RESEARCH LETTER:

Influence of living shoreline elements on wave run up elevations

By

Ashley Ellenson,[1] David Revell, Matt Jamieson, and Sam Blakesley

Integral Consulting Inc., 200 Washington Street, Suite 201, Santa Cruz, CA 95060

1) aellenson@integral-corp.com

ABSTRACT

Nature-based coastal protection, also known as engineering with nature or living shorelines, is becoming increasingly popular due to its dual benefits of reducing coastal flooding and providing ecological and recreational opportunities. In many coastal areas experiencing chronic erosion, changes in sediment supply, composition, and grain size are significant contributing factors to shoreline recession. One living shoreline strategy to consider includes the application of cobbles over more traditional sand nourishments. On sandy beaches that experience high-energy wave conditions, the introduction (or reintroduction) of cobbles can mitigate backshore erosion. Cobble-backed beaches have been found to mitigate the effect of coastal erosion and flooding in laboratory settings and field observations, and they have recently been piloted in locations such as Cape Lookout State Park in Tillamook County, Oregon, and Surfers Point in the City of Ventura, California. However, there are no formal engineering guidelines stipulating the calculation of wave run-up on cobble-backed beaches. This study applies three different wave run-up equations on a living shoreline design (i.e. mixed sand and cobble berm-backed beach) in Malibu, California, and compares the predicted run-up levels with existing condition flood levels for typical and eroded conditions. The different wave run-up equations were designed for cobbles only, revetments, and composite beaches, respectively, where the composite beach equation was most applicable to project design. For typical beach conditions (higher levels of sediment accretion resulting in shallower beach face and berm slopes), all three equations showed a reduction in wave run-up values. When applied to worst-case conditions (i.e. scoured by a creek channel and steeper fronting beach slopes), the equation most applicable to the design showed the highest reduction of total water levels. A sensitivity analysis found that the cobble-backed beach equation predicted the most consistent values of run-up (run-up values changed the least), even when input parameters (slope and water depth) changed. This study shows that cobble-backed beaches hold promise to mitigate coastal flooding in appropriate areas, in addition to being a natural solution for areas experiencing erosion. This study also points to the need for more studies and field observations to validate the run-up levels determined here.

KEYWORDS: Living shorelines, cobble berms, composite beaches, wave run-up.

Manuscript submitted 6 February 2023; revised & accepted 12 May 2023.

In the United States, coastlines are increasingly vulnerable to the combined effects of sea-level rise and increased frequency of major storms, the impact of which has already cost municipalities and the federal government billions of dollars in rebuilding efforts (Sutton-Grier *et al.* 2015). As traditional defense structures (e.g. coastal seawalls) are being recognized as expensive and potentially ecologically destructive (Morris *et al.* 2018), implementing nature-based protection strategies is gaining more popularity (Arkema *et al.* 2013; Sutton-Grier *et al.* 2015). Nature-based approaches work by harnessing inherent ecological and physical processes to the benefit of both people and the coastal environment. The strategies utilize native sediments to build coastal resilience through the support and creation of natural elements such as dunes, coral reefs, barrier islands, and coastal vegetation (Bridges *et al.* 2013). These elements also provide social and ecological benefits such as increasing habitat and improving water quality while maintaining a more "natural" beach that can be enjoyed by beach visitors (Arkema *et al.* 2017).

Beach engineering is a strategy used within nature-based solutions to mitigate coastal flooding that results from high total water levels (TWLs), of which wave run-up is one component. The specific type of beach engineering considered herein is the application of larger sizes cobbles (2.5 in. < D_{50} < 24 in., between baseballs to watermelons) to protect the foreshore and backshore (i.e. the zone between the still water line and the crest of a dune or cliff). This approach is based on geomorphic principles using native materials that would naturally be found in the watershed and transported downstream to the lagoon and beachfront, such as cobbles, gravels, large woody debris, and sands that transport in the littoral system (Komar and Allan 2010). Cobbles have been observed at beaches in Southern California (Torrey Pines, Cardiff, Carlsbad, and Encinitas) as appearing seasonally when incident wave energy is higher in the winter months (Everts *et al.* 2002; Matsumoto *et al.* 2020), and is depicted in Figure 1. There are several examples of cobble installations for shoreline protection along the West Coast to date, including in Oregon (Allan and Komar 2004), California (Winters *et al.* 2020), and Washington (Weiner *et al.* 2019). The design in Oregon included a berm slope of 7-10 degrees, rose 3-4 m along 12 m cross-shore and 300 m alongshore, and included the installation of vegetated sand dunes. Allan and Komar (2004) found that despite the structure not being built high enough to avoid overtopping, the berm remained intact and protected the backshore from erosion. The dynamic revetment in North Cove, Washington,

Figure 1. Project site where cobbles are naturally found. Image taken at the location of the star in Figure 2. The beach fronting the proposed cobble berm is composed of finer grained quartz and has a lower beach slope, and is dissipative in nature. The proposed engineering with nature element, the cobble berm, has a steeper slope and is more reflective in beach type. Together, the dissipative and reflective characteristics combine to form a stable, composite beach.

spanned approximately 2 km. Monitoring activities found that the revetment showed little to no landward retreat, and was also successful in protecting the backshore from erosion (Weiner *et al.* 2020).

