5 m/s. Note that Reference [30] provides case studies of offshore wind monopiles with scour depths of 1.47 times the pile diameter for marine peak currents, which are smaller, i.e., about 2 m/s.

A curious case, however, is given in Reference [95], which proposes a feasibility study of reducing scour around monopile offshore wind foundation using a tidal current turbine. According to this research, a tidal turbine is installed in an optimal position, and it may contribute to reducing scour at the monopile. If proven feasible in practical cases, this solution could be an interesting alternative to simultaneously produce energy and counteract the effects of scour, thus reducing the expenditures related to the scour protection. The numerical and physical modelling results showed the potential for scour reduction if the turbine is placed in front of the monopile, facing the oncoming flow. The operation of the rotor, which absorbs part of the tidal current energy and disturbs the water flow, enables the reduction of the strength of the vortices around the monopile.

The experimental results indicated that the maximum bed shear stress at the seabed was reduced by 8%, thus the scour depth was reduced significantly by 42%. A particular aspect that may hinder the generalisation of these findings is the fact that the effects of waves were not included in the analysis. For wave-dominated regimes, particularly in high KC numbers, the lee-wake vortices on the downstream side of the monopile may be the dominant scour mechanism. In Reference [95], while the turbine seems to be efficient in disturbing the strength of the horseshoe vortex at the front, this positive effect becomes less relevant if the lee-wake vortices are the ones causing the most severe scour. Perhaps due to this reason, the authors noticed that the scour reduction was highly dependent on the installation position.

Given the study of Reference [95], whether tidal and marine current turbines enhance or reduce scour effects, it is evident from the available literature that further research needs to be conducted to ensure that scour protections, namely, the rip-rap ones, account for the specificity for these converters. This specificity arises from the hydrodynamics around the foundation, which can be considerably different from the one studied in offshore wind applications. Hence, this topic of research remains a key opportunity to drop the costs associated with these harvesting technologies and their numerous tidal and wave related concepts, e.g., References [86,95–97] among others. This fact is aligned with the case for the WECs previously seen, thus synergies between both fields can contribute to a broader applicability of the results obtained in new research.

11. Conclusions

The paper critically reviewed and compiled the most recent knowledge gaps and findings related to unsolved aspects of scour protection applied to maritime foundations. Several questions that consist of upcoming scientific and practical challenges were raised, and the latest advances on these topics were analysed from a current perspective. This review shows that addressing these challenges will enable more efficient development and optimisation of scour protections, which in turn can contribute to lowering the levelised costs of energy in offshore wind and other marine renewable energies.

The following conclusions were derived from the present review:

1. Most of the existing knowledge on scour protections concerns the traditional static design, whereas optimisations as dynamic or wide-graded protections are yet to be developed to the same level of maturity;
2. The existing challenges on scour protection research for the marine environment are extended to a broad scope of activity, namely, in conceptual and design optimisation, including the aspects related to long-term damage evolution, damage characterisation and the combination of complex wave and currents directional regimes;
3. Albeit the field data arising from scour monitoring, there is still a lack of reported information from in situ studies. This is often a result of the sector's confidential policies;
4. Physical modelling research is by far more developed than the numerical one. Physical models on optimised scour protections registered significant advances in the last 10 to 12 years. However, inconsistencies in findings and the lack of large-scale models remain as challenges to be solved;
5. Numerical modelling studies are very scarce in the literature, with the main results being obtained using combined porous media and spherical elements modelling approach;
6. Numerical modelling studies tend to address the soil-structure and protection-structure interaction instead of the protection's behaviour itself. Relevant works have been produced recently on the natural frequency behaviour of protected and unprotected offshore foundations;
7. Scour protections for foundations with complex geometry are not commonly reported in the literature and, in practical applications, design and countermeasures implementations are made based on the existing knowledge for monopiles. However, the different hydrodynamics and scour patterns justify the development of research that can specifically address the challenges of complex foundation's shape;
8. Scour protections have a large range of application if wave, tidal and marine current energy devices are considered. While in some cases, the harvesting technology may contribute to reducing the scour severity, in others, there is a chance of enhanced

erosion at the foundation. Optimising scour protections also represents a contribution lowering the costs of these alternative energy sources, which are still less competitive than offshore wind.

Among the several topics analysed in this paper, numerical modelling studies concerning optimised scour protections and the analysis of scour phenomena and protection's behaviour, in wave and marine tidal currents energy converters, are considered by the authors as the fields with large potential for future developments.

Author Contributions: Authors that contributed in the conceptualization: J.C., T.F.-F., F.T.-P., P.R.-S., F.V.C.T.-P., G.G. and P.H.; methodology: J.C. and T.F.-F.; formal analysis and validation: J.C. and T.F.-F.; writing—original draft preparation: J.C., T.F.-F., F.T.-P., P.R.-S., F.V.C.T.-P., G.G. and P.H.; writing—review and editing: T.F.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the project POCI-01-0145-FEDER-032170 (ORACLE project), funded by the European Fund for Regional Development (FEDER), through the COMPETE2020, the Programa Operacional Competitividade e Internacionalização (POCI) and FCT/MCTES through national funds (PIDDAC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article. This is a review which collects literature existing data.

Acknowledgments: J. Chambel acknowledges T. Fazeres-Ferradosa (FEUP) for the support to his research studies, for the companionship and guidance through the years and for the enlightening discussions on all topics that involved scour and offshore engineering.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Unless stated otherwise in the text, the following symbols were used:

D_{cr}	Critical stone size
θ	Shields parameter
θ_{cr}	Critical Shields parameter
θ_{max}	Maximum Shields parameter
stab	Stability parameter
S_{3D}	Damage number
ρ_w	Water density
ρ_s	Density of rock material
τ_{cr}	Critical bed shear stress
τ	Bed shear stress
D^*	Dimensionless grain size as in Soulsby (1997)
D_i	Stone diameter for which i% is finer by mass, e.g., D_{10}, $D_{85.}$
a_i	Regression coefficients
b_i	Regression coefficients
U_c	Depth averaged current velocity
U_m	Orbital bottom velocity
w_s	Fall velocity
D_n	Nominal diameter, $0.84D_i$
g	Gravitational acceleration
$T_{m-1,0}$	Energy period
d	Water depth
N	Number of waves
s	Densities ratio
N_{charac}	Characteristic number of waves

H_s	Significant wave height
KC	Keulegen-Carpenter number
S_{3D}	Damage number
S_{3Dsub}	Damage number per sub-area
D_p	Pile diameter
V_e	Eroded volume
n	Integer number
U_{cw}	Velocity ratio
T_p	Wave peak period
α	Amplification factor
A	Area

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