# 1. Practitioner Survey

An online questionnaire was used to survey the community of engineers, managers, and other practitioners who interface with the coastal zone and practitioners with interest in dynamic cobble berm revetments, mainly from the west coast of the US. The goals of the survey were to understand and document the current state of the practice for the design, implementation, and monitoring of dynamic revetments, and to identify knowledge gaps with respect to dynamic revetment function, engineering design, and management needs. Respondents were encouraged to forward the survey to interested colleagues.

The questionnaire had two sections: an implementation section and an engineering section. The implementation section (Questions 1-6 and 11) was designed to establish the drivers and barriers to implementing dynamic revetments, and was written for a familiar, but non-technical audience, including planners or resource managers. The engineering section (Questions 7-10 and 12) was designed to understand the currently existing tools and practices used in the design of dynamic revetments and was written for respondents who had interest or experience in the technical aspects of dynamic revetment design. The questions were open-ended, and respondents were able to choose which questions they answered.

To process and analyze the survey responses, a list of topics covered by respondents was developed for each question. The list was edited for length and clarity by combining topics (e.g., concerns about recreation impacts due to cobble and general concern for cobble introduction on a sandy beach were combined into the general topic “change in beach character” for Q6). During analysis, a list of 5-10 topics was designated for each question based on the most common themes in the survey responses. Then, each survey response was classified by the different topics it mentioned (Table 1). The number of times each topic was mentioned was tallied for every question and summarized. For clarity, only the most mentioned topics (typically 3-6 topics) are presented in this manuscript; however, the supplementary material includes the full summary of the responses (Supplement, Section 1). When percentages are used to refer to how often a specific topic was mentioned, they are calculated based on the number of people that responded to that particular question. For more information, see Supplement Section 1.

Table 1: Example of survey responses and classifications for a survey question.

| **Do you have any concerns about the impacts of dynamic revetments on the beach and the surrounding environment? If so, what are your concerns?** | |
|---|---|
| **Example Response** | **Example Classification** |
| Some concern about walkability of beaches with more rock and if that changes the ecosystem/habitat of the area | Beach access, ecosystem disturbance, changing beach character |
| I have a concern regarding dynamic revetments being implemented in areas that are not suited for this type of measure. I think more research is needed to better define what types of shorelines and coastal settings are suitable for dynamic revetment installation. | Suitability to situation, not enough guidance. |

| | |
|---|---|
| Yes. Concern of refracting wave energy into surrounding unprotected property owners' shoreline, causing accelerated erosion. Concerns of leaving a natural sandy beach and not permanently altering the ecology for the sole purpose of preserving private property. | Disruption of sediment transport, changing beach character, ecosystem disturbance, other |

## 1.1. Demographics

A total of 48 responses were received. Respondents had a number of different roles, with engineers and coastal geomorphologists the most highly represented. The majority of the respondents were from the Pacific Northwest of the United States (Oregon and Washington), with additional representation from California, British Columbia, and other locations including the United Kingdom and New England (Figure 2).


Figure 2: Distribution of (a) respondent roles and (b) respondent work location. Some respondents indicated that they worked in more than one location.

## 1.2. Current Understanding

With the rapid increase in popularity for use of dynamic revetments as coastal protection measures, there has come uncertainty about the proper terminology and description of their purpose and function. We asked survey respondents how they define and name dynamic revetments (Q1 and Q2, Figure 3a-b). Respondents used the material of a dynamic revetment (i.e., cobble, gravel) (24 respondents), and the structure's dynamic nature (i.e., it is intended to evolve) (21) in their definitions. Other definitions included the purpose of the dynamic revetment (i.e., to reduce erosion or prevent flooding) (20), and how the structure achieved that purpose (i.e., dissipating wave energy, increasing in elevation during storms) (12). Some respondents (8) also mentioned that dynamic revetments are a nature-based or design-with-nature engineering method, and others (6) mentioned the placement location of the cobbles on the beach profile as important for defining the feature.

Respondents were asked if "dynamic revetment" was a suitable name for the cobble berms constructed for erosion control that are described in this study. The majority of respondents (21 respondents) said yes, 5 said no, and 9 said maybe (Q2, Figure 3b). An alternative name suggestion was "cobble berm" (suggested by 6). Some respondents also had concerns that the use of the word "revetment" would be associated with traditional riprap revetments (6) (Figure 3b).

We also asked survey respondents what metrics they would use to define dynamic revetment success and failure. The survey responses included multiple suggestions for metrics that can be used to evaluate dynamic revetment success (Q3, Figure 3c). The majority of responses (36) suggested shoreline protection as a metric for success, with proposed measurements including tracking shoreline retreat and impacts on backshore infrastructure. Many respondents (17) mentioned the retention of sand either on the foreshore, the revetment itself, or in dunes behind the revetment as a metric for success. Specific metrics mentioned for measuring sand retention included tracking foreshore sand volumes and dune heights. Other respondents (14) mentioned that positive or negative ecological impacts could also indicate success or failure, respectively, of a dynamic revetment. Species counts were suggested as a method of quantifying ecological impacts. Respondents (13) also suggested defining success by the extent to which maintenance occurred according to initial project goals. Other metrics of success included a reduction in overtopping (12), the structure remaining stable (9), and the impacts (both positive impacts and the lack of negative impacts) of the dynamic revetment on recreational uses of the beach (6).

In response to Questions 1-3, survey respondents accurately defined dynamic revetments as made of cobble or gravel and intended to change shape as a result of wave collision. They also agreed that "dynamic revetment" was an appropriate term. Other definitions of dynamic revetments described the purpose of a dynamic revetment and how it would achieve that purpose. Respondents also agreed that a successful dynamic revetment would provide protection from terrestrial land loss. However, there was variation in what respondents stated as other measures of success or failure of a dynamic revetment. Generally, there was agreement among survey respondents in the definition and purpose of a dynamic revetment; however, variation in their answers highlights a need for accurate communication of the purpose of a dynamic revetment on a project-specific level.