Cobbles can help stabilize a sandy beach because their application results in a beach that has characteristics of two stable beach types (dissipative and reflective) called a "composite" beach (Jennings and Shulmeister 2002). On a composite beach, the seaward side of the beach consists of fine grain sand with a shallower beach slope (3:100-1:10) in which spilling waves dissipate energy across the surf zone. This is known as a "dissipative" beach type (Wright and Short 1984). The landward side of the beach consists of larger cobbles or gravel with a steeper beach slope (1:10-1:6), where plunging waves might reflect off the steep beach slope (see Figure 1). This is known as a "reflective" beach type (Wright and Short 1984). The two beach types have characteristics that are the least likely to evolve given changing wave conditions; therefore, composite beaches have the stability benefits of the two types of beaches (Allan *et al.* 2005).

Cobbles dynamically respond to incident wave attack and corresponding water levels. In contrast with sand, cobbles are more likely to migrate landward than seaward with increasing water levels (Komar and Allan 2010). The most detailed laboratory study to date (Bayle *et al.* 2020) found that cobbles moved as a coherent structure, maintaining the majority of the cobble volume as they responded to the hydrodynamics of swash and increasing water levels. Over time, the cobbles established an equilibrium elevation in response to the frequency and intensity of wave exposure, resulting in an increase in crest height and steepening of the berm slope. Observations showed that the slope steepened because the underlying sand was transported seaward, causing the cobbles to sink. Additionally, shoreward motions by swash and vertical motions by gravity caused more seaward cobbles to roll over in a landward direction, eventually being transported up the face to the crest causing the crest height to increase. Finally, cobbles absorb and dissipate erosive wave energy in the pore spaces between the individual sediment clasts (Bradbury and Powell 1992). In a lab study, Foss *et al.* (2023) found that the poorly sorted, angular cobble resulted in a greater increase in crest height than the well-sorted, rounded cobble after wave attack in a laboratory study. Foss *et al.* (2023) also found that berm slope would likely change in response to wave attack and is therefore not an important design consideration. Because of their mobile character, cobbles can also be transported along the beach more rapidly than larger riprap, thereby requiring more often nourishment and maintenance compared to traditional engineering revetments. In some instances, cobbles can become projectiles as they are mobilized.

Both Bayle *et al.* (2020) and Blenkinsopp *et al.* (2022) observed reductions in wave run-up and overtopping with the installation of cobbles on a sandy beach, demonstrating that cobbles are an effective strategy at stabilizing shorelines. However, neither the Federal Emergency Management Agency (FEMA) nor the U.S. Army Corps of Engineers (USACE) has provided specific engineering guidelines for cobble-backed beaches with regards to which equations are most applicable and how to design volume, berm slope, cobble size or density. The available engineering guidelines provide calculations with respect to gravel beaches or revetments that incorporate porosity or friction, but not cobbles explicitly.

Figure 2. Project site and shore-normal transects used for analysis herein. The eastern transect runs toward the vertical seawall and upland over the pool and pool house; the central transect runs over existing rip rap revetment; and finally, the western transect runs closer to the Malibu Lagoon and upland through a heavily vegetated area. The slope of the beach is mildest to the west and increases to the east. The cobbles are to be installed generally in the areas of active erosion (outlined in magenta). The star denotes the location of the image in Figure 1. Image courtesy of Google Earth.

This study focuses on a proposed project at Surfrider State Beach in Malibu, California, where seasonal changes in TWLs and exacerbated erosive conditions threaten a state park and archeological site. The current threat of flooding to cultural resources appears to be related to several physical processes with compounding feedbacks: high spring tides, wave run-up, and fluvial scour from Malibu Creek. California State Parks is undertaking a project aimed to mitigate the erosion and protect the cultural resources, however, they would like to maintain public access to the beach and surf quality. They are therefore interested in using an innovative design with nature approach that is viewed as a pilot project and an interim 5-10 year solution in mitigating erosion.

Given that current engineering guidelines do not suggest an equation for a design-with-nature project, a new methodology was explored and compared against existing methodologies to predict TWLs at the site. The study herein showcases the application of several different equations to predict TWLs of the living shorelines design.. The different equations encompass: 1) a traditional coastal engineering perspective; 2) a cobbles-only perspective; and 3) a cobble-backed, composite beach engineering equation (Blenkinsopp *et al.* 2022). The study includes a comparison of the different run-up calculations applied to the project site and determines the sensitivity of the predictions to design elements such as berm slope.

