



Considerations on the Design of Shellfish Reef Against Coastal Erosion

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Abstract. The Catterline Bay in Scotland (UK) is regularly subjected to storm surges during spring tide periods which had led to coastal erosion and landslides. As a response to the local population whose material properties and lives are at risk, we have investigated the potential of design and construction of Nature-Based Solutions (NBS) against the geo-hydro-climatic hazards posed by a changing climate. This paper assesses theoretically the wave attenuation capacity of an off-shore shellfish reef, as an NBS, which could be implemented in Catterline. Although less rigid than a traditional, ‘grey’ solution, this strategy plays on the depth reduction created by its organic structure to break the wave before it reaches the shore. Through numerical modelling using R Studio, we calculated the wave breaking probability (Q_b) and the distribution of the wave energy flux (P) from the sea to the shore. Then, we compared two possible scenarios: the current conditions without a shellfish reef and a scenario with a constructed shellfish reef at three different locations and with different dimensions. The modelled NBS showed high wave breaking probability for each wave height trend. Moreover, the reef was shown to be more effective when located furthest from the shore. For maximum wave breaking effectiveness, the reef was shown to require relatively short length when located the furthest from the shore. Finally, based on the design and construction requirements, we offer recommendations about the reefs dimensions, and the shellfish species to implement as well as its management throughout the design life.

Keywords: Shellfish reef · Nature based solutions · Eco-engineering · Sustainability · Wave attenuation

1 Introduction

A Nature-Based Solution (NBS) is defined as a solution to improve the resilience of a site to natural hazards and provide social, environmental, and economic benefits [1]. They aim at mitigating meteorological hazards, which frequency is increasing with climate change [2], by improving the environmental footprint and raising the populations’ awareness.

Shellfish reefs have been used as NBS in the past [3], as a solution for water depth reduction created by its organic structure in order to break the wave before it reaches the shore by creating a shallow zone. Therefore, as the major part of the wave energy

stays in the upper layers of the sea [4], the reef position in the water column defines its attenuation capacity. Consequently, the first shellfish must be situated at depth with low to medium wave strength: deep enough to affect the wave strength and shallow enough to avoid movement caused by the wave energy. The shellfish reef is built with time, in layers upon layers of decomposed shellfish. Younger generations of shellfish are growing over their elders which by the time decompose and constitute a bed of organic matter. It is this succession of the decomposition process that expands the reef, strengthens it over time, reduces the water depth over it and increases the friction distance the wave is passing on. The deposition rate differs among species as well as their consistency and resistance to the erosion.

A wave reaching the shellfish reef is usually characterised by its height (H), wavelength (L), period (T), and water depth (h). There are different waves depending on their size and sources, but only wind waves will be studied and discussed in this paper; these are generated by the wind, with a wavelength and strength that increase as the fetch (horizontal distance on which the wind blows) increases. The energy of a wave depends on the wavelength and the water depth and, consequently, three different depth zones can be differentiated [4]: deep-water ($h > L/2$) below which the wave energy is negligible; intermediate zone ($L/20 < h < L/2$); and shallow water zone ($h < L/20$). In the shallow water zone around a shellfish reef, the wave breaks, its velocity decreases and it loses the energy which is dissipated in the surrounding waters in the form of turbulences. Normally, the natural slope of the beach plays this role as the wave goes from the deep-water through to the shallow-water depth zone, but a reef would allow to anticipate this phenomenon by breaking the waves upstream, thus protecting the shore.

The aim of this study is to assess the theoretical wave attenuation capacity of a shellfish reef as an NBS, which would be implemented in Catterline, as well as to recommend optimal reef location, dimensions, shellfish species, and management strategy. The objectives of this study are to assess the wave breaking probability (Q_b) and the distribution of the wave energy flux (P) from the sea to the shore through literature study and numerical modelling in R Studio, as well as to compare the effects of the shellfish reef in relation to the reef location within the bay.