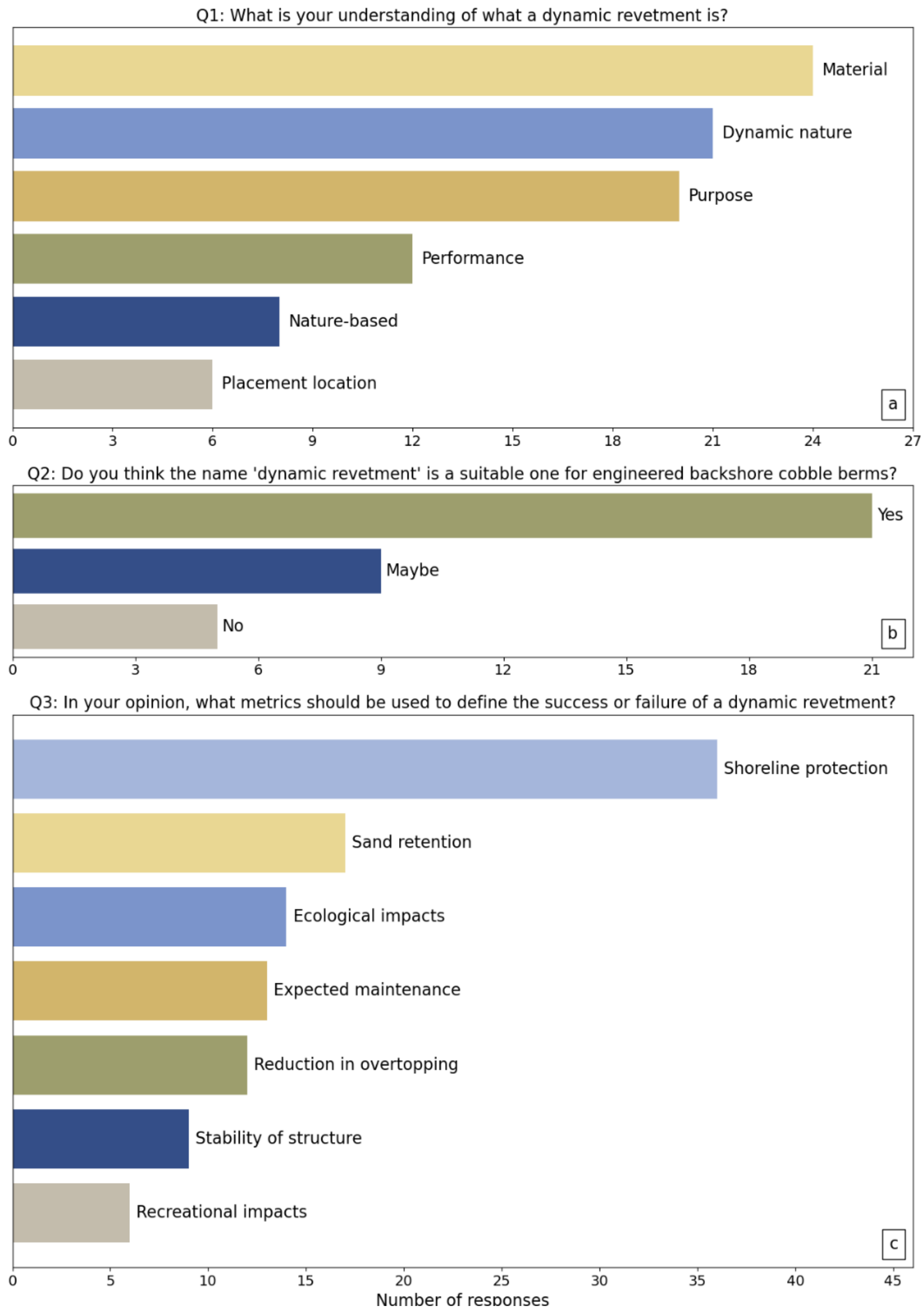


Figure 3: Number of times topics were mentioned in responses for Q1 (a), Q2 (b), and Q3 (c). The question text is above the associated subplot. Questions were open-ended, and respondents generally mentioned more than one topic in their response.

## 1.3. Barriers/Concerns

Respondents were asked what they saw as the biggest barriers to implementation of dynamic revetments (Q4, Figure 4a). The most common response was a general concern about the lack of knowledge about dynamic revetments (15 respondents). More specifically, respondents mentioned difficulties in permitting, including permitting for maintenance (13), uncertainty in the performance of dynamic revetments (12), and a public perception that dynamic structures may be less protective or more difficult to implement than traditional static structures (11). Some respondents were concerned about the maintenance required for dynamic revetments (9), and others felt that dynamic revetments were not an applicable solution for some sites (8).

Respondents also mentioned a wide variety of progress needed in policy for the encouragement of dynamic revetments as a coastal protection option (Q5, Figure 4b). The most common topics mentioned were a need for engineering guidance and performance expectations (17 respondents), and flexibility within permitting for maintenance and monitoring (10). Other topics mentioned included the consideration of NNBFs as an alternative to hard structures (9), interdisciplinary collaboration (2), and a characterization of habitat value (2).

When survey respondents were asked if they had concerns about the impacts of dynamic revetments, 30 respondents answered "Yes." (Q6, Figure 4c). The most common concern was ecosystem disturbance (17 respondents). Some respondents also expressed concern that adding cobbles to a beach would change the overall character of the beach (15), for example, changing recreational activities on the beach, damaging the natural ecosystem, or changing the beach in a way that is unacceptable to the public. Others had concerns that dynamic revetments might disrupt the sediment transport in the area (12). Several respondents mentioned concerns that dynamic revetments would be constructed in unsuitable locations or with designs unsuitable to a site (6). Examples given for unsuitable locations were naturally sandy beaches, or in front of a single home. Concerns about adverse impacts from over- or under-designed dynamic revetments were also mentioned. Other respondents had concerns about beach access being maintained (6). Respondents also had concerns about cobble migration along the beach to areas other than the project site (4).

Generally, a lack of knowledge and ability to predict the performance of dynamic revetments was stated as a major barrier to implementation of dynamic revetments. Lack of performance expectations was also mentioned specifically as a regulatory barrier to implementation, as permitting agencies may have difficulty saying with certainty how the dynamic revetment will perform. Concerns about the environment and ecosystem of project sites were also a concern, with respondents concerned about major changes in the beach due to the addition of cobble, the potential disruption of sediment transport, and potential adverse impacts for native species. These responses highlight the need for collaboration between coastal engineers, managers, researchers and ecologists to better understand the system in a practical and integrated way.

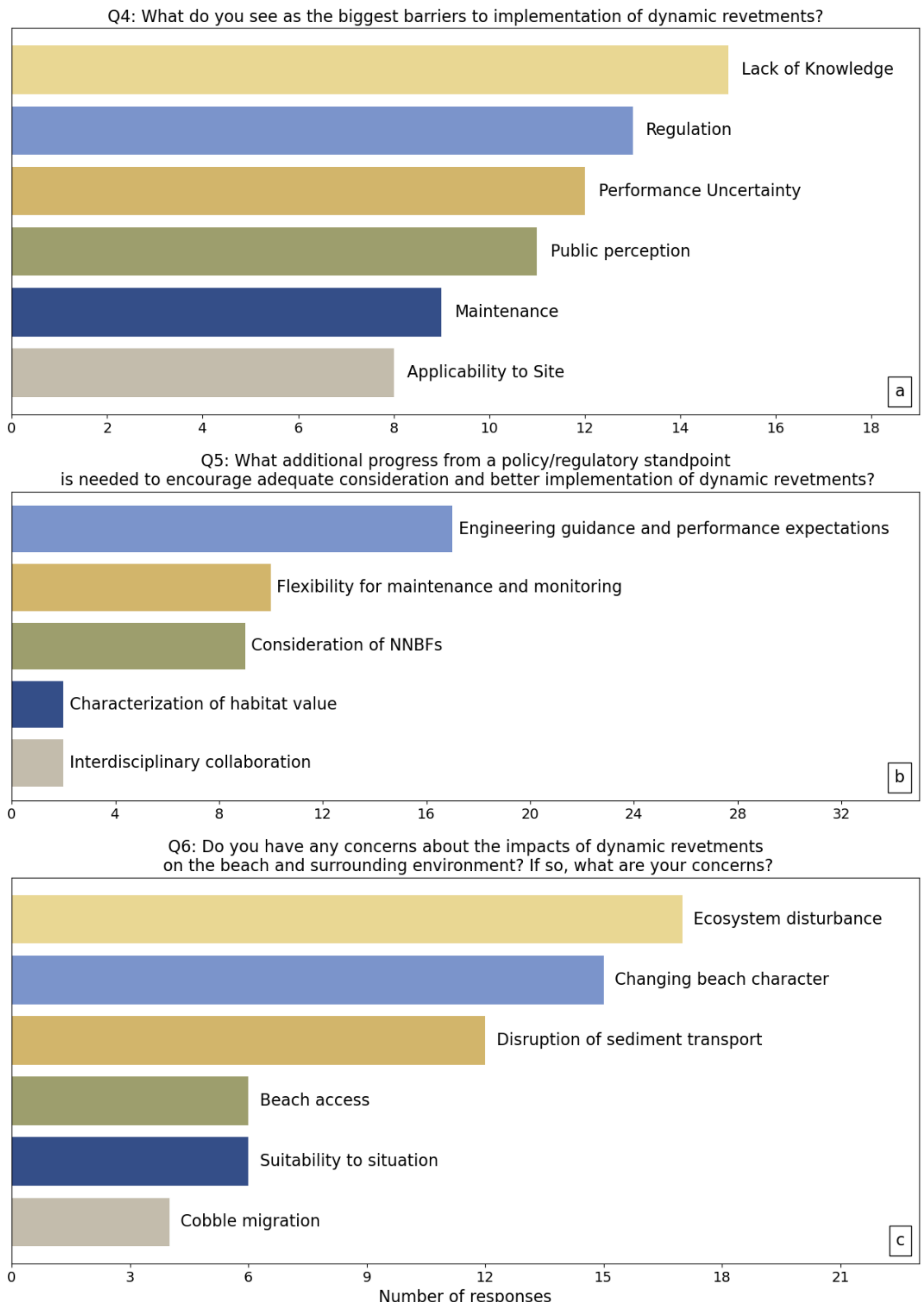


Figure 4: Number of times topics were mentioned in responses for Q4 (a), Q5 (b), and Q6 (c). The question text is above the associated subplot. Questions were open-ended, and respondents generally mentioned more than one topic in their response.