PROJECT SITE AND DESIGN

The project site description includes a description of the project design, associated important physical processes contributing to erosion and the geomorphic properties of the site. The project site is Malibu Beach State Park, a south facing location that includes where the Adamson House, a California Historical Landmark, is located. The beach is located within the Santa Monica littoral cell, where bluff erosion is thought to contribute approximately 60% of the sediment supply (150,000 yd^3/year) (Patsch and Griggs 2007). The Adamson House sits on top of a 12-15 ft terrace with a gently sloping beach fronting the terrace as illustrated in Figure 2. The property faces imminent erosion that has already damaged a bath house and the beach access. Emergency riprap and a seawall have been installed in front of the site, reducing the amount of sediment available to nourish the beach and potentially causing the beach width to shorten.

Historical imagery shows that the bar-built estuary on site cycles seasonally, typically closing in the summer and opening in the winter, as illustrated in Figure 3. The dominant littoral drift direction is west to east, with reversals occurring with southern waves (Patsch and Griggs 2007). In the spring, creek flows decline following a decline in rain, and the Malibu Creek outlet migrates from west to east due to wave driven currents. The eastern outlet contributes to erosion through a lowering of the beach profile in front of the Adamson House. Once the beach is scoured by the channel, summer southerly swells begin occurring. Short period waves, often associated with windy spring conditions, rapidly mobilize beach sand. The combined effect of southerly swells and an eastern creek alignment narrows the beach and causes erosion.

The project site is also subject to the impacts of reduced sediment transport and cobble supply from Malibu Creek

Figure 3. Aerial view of site, including the three transects and Malibu Creek. Images show how creek alignment adjusts and seasonal wave energy works in conjunction to increase or decrease beach width. In the first two panels, the estuary is closed, and the river is aligned west to east in front of the property. In the third (top right) and fourth (bottom left) panels, the creek is aligned north to south with an old channel in front of the property. Finally, the final two images (bottom center and bottom right), the outlet is open and the beach in front of the property is reduced.

(Inman and Jenkins 1999; Patsch and Griggs 2007). As is the case with many Californian beaches, cobbles are native to the site (Figure 1). Rindge Dam, some 2.6 mi inland from the project site, has trapped an estimated 800,000 yd^3 of sediment, including approximately 200,000 yd^3 of coarse grain gravels and cobbles (USACE 2017). This diminished sediment supply results in reductions in sediments available to the littoral system and can exacerbate erosion at the project site. With Rindge Dam poised for removal in the near future, positive benefits such as an increase in local sediment supply may be in store for the site (State Parks personal communication).

The project design to mitigate erosion is the installation of a cobble berm in the backshore in a living with nature strategy and is depicted in Figure 4. Specifically, the cobbles would extend below the still water line (~2 ft North American Vertical Datum of 1988 [NAVD 88]) and above the terrace (~10-15 ft NAVD 88) at the areas of active erosion at the site (see Figure 2). The installations would be in the western portion and eastern portions flanking the Adamson House and the existing revetment and span approximately 290 ft and 100 ft, respectively, with a D_{50} of approximately 4 in. Since the sand accretes and erodes seasonally, there would be times when the accreted sand is above the berm toe ("max" sand elevation, Figure 4), and times when the sand is eroded and the channel runs in front of the berm, resulting in scour at the berm toe ("min" sand elevation, Figure 4).

Table 1.
Geomorphic characteristics of transects used in the run-up analysis.

Transect	Beach face slope	Terrace toe (ft NAVD 88)	Terrace crest (ft NAVD 88)
Eastern	~0.07	10	15
Central	~0.045	~9	12
Western	~0.030	~9	12

The beach face slope was derived from the distance between the 2-ft and 7-ft contours for the beach face slope (NAVD 88). Beach face slope was determined by taking the average slope for all years with available data. One standard deviation was applied to determine the higher and lower bounds of the slope.

METHODS

Tides and wave conditions

This section provides information about the tide and wave values used in the TWL and run-up calculations. The project site is sheltered from the largest winter waves by offshore islands and headlands in the southern California Bight; however, the project site is relatively exposed to west and southerly swells. Tides along the southern California coast are characterized as mixed semidiurnal, with two daily highs and two daily lows. The closest tide gage station is at Santa Monica (Station: 9410840), where the mean higher high water is 5.24 ft relative to the NAVD 88, and was the value used in the TWL calcuation.

The U.S. Geological Survey (USGS) modeled future wave conditions (height and period) for 100+ years at nearshore locations (Hegermiller *et al.* 2017) that were used in this study. The expected project life is 5-10 years, therefore a 25-year recurrence interval was selected for use. The 25-year wave heights and periods were found by applying a block maximum extreme detection with a 1-year block size (Coles *et al.* 2001) to the USGS wave data. The 25-year wave height and peak wave period and the associated 5th and 95th percentiles are 8.96, 7.84, and 10.9 ft and 25, 22, and 25 seconds, respectively. When necessary, the significant wave height was reverse shoaled to offshore wave height using linear wave theory, and peak wave period was converted to mean wave period using a conversion factor of $T_m = T_p/1.1$ following Van der Meer (2002).

