The protective benefits of tsunami mitigation parks and ramifications for their strategic design

Brent Lunghino[a], Adrian F. Santiago Tate[b], Miho Mazereeuw[c], Abdul Muhari[d], Francis X. Giraldo[e], Simone Marras[f,g,1], and Jenny Suckale[a,b,h,1]

[a]Institute for Computational and Mathematical Engineering, Stanford University, Stanford, CA 94305; [b]Department of Geophysics, Stanford University, Stanford, CA 94305; [c]Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA 02139; [d]Directorate of Sustainable Utilization of Coastal Zone and Small Islands, Directorate General of Marine Spatial Management, Ministry of Marine Affairs and Fisheries, Jakarta, 10110, Indonesia; [e]Department of Applied Mathematics, Naval Postgraduate School, Monterey, CA 93943; [f]Department of Mechanical and Industrial Engineering, New Jersey Institute of Technology, Newark, NJ 07102; [g]Center for Applied Mathematics and Statistics, New Jersey Institute of Technology, Newark, NJ 07102; and [h]Department of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305

Edited by B. L. Turner II, Arizona State University, Tempe, AZ, and approved March 9, 2020 (received for review July 11, 2019)

Nature-based solutions are becoming an increasingly important component of sustainable coastal risk management. For particularly destructive hazards like tsunamis, natural elements like vegetation are often combined with designed elements like seawalls or dams to augment the protective benefits of each component. One example of this kind of hybrid approach is the so-called tsunami mitigation park, which combines a designed hillscape with vegetation. Despite the increasing popularity of tsunami mitigation parks, the protective benefits they provide are poorly understood and incompletely quantified. As a consequence of this lack of understanding, current designs might not maximize the protective benefits of tsunami mitigation parks. Here, we numerically model the interactions between a single row of hills with an incoming tsunami to identify the mechanisms through which the park protects the coast. We initialize the tsunami as an N wave that propagates to shore and impacts the coast directly. We find that partial reflection of the incoming wave is the most important mechanism by which hills reduce the kinetic energy that propagates onshore. The protective benefit of tsunami mitigation parks is thus comparable to that of a small wall, at least for tsunamis with amplitudes that are comparable to the hill height. We also show that hills could elevate potential damage in the immediate vicinity of the hills where flow speeds increase compared to a planar beach, suggesting the need to include a buffer zone behind the hills into a strategic park design.

tsunami risk mitigation | nature-based solutions | mitigation parks | green belts | coastal forests

In the past two decades, several devastating tsunami events have increased awareness of the threat that tsunamis pose to coastal communities and invigorated a debate about nature-based approaches for tsunami risk reduction (1–11). Nature-based approaches are attractive because they potentially offer numerous benefits beyond risk mitigation including social, economic, and environmental services (12) and can be cheaper to build than sea walls (see *SI Appendix* for additional factors contributing to the cost–benefit ratio of the two approaches). Our understanding of and ability to quantify how tsunamis interact with natural features, however, are limited, which translates into considerable uncertainty regarding the protective benefits of nature-based approaches and their optimal design (4).

One common nature-based approach to mitigating tsunami risk is the so-called tsunami mitigation park. Tsunami mitigation parks are intentionally designed landscape units on the shoreline that are built to protect critical infrastructures or communities at risk behind the park. Most designs for mitigation parks combine an engineered element, like a hillscape, with a natural element, like vegetation (Fig. 1). They are hence hybrid approaches to mitigating tsunami risk and are different from purely natural solutions like mangroves (1, 13–21) because they offer the possibility of strategic design.

Advancing our ability to design tsunami mitigation parks strategically to maximize their protective benefit requires an in-depth understanding of how tsunamis propagate through them, but very little research has looked at how to best combine traditional engineered structures (gray elements) and vegetation (green elements) to maximize tsunami risk mitigation. The goal of this paper is to improve our understanding of the protective benefits of tsunami mitigation parks to guide strategic park design. We focus on the engineered, topographic element of the park since it offers more opportunities for strategic design. Previous studies have mostly investigated the role of vegetation on tsunami runup (2, 22–27), but not specifically considered hybrid approaches to mitigating tsunami risk.

Significance

Hybrid approaches to mitigating tsunami risk combine vegetation (green element) with traditional engineering components (gray elements) to maximize protection and other benefits. While hybrid approaches like tsunami mitigation parks are being built worldwide, our understanding of the protective benefits they provide and our ability to optimally design these parks are limited. Here, we show that the main protective benefit of tsunami mitigation parks is the reflection of wave energy. Reflection can be maximized through strategic design of the park's hillscape, at least for tsunami amplitudes that are comparable to the hill height. Apart from the protective benefits of the park, we highlight that tsunami mitigation parks could locally increase tsunami risk, depending on the placement and arrangement of the hills.