## 1.4. Design and Construction

We asked survey respondents about their impressions of the best existing resources, the most crucial missing tools, and their opinions on the most important design parameters for dynamic revetments. We also asked about the information required to develop construction methods specific to dynamic revetments.

The most commonly-used resource for design was design and monitoring reports from existing dynamic revetment projects (18 respondents) (Q7, Figure 5a). Respondents also identified academic papers (e.g., Bayle *et al.* 2020; van der Meer 1988) as useful (10). Additionally, respondents mentioned several manuals as a design tool, such as the CIRIA Rock Manual (CIRIA, 2007), the Washington State Marine Shoreline Design Guidelines (Johannessen et al., 2014), or the USACE Coastal Engineering Manual (USACE, 2011) (4). Models such as XBeach-G (McCall et al., 2019) (3) and natural cobble beaches (2) were also mentioned as resources for dynamic revetment design.

Survey respondents also mentioned the tools they felt were missing from the current tools used for design (Q8, Figure 5b). The most common response (12 respondents) was the ability to model morphologic change in dynamic revetments with tools like XBeach-G (McCall et al., 2019). Other missing tools included recommendations for design parameters (9) and tools for predicting wave behavior on dynamic revetments (9).

As there is no standard procedure for the design and construction of dynamic revetments, there is still some uncertainty over what parameters are important in the design of dynamic revetments (Q9, Figure 5c). The most mentioned design parameter by survey respondents was cobble size (16 respondents). Revetment design volume was also commonly mentioned (14). Other design parameters included revetment slope (10), toe elevation (6), crest height (6), and cobble gradation (5).

Dynamic revetment construction has the potential to be cost-effective and simple; however, adapting traditional construction practices to dynamic revetments requires additional knowledge (Q10, Figure 5d). The needed information that the most respondents identified was a source for the cobble material (10 respondents). Another construction challenge was site access (4). Other respondents mentioned that more information was needed on material preparation (for example, sieving or washing the cobble) (3). Several respondents also mentioned that more knowledge of cobble dispersion rate is needed to understand if cobble can be placed in a single location and allowed to disperse alongshore (3).

In summary, respondents identified that existing projects and academic research were the two most useful existing tools, but wanted the state of the practice to evolve to more predictive tools like modeling. While it has been attempted to model bimodal (i.e. two sediment sizes) sediment dynamics (McCall et al., 2019), it has not been successful to date and needs further research. Respondents felt that cobble size and revetment volume were the two most important parameters for dynamic revetment design, and that sourcing cobble was the most challenging part of construction.

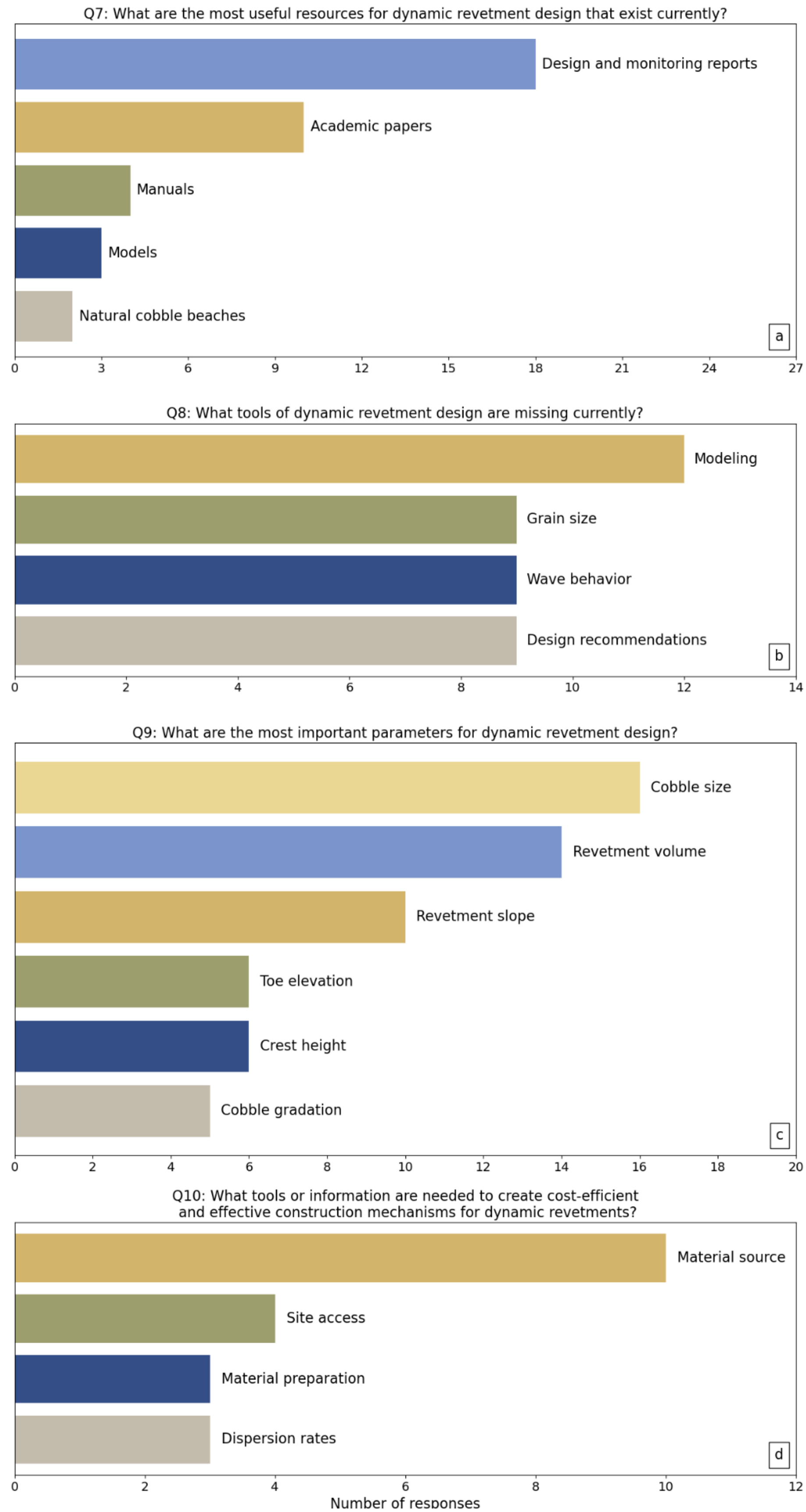
Q7: What are the most useful resources for dynamic revetment design that exist currently?
Design and monitoring reports
Academic papers
Manuals
Models
Natural cobble beaches
a
0
3
6
9
12
15
18
21
24
27
Q8: What tools of dynamic revetment design are missing currently?
Modeling
Grain size
Wave behavior
Design recommendations
b
0
2
4
6
8
10
12
14
Q9: What are the most important parameters for dynamic revetment design?
Cobble size
Revetment volume
Revetment slope
Toe elevation
Crest height
Cobble gradation
c
0
2
4
6
8
10
12
14
16
18
20
Q10: What tools or information are needed to create cost-efficient and effective construction mechanisms for dynamic revetments?
Material source
Site access
Material preparation
Dispersion rates
d
0
2
4
6
8
10
12
Number of responses

Figure 5: Number of times topics were mentioned in responses for Q7 (a), Q8 (b), Q9 (c) and Q10 (d). The question text is above the associated subplot. Questions were open-ended, and respondents generally mentioned more than one topic in their response.

## 1.5. Adaptive management and maintenance

Respondents were asked what they thought an adaptive management strategy for dynamic revetments would look like (Q11, Figure 6a). As expected, many respondents mentioned that monitoring and maintenance would be a part of an adaptive management plan (28 respondents and 24 respondents, respectively). Other respondents mentioned a need for a funding source (5) and an appropriate permitting process that allowed for adaptation as the project developed (3). Respondents also suggested the use of threshold conditions after which maintenance would be triggered (6). Respondents who mentioned monitoring suggested a range of different monitoring methods, including camera-based, topo surveys, lidar, drone structure-from-motion, and cobble tracking. They mentioned monitoring goals like identifying the cobble volume lost, the change in profile shape, and the change in crest height. Respondents also suggested monitoring and maintenance timings including from 6 months to annually, pre- and post-winter, and every 5 years. Some respondents also mentioned the need for the timing of monitoring and maintenance to be adaptable to the design life of the project and the project goals.