Geomorphic conditions: Transects

Three cross-shore transects were used for this study, which are illustrated in Figure 2. These transects were used as locations to generate beach profiles with elevations pulled from six years: 2002, 2007, 2010, 2014, 2016, and 2020.

All elevation data sets were resampled to a common resolution of 1.5 ft. Beach

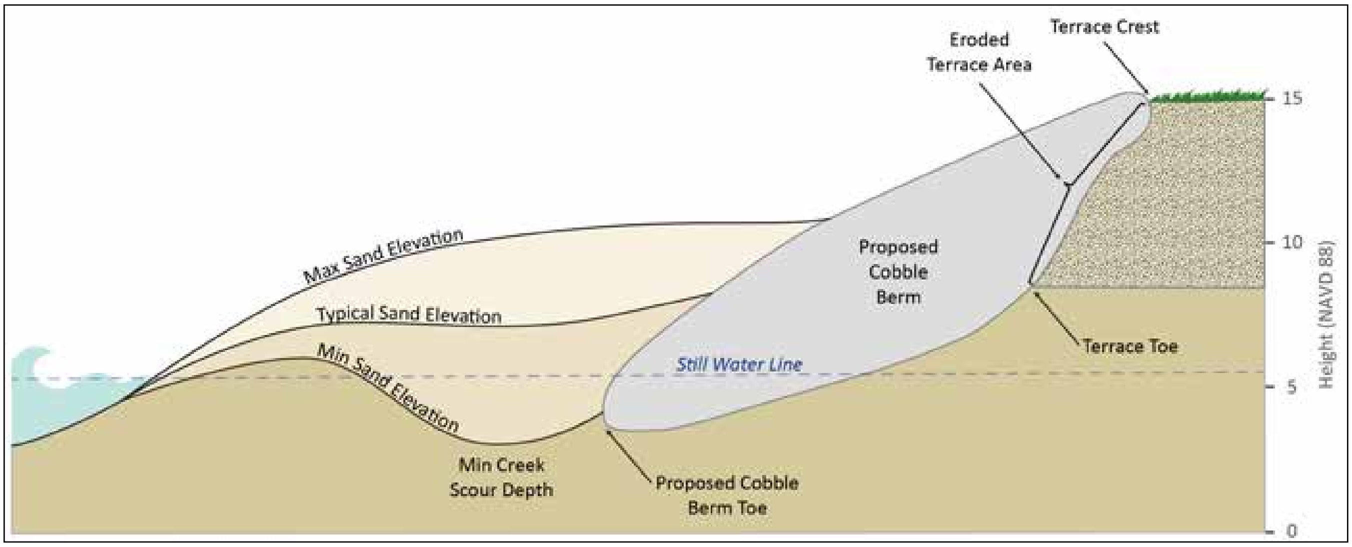

Figure 4. Profile idealization used in the design analysis. A beach will have different sand elevations given the amount of sand accreted in the system and the given season. The different profiles represent maximum, typical and eroded conditions. Typical and minimum sand elevations are considered in the scenarios. The cobble would be placed fronting the bluff and have a steeper beach profile than the finer grained sand, resulting in a composite beach.

Table 2.
Scenarios and design parameters.

Scenario	Description	Parameters
Typical	Open sandy beach with shallow slope leading to steeper cobble revetment	0.04 < beach slope < 0.08 Berm slope = 0.14 Water depth at the toe = 1 ft
Worst case	Open sandy beach with shallow slope leading to steeper cobble revetment where the creek runs in front of the toe of the revetment	0.04 < beach slope < 0.08 Berm slope = 0.2 Water depth at the toe = 3 ft

profiles were then extracted for each transect and were visually analyzed to identify geomorphic features for the wave run-up analysis. For each data set, the height and location of the terrace toe and terrace crest were determined. The geomorphic feature slopes used in this study are presented in Table 1 and illustrated in Figure 3.

Scenarios

For each transect, run-up levels were calculated for typical and worst-case conditions, which are shown conceptually in Figure 4. Typical conditions simulated times when there was high sediment accretion and the creek outlet was farther to the west, away from the Adamson House, quantified as lower water depths at the berm toe and shallower beach and cobble berm slopes. Worst-case conditions simulated conditions when there was low sediment accretion and the creek channel aligned in front of the Adamson House, quantified as deeper water depths and steeper beach and cobble berm slopes. This study applies three different run-up equations for the two different scenarios and compares against existing conditions. The two scenarios are detailed in Table 2.

Equation 1:

$$H_{toe} = 0.87 d_{toe}$$
$$R_{2\%} = 0.19 H_0 + 3.11 H_{toe} tan\beta_{berm} + 0.26$$

Equation 2:

$$R_{2\%} = H_{toe} 1.75(\gamma_f \xi_0) \quad \text{for } \xi_0 < 1.8$$
$$R_{2\%} = H_{toe} \gamma_f (4.3 - \frac{1.6}{\sqrt{\xi_0}}) \quad \text{for } \xi_0 > 1.8$$

Equation 3:

$$R_{2\%} = 0.21 D_{50}^{-0.15} tan(\beta_{berm}) T_m H_{toe}$$

Run-up equations

Existing run-up values were calculated using Stockdon *et al.* (2006). For calculating run-up levels at the proposed cobble berm, three run-up equations were used:

1) Composite Beach: equation developed based on field observations and laboratory settings of a cobble-backed beach and is most applicable to this scenario (Blenkinsopp *et al.* 2022).