2 Methods

2.1 Case Study Site

The Catterline Bay (Fig. 1) had been subjected to storm surges during spring tide periods which had led to important coastal erosion and landslides. As a response, the local community, whose houses are close to the cliffs, is looking actively for protection against coastal erosion. As the waves break permanently on the shore, their action on the beach slope erodes continuously the shore. Originally, ‘grey’ techniques (e.g. concrete blocks placed upstream or embankments) were used to fix this problem, but the lack of maintenance combined with the detrimental effects of climate change (storm surges, coastal erosion) limited their efficiency.

2.2 Wave Dynamics

Based on [5], the effects of the shellfish reef on the wave force have been assessed numerically by comparing the evolution of the breaking probability (Q_b) of the wave and its energy flux (P) within the three depth zones for two scenarios. Scenario 1 was the existing situation without a reef in the bay. Scenario 2 included the reef in the bay, located at three different positions: at 50 m, 100 m, and 150 m from the bay neck (respectively noted as X50, X100, X150). Also, different lengths of the reef in Scenario 2 have been tested to statistically indicate the optimal dimensions. Numerically, the water depth (h) is a variable of the maximum wave height achievable (H_m) which features in the calculation of the breaking probability (Q_b , [5]), a ratio varying from 0, for no breaking event, to 1, for a wave breaking at a definite point of depth. Normally, the natural slope of the beach plays this role as the wave goes through the different depth zones. A reef allows to anticipate this phenomenon by breaking the waves upstream.

Wave datasets for Aberdeen (nearest available measuring point, 20 km north of Catterline Bay), and the bathymetry data for Catterline were retrieved from the British Oceanographic Data Centre and analysed to determine the relevant wave and seabed variables. For the wave height, the average, the first, and third quartiles of the significant wave height values on 3-hourly measurements over 3 months were collected, and for each, the total mean calculated to determine respectively the average, the low, and high trend. The same process was applied to the wave crest period to calculate its average only. The wavelength was determined from the annual average wind speed data in Catterline between 2013 and 2016 available from Windfinder, using the Thurman method [6]. The wave propagation through the different seabed depth zones was calculated using the method described in [4] to obtain wave velocity. In our study, the assumption is that the wave breaks in the shallow water zone – a process which induces a complete loss of the wave energy that dissipates in the surrounding waters a form of turbulence [4].

2.3 Reef Dynamics

The wave effects were considered along a 1 m wide, 200 m long corridor situated in the middle of the bay neck, pointing towards the shore (Fig. 1); the wave corridor. Based on the bathymetry data, the bay was 2 m deep at its neck ($x = 0$ m, deepest water), with the depth decreasing linearly to the shore ($x = 200$ m, shallowest depth) with a 1% slope. For the Scenario 2, the reef was first placed at a 100 m seawards from the bay neck and was 2 m wide. Its top surface reached the shallow water depth at the maximum tidal height, corresponding to the most threatening conditions for the shore. Based on the history of hydrometeorological risks on the site, it was assumed that the waves propagated from the open sea, following a straight line to the shore, with no interactions from the sides, and with no reflection or diffraction. The shellfish reef was considered as a straight rectangle positioned across the bay and following the natural curve of the bay (Fig. 1b). The percolation effects and the seabed rugosity were not considered, while a full dissipation of the wave energy through the surrounding water was assumed [4].



Fig. 1. Location of Catterline Bay, showing the assumed wave corridor and distances from the bay neck ($x = 0$) to the shore ($x = 200$ m). Figure lined up on North.

3 Results and Analysis

3.1 Wave Dynamics

The average significant wave height (H) of the site was calculated as 1.85 m (1.2 m at low trend, and 2.34 m at high). The study site had an average wind speed of 13.81 km h^{-1} with a resulting wavelength (L) of 7.32 m, which meant that the shallow-depth water zone started at depth $h = 0.37$ m ($x = 163.4$ m). The maximum wave height achievable over the reef ($H_m = 0.322$ m) gives a breaking probability curve for each reef position. In general, all scenarios have a breaking probability superior to 72% at the beginning (Fig. 2a). The three wave height trends, modelled in R Studio, are mainly dissociated in deeper waters (Q_b low = 0.72, Q_b average = 0.87, Q_b high = 0.92; Fig. 2b-d). Their values then increase slowly as the water gets shallower. Eventually, they join each other at the entrance of the shallow depth zone of the wave ($h = 0.366$ m at X163, $Q_b > 0.96$).