When asked about the specifics of an adaptive management program (Q12, Figure 6b), the most common response was that a system of maintenance triggers should be used (6 respondents). For example, a specific reduction in volume in the revetment or a certain amount of shoreline retreat might trigger maintenance action. Respondents also specifically mentioned that measurements and knowledge of volume change in the revetment would be necessary information for a maintenance program (5), and other respondents pointed to the need for topographic surveys to get this information (6). In addition, other respondents also pointed to the need to understand the maintenance expectations of the stakeholders involved with the project (6).

Generally, respondents overwhelmingly agreed that monitoring and maintenance would be a part of an effective adaptive management plan. However, the details of such a plan remained less clear. Some respondents mentioned monitoring strategies, including camera-based monitoring, drone surveys, or cobble tracking. Some respondents also mentioned monitoring goals such as identifying the cobble volume lost or the change in crest height. Respondents suggested that these metrics could be implemented through a system of maintenance triggers (i.e. planning maintenance after a certain volume of cobble was lost from the revetment). However, these adaptive management plans will likely need to be site-specific based on permitting requirements and stakeholder expectations.

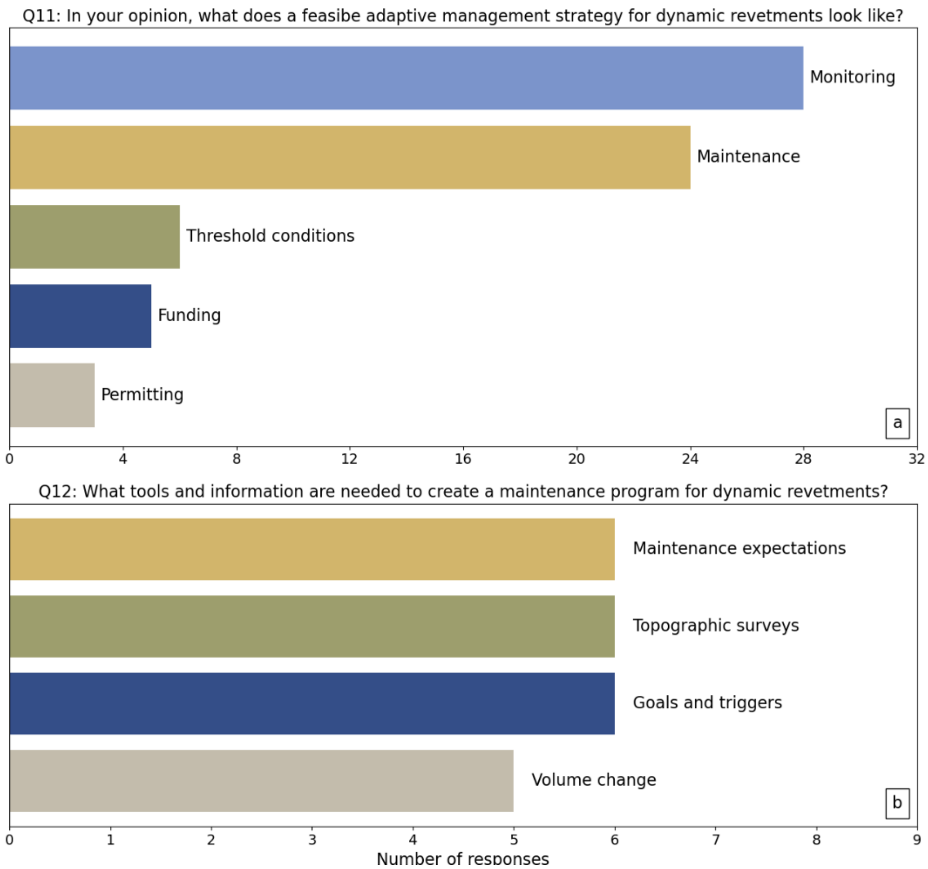


Figure 6: Number of times topics were mentioned in responses for Q11 (a) and Q12 (b). The question text is above the associated subplot. Questions were open-ended, and respondents generally mentioned more than one topic in their response.

# 2 Existing Design Tools

In this section of the supplement, we show the equations discussed in Section 2: Existing Design Tools. Variables are defined separately for each equation. Care has been taken to ensure these equations are correct, however, the reader is also encouraged to reference the existing source material.

## 2.1 Cobble Specifications

### 2.1.1 Stability number

Several studies and manuals (e.g. van der Meer and Pilarczyk 1986, CIRIA 2007) define different stability regimes for pure rock/cobble berms based a stability number, which is a ratio of the mobilizing force (wave height) to the stabilizing force (grain size). The stability number is defined as:

$$N_s = H_s/(\Delta D_{n50}) \tag{1}$$

van der Meer and Pilarczyk (1986) provides different structure types and their associated stability numbers. The structures are assumed to have no sand.

Table 1: Structure types and associated stability number

| Structure type | $N_s$ |
|---|---|
| Statically stable breakwaters | 1-4 |
| Berm breakwaters and S-shaped profiles | 3-6 |
| Dynamically stable rock slopes | 6-20 |
| Gravel beaches | 15-500 |
| Sand beaches | >300 |

Table 2: List of Symbols - van der Meer and Pilarczyk (1986)

| Symbol | Definition |
|---|---|
| $D_{n50}$ | Nominal diameter of average stone mass |
| $H_s$ | Significant wave height |
| $N_s$ | Stability number |
| $\Delta$ | Relative mass density (-) |

### 2.1.2 Minimum stable stone size (Lorang 2000)

For dynamic revetments, where stones are expected to be mobile, Lorang's (2000) equation for minimum stable stone size could be used to provide an upper limit of the cobble size. The minimum stable stone size is defined as:

$$M_{H_{sb}} = \frac{\rho_s f_{BF} U_{max} R_u H_{sb}^2 2\mathrm{f}}{K_r(\frac{\rho_s - \rho_w}{\rho_w}) g tan\theta} \tag{2}$$

where

$$f_{BF} = \frac{8}{(2.5ln(30\frac{R_u}{D_{50}}))^2} \tag{3}$$

and

$$U_{max} = \sqrt{g(h_{sb} + H_{sb})}. \tag{4}$$

In Lorang (2000), $K_r$ was set to 1.

Table 3: List of symbols - Lorang (2000)

| Symbol | Definition |
|---|---|
| $D_{50}$ | Median grain size (m) |
| f | Swash frequency, f $= 1/T$ (s$^{-1}$) |
| $f_{BF}$ | Flow drag between beach face and wave swash (-) |
| $g$ | Acceleration due to gravity (m/s$^2$) |
| $h_{sb}$ | Water depth at breaking (m) |
| $H_{sb}$ | Breaking wave height (m) |
| $K_r$ | Non-dimensional variable related to stability (-) |
| $M_{H_{sb}}$ | Minimum stable mass (kg) |
| $R_u$ | Runup elevation (m) |
| $U_{max}$ | Maximum swash velocity (m/s) |
| $\theta$ | Beach slope (°) |
| $\rho_s$ | Density of the stone (kg/m$^3$) |

## 2.2 Runup and Crest Height

### 2.2.1 van Gent (1999, 2001)

The equations in these papers were developed for runup on steep structures with shallow foreshores. A numerical model was used to model the Petten Sea defense, which was a sea dike in the Netherlands with a shallowly-sloping foreshore. The

numerical model was used to create a runup equation, which was then calibrated with results from a physical model.
To account for wave spectra that potentially had two frequency peaks, van Gent (1999, 2001) tested several ways of calculating the wave period, and found that the wave period $T_{m-1.0}$ was the most related to the modeled runup.

$$T_{m-1.0} = m_{-1}/m_0 \tag{5}$$

where

$$m_n = \int_0^{\infty} f^n S(f)\, df \tag{6}$$

After $T_{m-1.0}$ is calculated, it can be used in the following equations to predict runup.

$$z_{2\%}/(\gamma H_s) = c_0 \xi_{s,-1} \qquad \text{for } \xi_{s,-1} \leq p \tag{7}$$

$$z_{2\%}/(\gamma H_s) = c_1 - c_2/\xi_{s,-1} \qquad \text{for } \xi_{s,-1} \geq p \tag{8}$$