2) Revetment Structure: equation developed in a laboratory setting of an engineering revetment and is included in FEMA guidelines for run-up calculation (Van der Meer 2002).

3) Gravel Beach: equation developed from field observations and modeling output of a gravel beach (Poate *et al.* 2016).

The first equation considered was the Composite Beach equation by Blenkinsopp *et al.* (2022), an empirical parameterization of the highest 2% of wave run up elevation ($R_{2\%}$) based on field experiments at dynamic cobble berm revetments, similar to the design proposed in this study, which has two steps: *See Equation 1.*

Where d_{toe} is depth at the toe of the cobble berm, H_0 is offshore significant wave height, H_{toe} is the wave height at the toe of the berm and $tan\beta_{berm}$ is the slope of the cobble berm. The first step calculates wave height at the toe of the berm based on a parameterization derived from the field experiments. The second step calculates the wave run-up. The data from Blenkinsopp *et al.* (2022) were taken from beaches in England (Saltburn by the Sea and Westward Ho!) and the United States (North Cove, WA, USA) where average offshore significant wave height values ranged from 2.13-8.33 ft and mean wave period ranged from 5-15.4 seconds.

The second equation considered was the Revetment Structure equation developed in Van der Meer (2002), also used by the Technical Advisory Committee on Water Defences (TAW) in the design of dikes. The TAW method is recommended in the *FEMA Guidance for Flood Risk Analysis and Mapping* (2021): *See Equation 2.*

This formulation relies on the beach regime defined as the Iribarren number at the toe of the revetment defined as $\xi_0 = tan(\beta_{berm})/\sqrt{s_o}$. s_o is wave steepness; $s_o = 2\pi H_{toe}/gT^2_m$. The TAW formulation includes a ceiling on run-up values for high Iribarren numbers. The Iribarren number quantifies the steepness of the beach relative to the steepness of the waves; a steeper beach with short-crested waves will have a higher Iribarren number relative to a shallower sloped beach with long-crested waves. In this study, all Iribarren numbers were greater than 1.8. A friction factor, γ_f, was included to consider the retarding effect of friction due to the cobbles, which was taken here to be 0.7 following Van der Meer (2002).

The final run-up equation considered is the Gravel Beach equation developed by Poate *et al.* (2016): *See Equation 3.*

Where D_{50} is the median grain size of the gravel used, taken here to be 40.3 in. The Gravel Beach equation is an empirical parameterization of wave run-up based on both field experiments and modeling (X-BEACH-G) at gravel beaches. The data in the Poate *et al.* (2016) were taken from a variety of beaches in England, where significant offshore wave height reached maximum values of 6-24 ft, and maximum periods reached 7-22 seconds. In this study, the design was for a composite beach; however, the berm itself can be modeled as a steep gravel beach. Therefore, the Gravel Beach equation was considered applicable starting at the toe of the berm.

For all scenarios, H_{toe} was calculated using Step 2 from the Composite Beach equation using water depth at the toe of the berm as in Table 2. H_{toe} was different than the wave height in the breaker zone offshore because much of the wave energy has dissipated by the time it reaches the toe of the berm, and so the wave height at the toe of the berm is smaller than wave height at the breaker zone. H_{toe} will determine how much energy will be dissipated on the cobble berm. TWLs were calculated as a sum of run-up, mean higher high water (5.4 ft), and setup (assumed to be 1 ft).

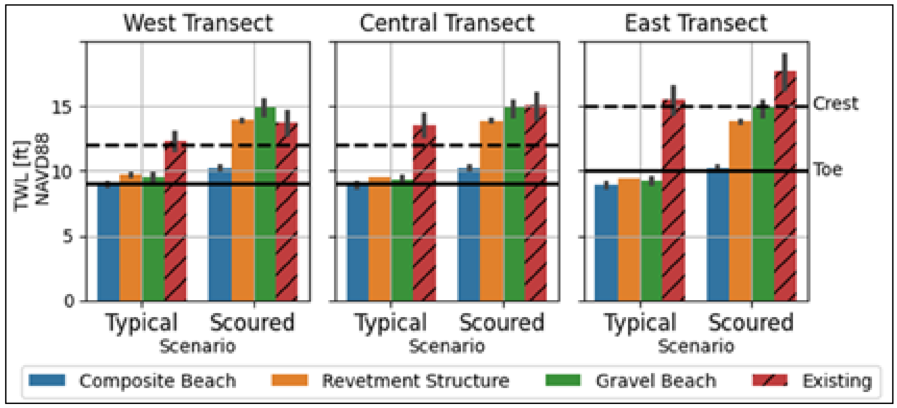

Figure 5. Runup elevations in feet from the scenario analyses. The bars show the mean, and the error bars show the results from the 5th and 95th percentile 25-year wave heights from the extreme value analysis. The equation best suited for the project design, the Composite Beach formulation, predicted the lowest TWLs that never overtop the bluff crest.