3.2 Shellfish Reef Efficiency

For each wave height trend calculated in R Studio using the datasets and methods described in Sects. 2.2. and 2.3, the wave was shown to have a very high chance to break over the reef placed at any of the positions considered in Scenario 2 ($Q_b > 0.96$). Table 1 shows the increase in breaking probability for each reef position for every trend compared to the ‘no reef’ scenario (Scenario 1). As a result, the reef located the furthest from the shore (X50) shows a larger increase in the breaking probability of the wave (+20% of breaking probability in low trend wave height (1.2 m)). On the other hand, the reef closest to the shore (X150) has the smallest increase in this value (+6% in low trend as well).

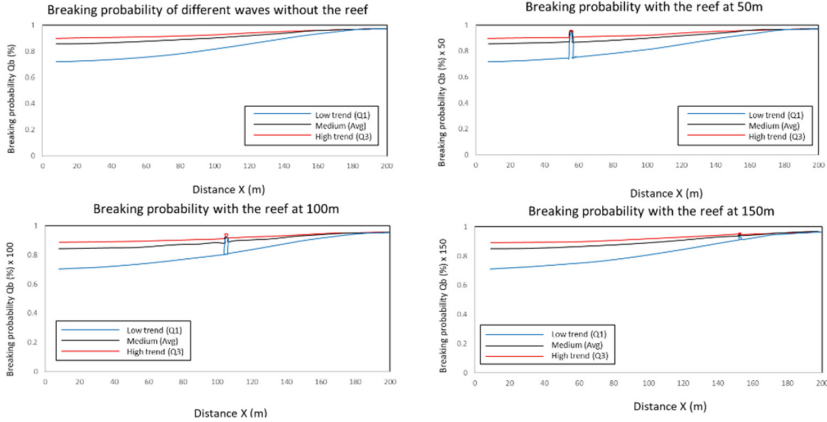


Fig. 2. Breaking probability curves for each reef scenario

However, even though the reef furthest from the shore showed higher efficiency in breaking probability, none of the modelled reef positions showed statistical differences when compared to the ‘no reef’ scenario ($p > 0.05$). The Kruskal-Wallis test Table 2 also showed that the different trends in wave height have no influence on the statistical impact of the reef.

Since the wave breaking process is affected by the wave velocity decrease due to the friction between the water and the seabed, different reef lengths were tested for each position to increase the wave friction distance until which the reef would show statistical significance (Kruskal test p -value < 0.05) compared to the ‘no reef’ scenario (Scenario

Table 1. Increase in Q_b compared to ‘no reef’ scenario (%).

Reef position	Increase in Q_b compared to ‘no reef’ scenario (%)		
	Low trend	Average	High trend
X50	20	9	6
X100	12	5	4
X150	2	0	1

Table 2. Kruskal-Wallis test comparison

Reef position	Kruskall-Wallis p-values		
	Low trend	Average	High trend
X50	0.5221	0.5221	0.5221
X100	0.7242	0.7242	0.7242
X150	0.9478	0.9478	0.9478

1). The models showed that the distance between the reef and the shore has an impact on the required reef length to be statistically different: the reef furthest from the shore (X50) would require a minimum reef length of 7 m, the reef in the middle position (X100) would need a reef length of 13 m, whereas the closest (X150) would require a length greater than 50 m (i.e. is not viable for the existing bay geometry).

The ‘no reef’ scenario modelled in R Studio showed an increasing value of the energy flux (P) as long as the waves are located in its deep or intermediate depth zone ($x = 0$ m to $x = 163$ m; Fig. 3). Then it reaches its maximum before the wave enters shallow waters ($P_{163} = 58290.35 \text{ Wm}^{-1}$). Starting from the shallow water zone ($x = 163$ m), the energy flux starts to decrease as the wave is affected by the proximity of the seabed, which reduces its velocity and dissipates its energy with the friction (shoaling effect). The modelled ‘no reef’ wave finally reaches the shore with the energy that has not been dissipated and thus being delivered to the shore ($P_{200} = 11413.59 \text{ W.m}^{-1}$). Our models showed that each reef scenario exhibits a similar progression of the energy flux until the wave encounters the reef. After breaking at the reef, the wave energy is dissipated in the reef surroundings resulting in a drop of the wave energy flux value to 0 W.m^{-1} in the shallow waters between the reef and the shore as classified by [7].