Where

$$\gamma = \gamma_f \gamma_\beta \tag{9}$$

$$tan\phi = 2c_{BERM} H_s/L \tag{10}$$

$$\xi_{s,-1} = tan\phi / \sqrt{(2\pi/g \cdot H_s/T^2_{m-1.0}} \tag{11}$$

$$c_2 = 0.25 c_1^2/c_0 \tag{12}$$

$$p = 0.5 c_1/c_0 \tag{13}$$

$$\gamma_f = \begin{cases} 0.5 & \text{for rock slopes with two or more layers} \\ 0.6 & \text{for rock slopes with one layer} \\ 0.95 & \text{for grass} \\ 1 & \text{for smooth impermeable slopes} \end{cases} \tag{14}$$

$$\gamma_b = 1 - 0.0022 \cdot \beta \quad \text{for } \beta \leq 80^\circ \tag{15}$$

Reduction factors are given in van Gent (1999). The $c_{BERM}$ used in van Gent (2001) was 2 m, and the $\gamma$ used in van Gent (2001) was 0.7. Suggested values for $c_0$ and $c_1$ for characteristic wave heights calculated from the time and frequency domains:

Table 4: Recommended $c_0$ and $c_1$

| Wave energy spectra | Wave height | Wave period | $c_0$ | $c_1$ |
|---|---|---|---|---|
| Total: long and short waves | $H_{m0}$ | $T_{m-1.0}$ | 1.45 | 3.8 |
| Total: long and short waves | $H_s$ | $T_{m-1.0}$ | 1.35 | 4.7 |

Table 5: List of symbols - van Gent (1999, 2001)

| Symbol | Definition |
|---|---|
| $C_{BERM}$ | coefficient in method to obtain characteristic slope (-) |
| $H_s$ | Significant wave height of the incident waves at the toe of the structure (m) |
| $L$ | length to obtain reduction factor for berms (m) |
| $\beta$ | angle of wave attack (°) |
| $\gamma$ | reduction factor (-) |
| $\gamma_\beta$ | reduction factor that takes the effects of angular wave attack into account (-) |
| $\gamma_f$ | reduction factor that takes the effects of roughness into account (-) |
| $\phi$ | slope of structure (°) |

#### 2.2.2 Zaalberg (2019)

Zaalberg (2019) defined the relative pore volume as follows:

$$\frac{n_p \cdot R_c \cdot \sqrt{1 + cot^2\alpha} \cdot T_c}{H_{m0}^2} \tag{16}$$

Zaalberg (2019) then used experimental and modeling results to empirically define the roughness factor $\gamma_f$ based on the relative pore volume per area ($\frac{n_p \cdot T_c}{H_{m0}}$) as follows:

$$\gamma_f = 0.77 - 0.46 \cdot \frac{n_p \cdot T_c}{H_{m0}} \tag{17}$$

for

$$0.21 \leq \frac{n_p \cdot T_c}{H_{m0}} \leq 2.77 \tag{18}$$

and

$$T_c \leq L_{infiltration} \tag{19}$$

The roughness factor can be used in the EurOtop formula (van der Meer et al. 2018) to more accurately calculate runup on cobble slopes with infilled sand.

Table 6: List of symbols - Zaalberg (2019)

| Symbol | Definition |
|---|---|
| $H_{m0}$ | Spectral wave height (m) |
| $L_{infiltration}$ | Vertical distance that water will infiltrate during a wave period (m) |
| $n_p$ | porosity (-) |
| $R_c$ | crest height (m) |
| $T_c$ | effective thickness of cobble layer above the waterline (m) |
| $\alpha$ | slope of the revetment above the waterline (°) |
| $\gamma_f$ | reduction factor that takes the effects of roughness into account (-) |

### 2.2.3 Blenkinsopp et al. (2022)

Blenkinsopp et al. (2022) used measurements from five field and large-scale laboratory experiments to create runup equations for composite beaches. There are two equations, one of which accounts for the short-wave and infragravity components of swash and one which does not.

The first equation, which does not account for short-wave and infragravity components of swash is as follows:

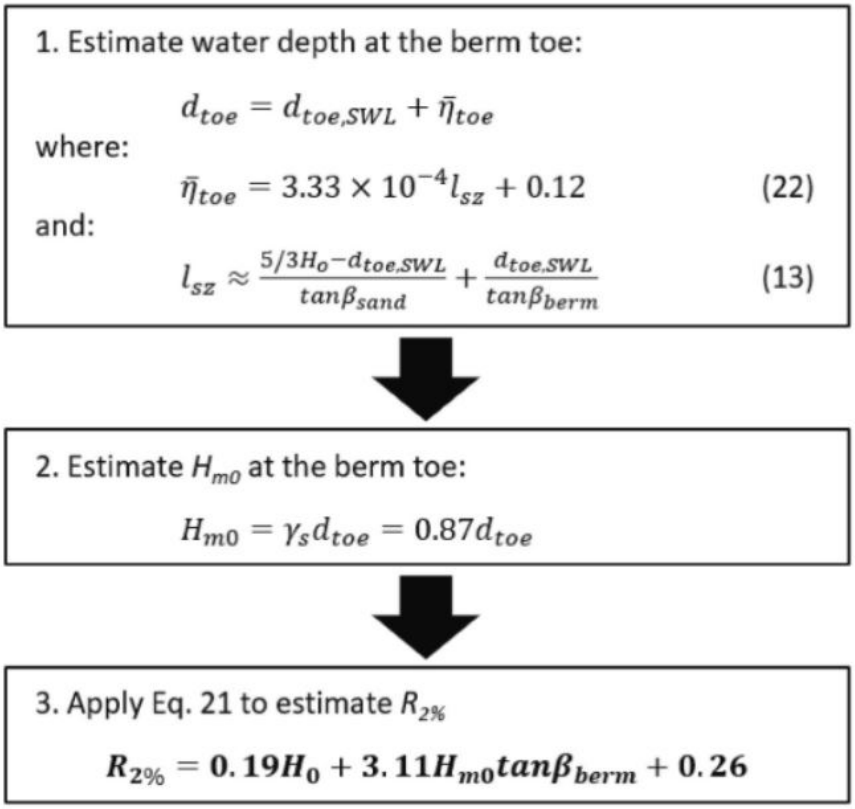


Figure 1: Flowchart for application of the first equation from Blenkinsopp et al. (2022)

The second equation, which does account for short-wave and infragravity components of swash is as follows:

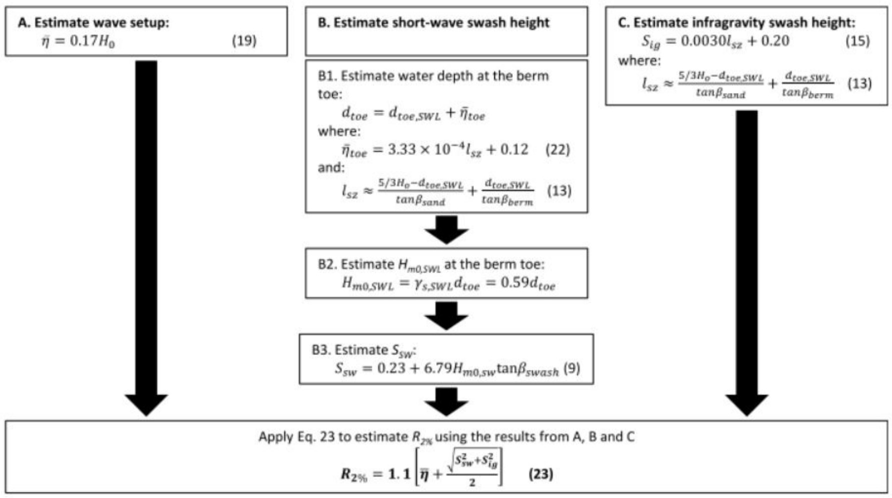


Figure 2: Flowchart for application of the second equation from Blenkinsopp et al. (2022)