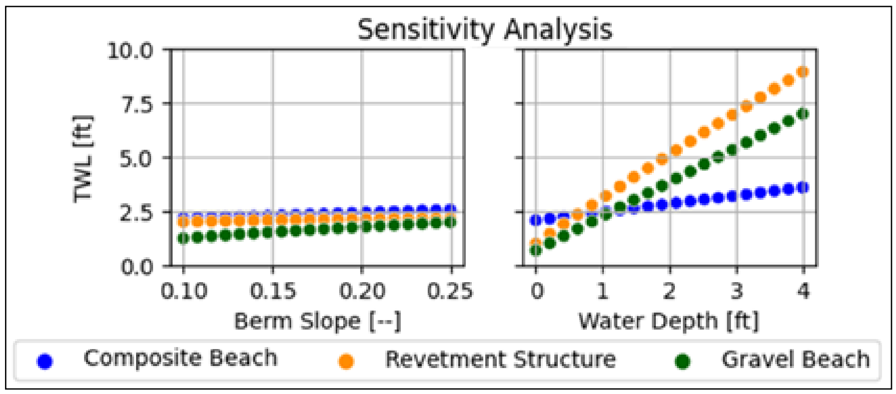

Figure 6. Sensitivity analysis of the equations to berm slope (left panel) and water depth at the toe of the structure (right panel). The wave height and peak wave period were held to 6.3 ft and 18 s during the sensitivity analyses. The equations were less sensitive to berm slope and more sensitive to water depth at the toe of the structure, and the Composite Slope equation was the least sensitive of all.

RESULTS

Results for all the wave run-up formulations showed that the design for the project, represented in the Composite Beach equation, predicted total water levels that never overtopped the terrace crest and only slightly flooded the terrace toe, whereas the other equations predicted overtopping or near-crest TWLs for worst case ("scoured") conditions. Figure 5 shows the run-up elevation results for each transect and each scenario. For all transects, TWLs were higher for the worst-case conditions than typical conditions, as was expected. Between the transects, the eastern transect, with the highest beach slope, had the highest run-up elevations for both typical (TWL ~11 ft) and for worst-case conditions (TWL ~14 ft).

For worst-case conditions, the Revetment Structure and Gravel Beach equations predicted overtopping of the crest for the Western and Central Transects and near-crest TWL for the eastern transect (TWL~14ft). The Composite Beach equation still only predicted flooding near the toe (TWL~10 ft). Therefore, the Composite Beach equation predicted significantly greater run-up reduction compared to existing and the other design equations: 55 percent compared to 15 percent and 4 percent reduction for the Revetment Structure and Gravel Beach equations, respectively.

An analysis was performed to determine how sensitive the three equations were to input parameters. In the sensitivity experiments, the wave height and peak wave period were held constant (H_s=6.6 ft, T_p=18 seconds), and the berm slope and depth at the toe of the berm (d_{toe}) were varied individually.

The sensitivity analysis showed that the depth at the toe of the barrier is more important than berm slope for estimating run-up on a cobble berm. Additionally, Foss *et al.* (2023) found that berm slope is likely to change to changing incident wave conditions, and therefore is not as important of a design parameter. Between the equations, the Revetment Structure and Gravel Beach equations were more sensitive to the depth at the toe of the structure than the Composite Beach equation (Figure 6, right panel). While both the Revetment Structure and Gravel Beach estimations of run-up more than doubled for the range of d_{toe} values, the Composite Beach formulation only increased by 50%. The greater d_{toe} resulted in a greater wave height at the toe of the structure that can run up onto the structure. The equations were less sensitive to the changes in berm slope (Figure 6, left panel); the values only increased marginally (TWL only increase about 2 ft for all equations). The lower sensitivity of the Composite Beach equation to water depth explains why the Composite Beach equation predicted significantly lower run-up values than the other two equations for worst case conditions where the water depth was higher.

An additional parameter that could be of importance, but is not included in Blenkinsopp *et al.* (2022), is the length and/or location of the cobble berm in the cross shore, which can increase the exposure of wave run-up to cobbles. Assuming a monotonically decreasing beach profile, a cobble berm placed farther into the cross-shore increases the cross-shore length of cobble exposed to run-up, as well as increasing d_{toe}. However, as discussed above in the Introduction section, these cobbles would likely be transported by waves inland and upward until they reached an equilibrium with the existing storm wave energy. Using Blenkinsopp *et al.* (2022), placing the berm farther into the cross shore would cause an increase in $d_{toe,}$ and would increase run-up elevations, without accounting for the mitigating effect of increased length of the cobble berm that could be absorbing or dissipating wave energy.