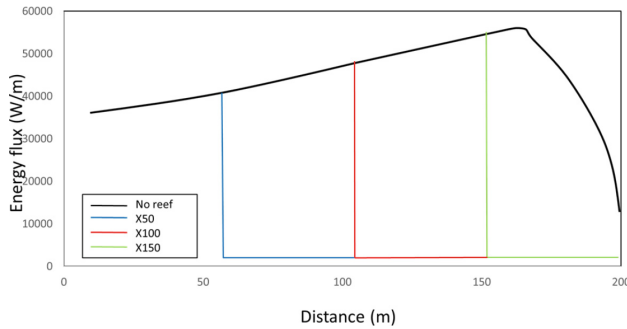


Fig. 3. Wave energy flux (P) scenario comparison.

4 Discussion and Conclusions

This study aimed at theoretical assessment of the efficiency of a shellfish reef to attenuate the wave energy flux to avoid further coastal erosion in Catterline Bay based on readily available data. The datasets were retrieved from open-sourced databases such as meteorological and bathymetric datasets to derive the variables used in the numerical model. A numerical model was created to determine the impact of the reef on the breaking probability of the incoming wave. The energy flux reduction from the waves by the shellfish reef was also modelled. Consequently, this study showed that the efficiency of a reef to attenuate the wave strength in Catterline is affected by its position in the bay as well as its dimensions. The main limitation of this study is that no experiments have been performed to validate the theoretical results due to the feasibility nature of this study and the lack of funding for the local community affected by coastal erosion and

instability. Similarly, the calculations considering wave reflection, diffraction and percolation were not carried out but could be added in future studies. The results obtained in this study, however, could be used as a comparison for future both experimental and theoretical studies. The accuracy of the results presented here can be verified by construction and monitoring which should be relevant to the site area and the model used for verification. The relevance to the site area could be taken into account by including the effects of waves propagating from the deep sea to the shore (surge waves) which will be predominant over the wind waves in the nearshore area.

The secondary aim of this paper was to provide guidelines regarding the implementation and management of a shellfish reef on the study site based on a literature study. It does not aim at assessing the suitability of the site to receive a shellfish reef, nor studying the ecology of the advised shellfish species. The feasibility to implement a shellfish reef in Catterline coast must be investigated separately in an environmental study since certain living conditions are required to ensure the shellfish to thrive in the bay. Future studies (feasibility and environmental) should focus on three spheres of interest: the hydrosphere for the hydrological characteristics of a live shellfish reef, the lithosphere for the sedimentation and substrate availability for the shellfish, and the biosphere for ecological assessment of the type and place of the shellfish in its local food chain as well as its interactions with the surrounding flora and fauna. The site must fit all of the criteria within each sphere in order to be potentially suitable for shellfish reef implementation. For example, *Modiolus modiolus*, an ecosystem engineering shellfish species could be used in building the reef based on its current presence in Scotland habitats (67 beds) and its relatively long lifespan (>45 years). Such reef would not only contribute towards the protection of the sea shore but also to increase in knowledge of the ecology of this species as indicated by the OSPAR Commission [8] if a suitable monitoring programme is deployed during and after reef build-up. The implementation of this species could also allow Catterline to be an OSPAR Marine Protected Area. On the other hand, further studies are required with different species to assess the optimum species to implement at a specific site, and it would be recommended to conduct further research on co-habitation possibilities of several species in the reef. The actual management of the shellfish reef which would include management of a potential overgrowth and disturbance of the local food web can be supported by existing tools such as Ecopath with Ecosim model (<https://ecopath.org/>). Finally, the social acceptance of such a project must be investigated to make sure the project does not oppose the views of the local community and stakeholders. Adapting existing tools such as [9] to gauge the thoughts and views of the relevant stakeholders on the implementation of a shellfish reef as a NBS for coastal protection strategy.

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