Table 7: List of symbols - Blenkinsopp et al. (2022)

| Symbol | Definition |
|---|---|
| $d_{toe}$ | Water depth above berm toe (m) |
| $d_{toe,SWL}$ | Vertical elevation difference between berm toe and SWL (m) |
| $H_0$ | Significant wave height measured offshore (m) |
| $H_{m0}$ | Spectral significant wave height at berm or structure toe (m) |
| $H_{m0,sw}$ | Short wave spectral significant wave height at berm or structure toe (m) |
| $l_{sz}$ | Composite beach surf zone width (m) |
| $R_{2\%}$ | Runup elevation exceeded by 2% of incident waves (m) |
| $S_{ig}$ | Significant infragravity swash height (m) |
| $S_{sw}$ | Significant short wave swash height (m) |
| $SWL$ | Mean water surface elevation seaward of the surf zone within 10-min time windows (m) |
| $\beta_{berm}$ | Angle between the mean gravel berm slope and horizontal (°) |
| $\beta_{sand}$ | Angle between the mean sand beach slope and horizontal (°) |
| $\beta_{swash}$ | Angle between the mean swash slope and horizontal within a 10-min time window (°) |
| $\overline{\eta}$ | Wave setup at the shoreline (m) |
| $\overline{\eta}_{toe}$ | Superelevation of the mean water level at the berm toe due to wave setup (m) |
| $\gamma_s$ | Wave height to water depth ratio at the berm toe (-) |
| $\gamma_{s,sw}$ | Short wave height to water depth ratio at the berm toe (-) |

#### 2.2.4 Conlin et al. (2025)

Conlin et al. (2025) used video-derived imagery from two sites to create a runup equation based on wave height, beach slope, and wave period. The equation is as follows:

$$R_{2\%} = 1.3(\overline{\eta} + \frac{S}{2}), \tag{20}$$

where:

$$\overline{\eta} = 0.92\beta_{beach}H_0(\frac{H_0}{L_0})^{-0.3} \tag{21}$$

$$S = 2.99\beta_{avg}H_0 + 1.28. \tag{22}$$

Table 8: List of symbols - Conlin et al. (2025

| Symbol | Definition |
|---|---|
| $H_0$ | Deep water wave height (m) |
| $L_0$ | Deep water wave length (m) |
| $R_{2\%}$ | The elevation exceeded by 2% of runup events (m) |
| $S$ | Significant swash height (m) |
| $\beta_{avg}$ | Average slope: Average of $\beta_{beach}$ and $\beta berm$ (-) |
| $\beta_{beach}$ | Beach slope: Best-fit slope to portion of profile seaward of toe location (-) |
| $\beta_{berm}$ | Berm slope: Best-fit slope to portion of profile landward of toe location (-) |
| $\overline{\eta}$ | Wave setup (m) |

### 2.3 Alongshore transport

#### 2.3.1 Kamphuis (1991): Equation for alongshore transport rate

Kamphuis (1991) used the results of a laboratory experiment to create an equation for alongshore sediment transport that was then tested on field data. The equation was developed for sandy beaches, but was also shown to apply to gravel beaches The equation is as follows:

$$Q = 2.27H_{sb}^2T_p^{1.5}m_b^{0.75}D_{50}^{-0.25}sin^{0.6}(2\alpha_b) \tag{23}$$

or, assuming a medium dense sand with porosity = 32%

$$Q' = 6.4 \cdot 10^4 H_{sb}^2T_p^{1.5}m_b^{0.75}D_{50}^{-0.25}sin^{0.6}(2\alpha_b) \tag{24}$$

Table 9: List of symbols - Kamphuis (1991)

| Symbol | Definition |
|---|---|
| $D_{50}$ | Median grain size (m) |
| $H_{sb}$ | Significant breaking wave height (m) |
| $m_b$ | Beach slope in the breaking zone (-) |
| $Q$ | Alongshore sediment transport rate (immersed mass - kg/s) |
| $Q'$ | Alongshore sediment transport rate (m$^3$/yr) |
| $T_p$ | Peak period (s) |
| $\alpha_b$ | Breaking wave angle (°) |

#### 2.3.2 van Wellen et al. (2000): Equation for alongshore transport rate on coarse-grained beaches

van Wellen et al. (2000) developed an equation for alongshore transport on gravel beaches that accounted for sediment transport in the swash zone and for critical mobility. The equation is as follows:

$$Q = 1.34\frac{(1+e)}{(\rho_s-\rho)}H_{sb}^{2.49}T_z^{1.29}tan\alpha^{0.88}D_{50}^{-0.62}sin2\theta_b^{1.81} \tag{25}$$

Table 10: List of symbols - van Wellen et al. (2000)

| Symbol | Definition |
|---|---|
| $D_{50}$ | 50% representative grain diameter (m) |
| $e$ | Void ratio (-) |
| $H_{sb}$ | Significant wave height at breaking (m) |
| $Q$ | Alongshore sediment transport rate (m$^3$/s) |
| $T_z$ | Zero-crossing wave period (s) |
| $\alpha$ | beach slope (rad) |
| $\theta_b$ | Wave angle at breaking (°) |
| $\rho_s$ | Density of sediment (kg/m$^3$) |
| $\rho$ | Density of fluid (kg/m$^3$) |

#### 2.3.3 van Rijn (2014): Equation for alongshore transport rate for sand, gravel, and shingle

van Rijn (2014) used a range of field data as well as a model to create an equation for alongshore transport rate for a range of sediment sizes. The equation is as follows:

$$Q_{t,mass} = 0.0006 K_{swell} \rho_s (\tan\beta)^{0.4} (d_{50})^{-0.6} (H_{s,br})^{2.6} V_{wave} \tag{26}$$

where

$$K_{swell} = 0.015 p_{swell} + (1 - 0.01 p_{swell}) \tag{27}$$

$$V_{wave} = 0.3 (g H_{s,br})^{0.5} sin(2\theta_{br}) \tag{28}$$

$p_{swell}$ is the percentage of low-period swell waves of the total wave height record. $p_{swell}$ is approximately 10%-20% for sea coasts and 20%-30% for open coasts. If swell is absent or unknown, $K_{swell}$ = 1.

Table 11: List of symbols - van Rijn (2014)

| Symbol | Definition |
|---|---|
| $Q_{t,mass}$ | Total alongshore sediment transport (kg/s) |
| $K_{swell}$ | Swell factor |
| $\rho_s$ | Sediment density (kg/m$^3$) |
| $tan\beta$ | Slope of beach/surf zone (-) |
| $d_{50}$ | median grain size (m) |
| $H_{s,br}$ | Significant wave height at breaker line (m) |
| $\theta_{br}$ | Wave angle at breaker line (°) |

## 2.4 Cross-shore transport and berm evolution

### 2.4.1 van der Meer and Pilarczyk (1986): Berm Evolution Model

van der Meer and Pilarczyk (1986) used the results of a laboratory experiment to develop a model to predict berm evolution of a gravel beach. The equations are valid for high $HoTo$ ($HoTo > 1000 - 2000$), which is a combined parameter that accounts for wave height and period. Equations are used to determine six parameters (hc, hs, ht, lr, lc, and ls), and Figure 3 illustrates how those parameters can be combined to draw a profile.

$$HoTo = \frac{H_s}{\Delta D_{n50}} \cdot \sqrt{g/D_{n50}} T_z \tag{29}$$

hc, hs, and ht can be determined from the following equations:

$$hc/H_s N^{0.15} = 0.89 (H_s/L_z)^{-0.5} \tag{30}$$

$$hs/H_s N^{0.07} = 0.22 (H_s/L_z)^{-0.3} \tag{31}$$

$$ht/H_s N^{0.04} = 0.73 (H_s/L_z)^{-0.2} \tag{32}$$

lr, lc, and ls can be determined from the following equations:

$$HoTo = 2.9(lr/D_{n50}N^{0.05})^{1.3} \tag{33}$$

$$HoTo = 21(lc/D_{n50}N^{0.12})^{1.2} \tag{34}$$

$$HoTo = 3.8(ls/D_{n50}N^{0.07})^{1.3} + 180 \tag{35}$$

Once the coefficients hc, hs, ht, lr, lc, and ls have been determined, the profile can be calculated according to:

$$y = ax^{0.83} \quad \text{below SWL and,} \tag{36}$$

$$y = a(-x)^{1.15} \quad \text{above SWL} \tag{37}$$

where a is calculated based on hs and ls, and hc and lc (Figure 1).