Author contributions: J.S. designed research; B.L., A.F.S.T., and S.M. performed research; M.M., A.M., and F.X.G. contributed new reagents/analytic tools; B.L., A.F.S.T., and S.M. analyzed data; B.L., A.F.S.T., S.M., and J.S. wrote the paper; M.M. provided critical input on design practices; and A.M. provided critical input on implementation practices.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

Data deposition: All codes needed to reproduce our main results through the open-source package GeoClaw are available as a GitLab repository from the SIGMA research group at Stanford University: http://zapad.stanford.edu/jsuckale/pnas-2020-tsunami-mitigation-parks.

[1]To whom correspondence may be addressed. Email: jsuckale@stanford.edu or smarras@njit.edu.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1911857117/-/DCSupplemental.

First published May 4, 2020.

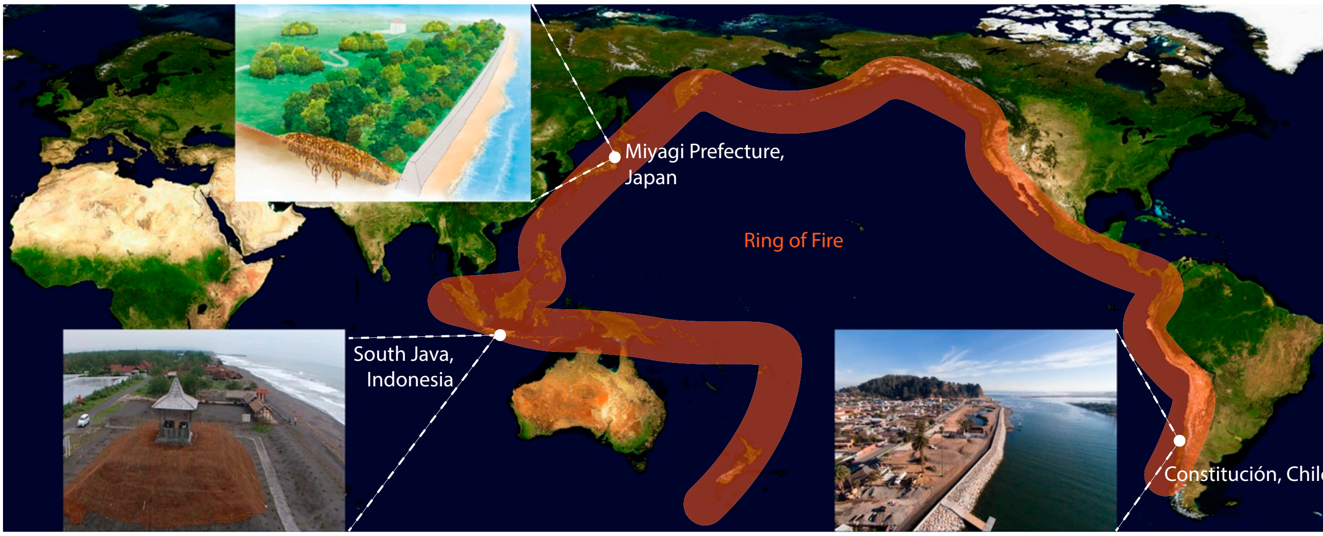

Fig. 1. Three examples of tsunami mitigation parks along the ring of fire that are currently being planned and/or constructed in South Java, Indonesia (image courtesy of A.M.); Miyagi Prefecture, Japan and Constitución, Chile. Miyagi prefecture image and Constitución image credit: Morino Project and Felipe Diaz Contardo (photographer).

The motivation behind integrating a hillscape into the design of a tsunami mitigation park is to create obstacles that reduce the destructive reach of the tsunami. Field studies have shown that local topographic effects can create dramatic variability in onshore flow conditions (28–30). For example, during the 2009 tsunami in Samoa, runup heights varied from under 2 m to just over 15 m along a 100-km span of coastline on the southern side of Upolu Island (29). Similarly, during the 2001 tsunami in Peru, runup ranged from less than 4 m to over 8 m in a 100-km stretch of coastline (28). While these field observations suggest that regional bathymetry and local topography increase variability in local wave height, flow speed, and inundation distance, they also imply that obstacles may not always have a protective benefit. This cautionary insight has been confirmed through laboratory studies (31–34).