DISCUSSION AND CONCLUSIONS

The study focused on predicting wave run-up changes based on a proposed living shoreline project. The project site in Malibu, California, is subject to the compounding hazards of wave run-up and creek scour, resulting in erosion. A proposed design to protect the structure from a 25-year wave event included an "engineering with nature" design: the installation of a cobble berm, where the cobbles are naturally found in the watershed and littoral system but whose supply has been reduced from reaching the beach due to a dam blocking sediment up-river. Engineering with nature designs have been increasing in popularity; there are at least three well documented projects in California (Surfers Point), Oregon (Komar and Allen 2010), and Washington (Weiner *et al.* 2019) where cobbles have been added to the backshore. Monitoring of these projects has found that even if overtopping occurred, the cobbles have protected the backshore from erosion. Additionally, cobble-backed beaches are preferred in places where public access and aesthetics would like to be preserved. Observations from the cobble-backed beach in Washington were included in the Blenkinsopp *et al.* (2022) study, but not included in the final parameterization of wave run-up. There are no formal engineering guidelines to advise which equation is most fitting to use to design elevations of structure heights on cobble-backed beaches. The goal of this study was to compare several run-up equations that were potentially appropriate for cobbled-backed beaches and to evaluate the potential effect of the proposed project on wave run-up.

The effect of the cobble berm was determined in typical and worst-case conditions and compared to existing conditions. The popular Stockdon *et al.* (2006) parameterization was applied for existing conditions, and three different parameterizations were applied for the design conditions. The parameterization developed for cobble-backed beaches (Blenkinsopp *et al.* 2022) equation estimated the lowest TWLs overall. Traditionally, hard structures, such as seawalls, revetments, or large rip-rap have been used for shoreline protection, which is modelled here with Van Der Meer (2002). The revetment structure equation predicted overtopping of the terrace crest. The influence of structural elements within a revetment is represented as a frictional factor, reflecting that the revetment does not respond dynamically to changing water levels, but instead remains static. Run-up, therefore, simply runs up the structure and the height that it reaches is a strong function of structure slope. In contrast, implicit within Blenkinsopp *et al.* (2022) is the dynamics of the cobbles; the cobbles roll over each other to respond to changing water levels and wave energy is dissipated between the cobbles, making the cobble design more robust to changes in water levels.

The third equation applied was designed for gravel beaches, Poate *et al.* (2016). This equation also estimated overtopping of the berm crest for worst-case. The Poate *et al.* (2016) equation was designed for pure cobble beaches which are characterized by a steep slopes and short surf zones (i.e. reflective beach type). In contrast, the Blenkinsopp *et al.* (2022) parameterization was designed for a composite beach that incorporated a long surf zone (i.e. dissipative beach type) where wave energy could be dissipative before reaching the reflective section of beach. The incorporation of both beach types within the development of the parameterization could contribute to why the Blenkinsopp *et al.* (2022) parameterization predicted lower TWLs overall.

Blenkinsopp *et al.* (2022) was the most applicable equation in this case study because it directly accounts for the unique characteristics of a composite beach being proposed in this project (i.e., different beach slopes due to disparate grain sizes). While this study executed a thorough analysis and discussion of different run-up formulations applied to a real-world situation, there are no field observations to validate these estimations and determine which parameterization is most accurate and therefore appropriate to use in design. The Blenkinsopp *et al.* (2022) study is the most thorough study to date that quantifies observations of TWLs on cobble-backed beaches for field and laboratory observations. The lack of run-up observations at living shorelines points to the need for further studies on the effect of cobble-backed beaches on coastal flooding as well as monitoring of already implemented cobble-berm projects. The additional studies should include explicit monitoring of run-up heights to be used for validating modeling approaches. This should result in official guidance as to which parameterization is most appropriate in design and inform other design specifications such as cobble size, angularity, and volume.

REFERENCES

Allan, J.C., Geitgey, R.P., and R. Hart, 2005. "Dynamic revetments for coastal erosion stabilization: A feasibility analysis for application on the Oregon Coast." Oregon Department of Geology and Mineral Industries. https://digital.osl.state.or.us/islandora/object/osl:27151.

Allan, J.C., and P.D. Komar, 2004. "Environmentally compatible cobble berm and artificial dune for shore protection." *Shore & Beach,* 72(1), 9-18.

Arkema, K.K., Guannel, G., Verutes, G., Wood, S.A., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M., and J.M. Silver, 2013. "Coastal habitats shield people and property from sea-level rise and storms." *Nature Climate Change*, 3(10), 913-918.

Arkema, K.K., Griffin, R., Maldonado, S., Silver, J., Suckale, J., and Guerry, A.D., 2017. "Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities." *Annals of the New York Academy of Sciences*, 1399(1), 5-26.

Bayle, P.M., Blenkinsopp, C.E., Conley, D., Masselink, G., Beuzen, T., and R. Almar, 2020. "Performance of a dynamic cobble berm revetment for coastal protection, under increasing water level." *Coastal Engineering*, 159, 103712.