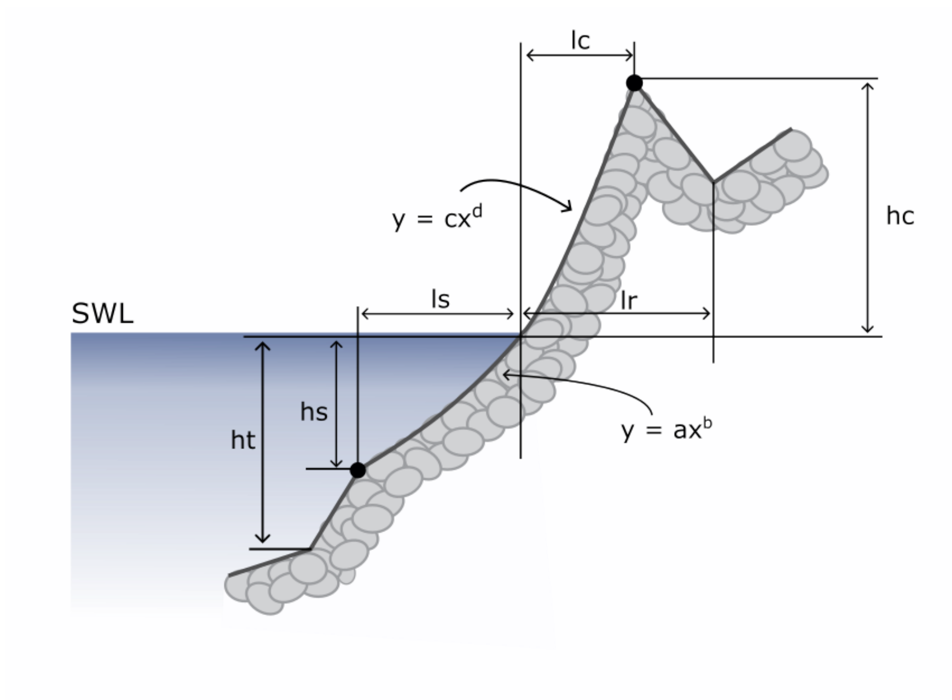


Figure 3: Diagram of hc, hs, ht, lr, lc, and ls (adapted from van der Meer and Pilarczyk, 1986).

Table 12: List of symbols - van der Meer and Pilarczyk (1986)

| Symbol | Definition |
|---|---|
| $D_{n50}$ | Nominal grain diameter (m) |
| $g$ | Acceleration due to gravity (m/s$^2$) |
| $hc$ | Crest height (m) |
| $hs$ | Step height (m) |
| $ht$ | Transition height (m) |
| $H_s$ | Significant wave height (m) |
| $L_z$ | Wavelength (m) |
| $lr$ | Runup length (m) |
| $lc$ | Crest length (m) |
| $ls$ | Step length (m) |
| $N$ | Number of waves (-) |
| $T_z$ | Wave period (s) |
| $\Delta$ | Relative mass density (-) |

### 2.4.2 Powell (1993): Equilibrium slope equation

Powell (1993) developed an equation for the equilibrium slope, which is defined as a single slope from crest to base, based on the results of a laboratory experiment. The equation is as follows:

$$sin(\theta) = 0.206(\frac{H_s}{L_m})^{-0.124}(\frac{D_{84}}{D_{16}})^{-0.223})(\frac{H_s}{D_{50}})^{-0.174} \tag{38}$$

Table 13: List of symbols - Powell (1993)

| Symbol | Definition |
|---|---|
| $D_{84}$ | Sediment grain size: 84% of grains are smaller |
| $D_{16}$ | Sediment grain size: 16% of grains are smaller |
| $D_{50}$ | Median grain size |
| $H_s$ | Significant wave height |
| $L_m$ | Average zero-crossing wavelength |

# 3 Confidence Assessment

In this section of the supplement, we give our rationale for each of the confidence levels assigned in Table 3 of the manuscript. Lines in italics correspond to each statement or tool given in Table 3.

## 3.1 Cobble Specifications:

*$D_{50}$ should be between 64-256 mm.*

This recommendation is based on observations of cobble on the open coast of Oregon (Allan et al. 2005) and based on the cobble sizes used in all dynamic revetment projects discussed in this paper. We have placed it as medium confidence because previous observations and projects have used cobble in this approximate size range. Additionally, in the absence of other information, we feel that using cobble-sized rocks to replicate a cobble berm seems like a reasonable first assumption. However, we cannot rate this statement any higher in confidence because the impact of cobble size on dynamic revetment performance has not been scientifically tested.

*The largest cobbles should move under expected hydrodynamic conditions.*

This recommendation is based on the general understanding of a dynamic revetment reflected in the survey: the cobbles expected to move under the design wave conditions. In addition, observations from Bayle et al (2021) suggest that rocks too large to be moved by hydrodynamic conditions may increase the chance of cusp formation and, therefore, overtopping in the lower-elevation cusp bays. We rate this statement as medium-high confidence because cobbles that move under expected hydrodynamic conditions fit with the general understanding of dynamic revetments. However, we cannot rate this statement higher because the impact of immovable cobbles have not been fully tested.

*Cobble should be poorly sorted.*

This recommendation is based on laboratory testing of poorly sorted and well sorted cobble (Bayle et al. 2020, Foss et al. 2023), and on field observations by Bayle et al. (2021). In the lab, it was observed that the use of well sorted cobble led to erosion of the sand beneath the constructed revetment (Bayle et al. 2020), while the use of poorly sorted cobble led to the formation of a filter layer below the constructed revetment that prevented erosion of the underlying sand (Foss et al. 2023). A naturally occurring filter layer was also observed in North Cove, WA by Bayle et al. (2021). Based on laboratory and field evidence, we have high confidence that cobble used for dynamic revetment construction should be poorly sorted.

*Angular cobble may have structural advantages.*

In a comparison between angular, poorly sorted cobbles and rounded, well sorted cobbles, it was observed that angular cobbles were able to interlock and form a more stable crest than rounded cobbles. Based on this observation and observations of the success of composite beaches with angular cobbles, we rate this observation with a medium confidence. More studies that specifically focus on the impact of angularity are needed to increase our confidence.

*The use of Lorang et al. (2000) to determine the minimum stable stone size*

The equations developed by Lorang et al. (2000) use stone properties and runup characteristics to calculate the minimum stable stone size (i.e., the size of the smallest stone that will not be moved by the design wave conditions). This equation could provide an upper limit for cobble size, as we also recommend that the largest cobbles should move under the expected hydrodynamic conditions. The equations were shown in Lorang (2000) to be an improvement over the stability number given in , which was discussed in this paper in the context of results from van der Meer & Pilarczyk (1986) and CIRIA (2007). However, the results were tested on a boulder beach rather than a composite beach, so we rate this tool at a medium level of confidence and encourage further testing.

*Observations of cobble specifications at nearby composite beaches*

Observations of cobble specifications from nearby composite beaches may provide good guidance on the cobble sizes and shapes that are appropriate for the wave conditions in any given area. We rate this tool as medium-high confidence, because there may be site specific factors that could cause a difference in the appropriate cobble specifications from the nearby composite beach to the project site.

## 3.2 Crest Elevation:

*Design crest elevation should be determined based on runup predictions*

We believe that runup predictions are the best way to design the crest height of the dynamic revetment. We have high confidence that it is conservative to set the design crest height at an elevation that meets project goals based on predicted runup. As we can think of no other factor that would control design crest height, we rate this recommendation high confidence.

*The use of Blenkinsopp et al. (2022) to determine runup elevation*

The runup equation by Blenkinsopp et al. (2022) was developed for and tested on composite beaches. Therefore, we rate it with the highest confidence of the runup equations suggested. However, the equation has only been tested for North Cove, WA, and was only tested during periods in which the still water level was above the cobble toe. Therefore, we rate it with medium confidence, because the equation could still benefit from more extensive testing in the PNW.

*The use of van Gent (1999, 2001) to determine runup elevation*

The main feature of the van Gent (1999, 2001) runup equation that applies to cobble beaches is that it was developed for shallow foreshores with a steep backing berm. However, the equation was not tested on cobble or on the wave conditions in the PNW, so we rate the equation with a low-medium confidence.