Numerical simulations provide an attractive complement to field observations and laboratory experiments because they allow the study of tsunami runup in an idealized setting that is not limited to conditions realizable in the laboratory. One important contribution of runup modeling is to point out the importance of the tsunami waveform (35–37). The nonlinearity of the tsunami wave affects onshore flow velocities significantly due to differing degrees of wave steepening (36) and wave breaking (35) in one-dimensional simulations. The degree to which an obstacle reduces the inundation distance hence depends on the form of the incoming wave (35, 36) and, potentially, the existence of a leading depression in the waveform (38). The insight that the characteristics of the tsunami wave have a large effect on runup (35–37) implies that the protective benefit of tsunami mitigation parks may depend sensitively on how much the incoming wave resembles the "design event," namely the tsunami wave that the park was designed to protect against.

Results

Reflection Is the Primary Protective Benefit of Tsunami Mitigation Parks. We study tsunami runup over an idealized planar beach with a park onshore (see Fig. 2 *A* and *B* for the model setup), using the two-dimensional (2D) shallow water equations. While the setting is abstract, it allows us to identify general insights that could inform the design of parks at different geographic sites. Inspired by the Morino project (39), we assume that the tsunami mitigation park consists of a single row of ellipsoidal hills (Fig. 2 *A* and *B*). In *SI Appendix*, we also investigate conical hills similar to those currently under construction at Constitución, Chile. For the coastal bathymetry, we assume a constant, moderate offshore slope of 1/50, but show results for a wide range of slopes in *SI Appendix*. We generate an N wave using Carrier's expression (40) (see *Methods* and *SI Appendix* for a comparison of N waves with a leading depression as opposed to a leading elevation). This waveform, while still idealized, is more representative of a near-field tsunami waveform than a soliton (38).

Fig. 2 *C*–*F* shows the evolution of the free surface at different stages of tsunami approach and impact in the near field. The initial waveform (Fig. 2*C*) propagates in both directions driven by gravity (Fig. 2*D*), impacts with the hill (Fig. 2*E*), and continues onshore past the hill until it runs out of kinetic energy to move up the slope (Fig. 2*F*). A significant reflected wave forms when the tsunami impacts the hill, which is seen most clearly in the zoom-in (Fig. 2*G*). This result suggests that reflection is the main mechanism by which mitigation hills reduce destructive flux onshore for tsunamis that are at least approximately described by the assumed N-wave form. In *SI Appendix*, we show that the green component of tsunami mitigation parks, namely vegetation, has a comparatively minor effect on the waveform of the incoming tsunami.

The potential of a tsunami to cause damage depends on the hydrodynamic force it exerts on structures or, equivalently, the kinetic energy it transports onshore (41–43). In Fig. 3*A* we estimate the energy flux over time integrated over the alongshore transect through the hill centers to isolate the effect of reflection on the energy flux. For a tsunami with an initial amplitude that is comparable to the height of the hills, runup through a single row of hills reduces the peak kinetic energy flux by about 29% compared to the same tsunami impacting a planar beach. Fig. 3*B* highlights that reflection reduces the kinetic energy flux specifically without altering potential energy flux.

Differences in park design alter the reflective flux and affect the protective benefits of the mitigation park sensitively. In *SI Appendix*, we provide a preliminary analysis of some of the key design parameters, namely hill spacing, hill height, and hill shape. Not surprisingly, we find that tightly spaced hills reflect