Blenkinsopp, C., Bayle, P., Martins, K., Foss, O., Almeida, L.P., Kaminsky, G., Schimmels, S., and H. Matsumoto, 2022. "Wave run-up on composite beaches and dynamic cobble berm revetments." *Coastal Engineering*, 104-148.

Bradbury, A., and K. Powell, 1992. "The short term profile response of shingle spits to storm wave action." *Coastal Engineering Proceedings*, https://doi.org/10.1061/9780872629332.205.

Bridges, T., Henn, R., Komlos, S., Scerno, D., Wamsley, T., and K. White, 2013. "Coastal risk reduction and resilience: using the full array of measures." U.S. Army Corps of Engineers, Washington, DC. https://ewn.erdc.dren.mil/wp-content/uploads/2021/02/2_USACE_CW-Coastal_Risk_Reduction_and_Resilience_Reduced.pdf.

Coles, S., Bawa, J., Trenner, L., and P. Dorazio, 2001. *An introduction to statistical modeling of extreme values*. Volume 208. Springer.

Everts, C., Eldon, C., and J. Moore, 2002. "Performance of cobble berms in southern California." *Shore & Beach*, 70(4), 5-14.

Federal Emergency Management Agency (FEMA), 2021. *Guidance for Risk Analysis and Mapping, Coastal Wave Run-up and Overtopping.* https://www.fema.gov/sites/default/files/documents/fema_coastal-wave-run-up-overtopping_112021.pdf.

Foss, O., Blenkinsopp, C.E., Bayle, P.M., Martins, K., Schimmels, S., and Almeida, L.P., 2023. "Comparison of dynamic cobble berm revetments with differing gravel characteristics." *Coastal Engineering*, 104312. https://doi.org/10.1016/j.coastaleng.2023.104312.

Hegermiller, C., Rueda, A., Erikson, L.H., Barnard, P.L., Antolinez, J., and F.J. Mendez, 2017. "Controls of multimodal wave conditions in a complex coastal setting." *Geophysical Research Letters*, 44(24), 12-315.

Inman, D.L., and S.A. Jenkins, 1999. "Climate change and the episodicity of sediment flux of small California rivers." *J. Geology*, 107(3), 251-270.

Jennings, R., and J. Shulmeister, 2002. "A field based classification scheme for gravel beaches." *Marine Geology*, 186(3-4), 211-228.

Komar, P.D., and J.C. Allan, 2010. "'Design with nature' strategies for shore protection: The construction of a cobble berm and artificial dune in an Oregon state park." *Puget Sound Shorelines and the Impacts of Armoring—Proc. a State of the Science Workshop,* 117-126. https://pubs.usgs.gov/sir/2010/5254/pdf/sir20105254_chap12.pdf.

Matsumoto, H., Young, A.P., and R.T. Guza, 2020. "Observations of surface cobbles at two southern California beaches." *Marine Geology*, 419, 106-149.

Morris, R.L., Konlechner, T.M., Ghisalberti, M., and S.E. Swearer, 2018. "From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defense." *Global Change Biology*, 24(5), 1827-1842.

Patsch, K., and G. Griggs, 2007. *Development of Sand Budgets for California's Major Littoral Cells.* Institute of Marine Sciences, University of California, Santa Cruz, 115 pp.

Poate, T.G., McCall, R.T., and G. Masselink, 2016. "A new parameterization for run-up on gravel beaches." *Coastal Engineering*, 117, 176-190.

Stockdon, H.F., Holman, R.A., Howd, P.A., and A.H. Sallenger Jr., 2006. "Empirical parameterization of setup, swash, and run-up." *Coastal Engineering*, 53(7), 573-588.

Sutton-Grier, A.E., Wowk, K., and H. Bamford, 2015. "Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems." *Environmental Science & Policy*, 51, 137-148.

USACE, 2017. *Malibu Creek Ecosystem Restoration Study, draft Integrated Feasibility Report (IFR) with Environmental Impact Statement/Environmental Impact Report (EIS/EIR), Los Angeles and Ventura Counties, California*. U.S. Army Corps of Engineers, Los Angeles District.

Van der Meer, J., 2002. "Technical report wave run-up and wave overtopping at dikes." *TAW report (incorporated in the EurOtop manual)*.

Weiner, H., Kaminsky, G., Hacking, A., and D. McCandless, 2019. "North cove dynamic revetment monitoring: Winter 2018-2019." Technical report, Technical Report 19-06-008 Shorelands and Environmental Assistance Program Washington Department of Ecology.

Winters, M.A., Leslie, B., Sloane, E B., and T.W. Gallien, 2020. "Observations and preliminary vulnerability assessment of a hybrid dune-based living shoreline." *J. Marine Science and Engineering*, 8(11), 920. https://doi.org/10.3390/jmse8110920.

Wright, L.D. and A.D. Short, 1984. "Morphodynamic variability of surf zones and beaches: a synthesis." *Marine Geology*, 56(1-4), 93-118.