*The use of Stockdon et al. (2006) to determine runup elevation*

Stockdon et al. (2006) proposed a widely used runup equation. While not developed with composite beaches in mind, it has been tested in Oregon (Allan 2005) using an average of the beach and cobble slope. We rate the equation with low-medium confidence because it was not developed for cobble berms.

*Observation of crest height at nearby composite beaches*

Observations of crest height and the condition of the backshore on nearby composite beaches can be useful to determine a range of typical cobble berm crest heights in the area. Observations of the condition of the backshore may also be useful to determine if overtopping is occurring. We rate this method with medium-high confidence, because site specific factors may cause crest heights that are appropriate for the observation site to not be appropriate for the project site.

## 3.3 Slope:

*The slope of the project should be expected to evolve over time in response to wave conditions.*

Slope evolution has been observed in the lab (e.g., Bayle et al. 2020, Foss et al. 2023, Ahrens 1990, van der Meer and Pilarczyk 1986), and the field (e.g., Allan et al. 2005, Bayle et al. 2021, and project examples given in this manuscript). Therefore, we have high confidence that slope evolution will nearly always occur and should be expected. However, predicting the slope evolution is an area for future work.

*The initial constructed design slope is not an important design consideration.*

van der Meer and Pilarczyk (1986) and Ahrens (1990) observed in a laboratory experiment that the initial constructed slope was not related to the final slope of a dynamic revetment (van der Meer with the caveat that the ratio between the wave height and the D50 must be greater than 10-15 for this statement to hold true). However, both of these tests were done on gravel beaches (i.e., with no sand). Additionally, based on personal experience, in the PNW, we know that the transition to an equilibrium slope may take time. We also believe that a slope that is significantly greater than or less than the equilibrium slope could impact the performance of the dynamic revetment while it evolves. Therefore, we rate this statement as medium confidence until it can be tested on composite beaches.

*Observations of cobble slope at nearby composite beaches*

We rate this statement with medium-high confidence because, while cobble slope is a relatively easy parameter to measure in the field, there could be site-specific factors that could cause the observations from one beach to not apply to the project site.

*The use of van der Meer and Pilarczyk (1986) to predict slope evolution*

van der Meer and Pilarczyk (1986) created a formula that predicted the equilibrium slope based on the wave height, wave period, number of waves, and D50 of the rock. Foss et al. (2023) tested the equation's capability of predicting their observed laboratory results, and found that the wave excursion and the distance between the shoreline and the revetment crest agreed with the equation, but the crest height did not. Therefore, we rate this equation with low-medium confidence for the prediction of profile evolution.

*The use of Powell (1993) to determine equilibrium slope*

Powell (1993) developed an equation for calculation of the equilibrium slope of a shingle beach. The equation is based on the wave steepness, sediment gradation, and the relationship between the wave height and the D50. Powell states that the equation was limited in application to shingle beaches. However, in the design process for the dynamic revetment in Westport, WA, this equation was used and gave similar results to the cobble slopes observed in Allan et al. (2005). Therefore, we rate this tool with a low-medium confidence.

## 3.4 Toe elevation:

*The expected toe elevation should be designed no lower than MHW*

We rate this statement with low-medium confidence because there are very limited observations of the impact of toe elevation on dynamic revetment performance. In the absence of other literature, we make this recommendation based on existing project information (i.e., none of the example projects in this manuscript have their toe constructed below high water), and on personal observations of natural and engineered composite beaches.

*The design toe may lower due to seasonal beach change and slope equilibration.*

We rate this statement with medium-high confidence. The toe location may migrate due to seasonal beach changes as the sand erodes during energetic wave events in the winter and as the cobble slope equilibrates to the hydrodynamic conditions.

*Observation of toe elevation at nearby composite beaches*

We rate this statement because, like other field observations, the observations from nearby beaches may not translate to the project site. In addition, observations of the cobble toe in the field are impossible to separate from the signal of sand erosion and accretion at the site, as sand can cover or expose the cobble toe. However, observations of a range of cobble toe elevations at different times throughout the year may be helpful to determine a range for the cobble toe elevation.

## 3.5 Crest Width:

*Crest width can be used as a tunable parameter to achieve the desired cobble volume*

We rate this statement with medium-high confidence because, as the dynamic cobble berm revetment is expected to reshape, the crest width may change. If it is important to have enough cobble on the beach to account, for example, for expected alongshore losses, the crest width could be altered.

*A wider crest may reduce the chance of overtopping*

Blenkinsopp (2022) showed observations of overtopping rates on a dynamic cobble berm revetment in a laboratory experiment and observed higher infiltration rates than would be expected on a sandy beach. Therefore, they hypothesized that rates of overtopping could be reduced by widening the dynamic cobble berm revetment. We rate this statement with medium-high confidence because it has been shown in the lab, but not tested at different kinds of field sites.

## 3.6 Volume:

*There is a critical volume threshold that determines a dynamic revetment's success or failure under certain wave and water level conditions.*

We rate this statement with medium confidence because, while the critical volume idea was rigorously tested in the laboratory, it is uncertain if the results translate to the field, especially because the laboratory setup did not include sand.

*Observations of nearby composite beaches*

We rate this statement with medium confidence because, like other field observations, the observations from nearby beaches may not translate to the project site. In addition, the determination of cobble volume can be difficult on natural beaches, as part of the cobble is typically infilled with sand, making it unclear what portion of the profile should be used to calculate the cobble volume. Additionally, care should be taken to ensure that the observed composite beach is not experiencing erosion, as that may make it an unsuitable reference.

*The use of Ahrens (1990) to determine critical volume*

Ahrens (1990) provides an equation to calculate the critical volume of a dynamic revetment based on the expected hydrodynamic conditions. In their study, the critical volume is one that leads to an increase in crest height with no overtopping under the expected conditions. However, the Ahrens equation was developed in a small-scale laboratory experiment for a setup that did not include sand. Therefore, its relevance to the dynamic cobble berm revetments considered here is questionable. We therefore rate the Ahrens (1990) equation for critical volume with medium confidence.

## 3.7 Alongshore transport:

*Alongshore transport rates should be considered when deciding on maintenance volumes and intervals.*

While there may be other factors that lead to the choice of maintenance volumes and intervals, we are confident that alongshore transport rates should be considered. Existing projects, including North Cove, Washington and the South Jetty of the Columbia River, Oregon, have seen significant alongshore movement of cobble leading to maintenance needs.

*The use of Kamphuis (1991) to calculate alongshore transport rate.*

We rate this alongshore transport tool with low-medium confidence because it was developed for sandy beaches, and, while tested on gravel beaches, has not been experimentally tested on composite beaches. However, Kamphuis (1991) was used to estimate the required maintenance volumes at dynamic revetment project at the South Jetty of the Columbia River, and the estimate was accurate within an order of magnitude.

*The use of Van Wellen et al. (2000) and van Rijn (2014) to calculate alongshore transport rate*

We rate these two alongshore transport tools with low confidence because they were developed for gravel beaches, which have little to no sand, rather than composite beaches, which have a flat sandy foreshore that significantly changes wave behavior and sediment transport. They have not, to our knowledge, been tested or applied to composite beaches.

## 3.8 Berm Evolution:

*The majority of cobble will remain on the berm.*

We rate this statement with medium-high confidence because both Bayle et al. (2020) and Foss et al. (2023) observed cobbles remaining on the berm during lab experiments in which alongshore transport was not considered. Further work on the capacity of rip current to transport cobble offshore under bed load transport need to be undertaken. It should also be noted that the footprint of the berm may evolve over time, resulting in seaward transport of cobbles while they still remain a coherent part of the berm.

*If poorly sorted, angular cobble is used, a filter layer of smaller gravel will form at the base of the cobble.*

We rate this statement with medium-high confidence because the formation of a filter layer from poorly sorted, angular cobble has been observed in the field (Bayle et al. 2021) and the laboratory (Foss et al. 2023). However, more testing and observations at other sites would improve our confidence in this statement.

*The berm will grow in elevation in response to rising water levels*

The increase in elevation of dynamic revetment crests has been observed in the laboratory (Ahrens 1990, Foss et al. 2023). However, the conditions under which the crest elevation will increase are unclear. It may require for example, poorly sorted material, angular material, or a sufficient material volume. The conditions under which crest elevation increase will occur should be further tested in the lab and the field, therefore, we rate this statement with medium confidence.