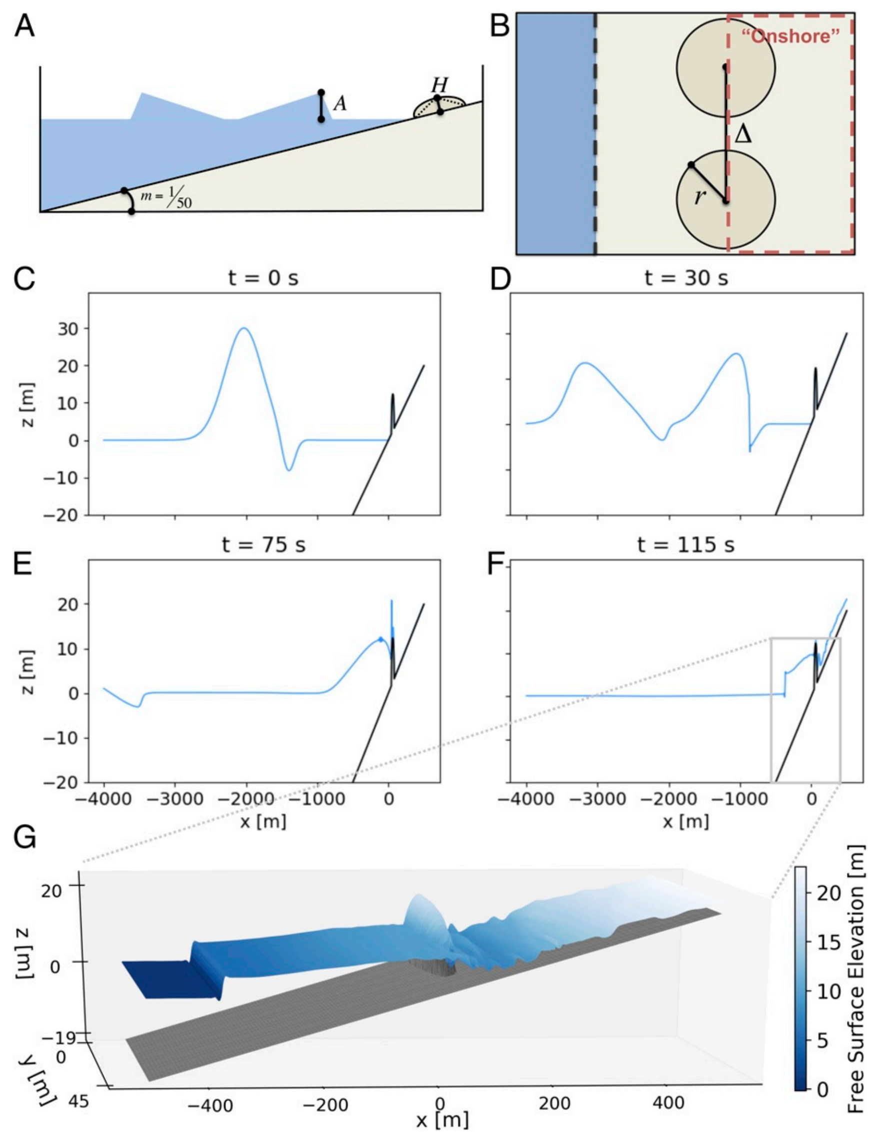

Fig. 2. (*A*) Schematic diagram of the model domain in cross-section. (*B*) Map view of the domain at the shoreline. The black dashed line indicates the initial shoreline and we define the red dashed box as the onshore region. (*C*) Carrier N wave used as initial condition. (*D*) Offshore propagation of the tsunami. (*E*) Impact of the tsunami bore onto the hills. (*F*) Formation and backward propagation of the reflected wave. (*G*) Zoom-in onto the three-dimensional free surface of *F*.

more flux and smaller hills reflect less flux. As the degree of reflection depends not only on the park design but also on the large-scale bathymetry, it is valuable to perform a detailed, site-specific analysis prior to the design of a new tsunami mitigation park to quantify energy reflection for the site under consideration.

Protective Benefits Are Limited for Tsunami Amplitudes That Exceed the Hill Height. The insight that reflection is the main protective benefit of tsunami mitigation parks highlights the opportunity for maximizing risk mitigation through strategic park design, because the degree of reflection depends on various design parameters including hill spacing, shape, and height. The challenge is that the tsunami characteristics such as wave length, wave height, and number of waves are unknown. The design challenge is particularly pronounced in the near field, where the amplitude and wavelength of the tsunami may vary by several orders of magnitude and the incidence angle may span a wide range. Previous studies have pointed out that increasing the offshore amplitude of the tsunami wave for a fixed hill height will increase inundation distance and onshore kinetic energy (10, 44). In this study, we quantify how quickly the protective benefit provided by the mitigation hills decays with the

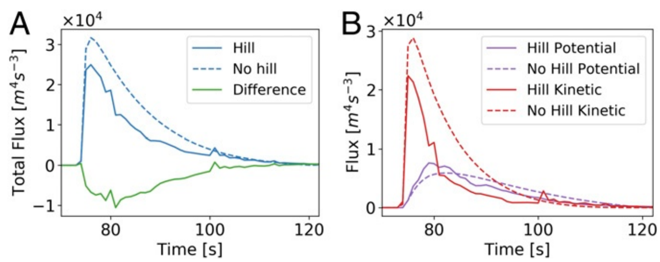

Fig. 3. (*A*) Time series of the total energy flux at $x = 60$ for simulations with hills compared to a planar beach. We estimate the reflected energy flux by subtracting the total energy flux in the absence of hills from the energy flux through the hills. (*B*) Comparison of the kinetic and potential contribution to total energy flux with and without hills.

tsunami amplitude, A, and wavelength, λ, for different park designs.

Fig. 4*A* shows the time series of total kinetic energy onshore, where we define the onshore zone as starting from the transect between hill centers to the end of the domain (Fig. 2*B*). We consider three different wave amplitudes from less than half the hill height, $A/H = 0.4$ representative of a small tsunami; to an intermediate tsunami with an amplitude that is comparable to the hill height, $A/H = 1$; to a large tsunami with amplitude two times the hill height, $A/H = 2$. For all three cases, we normalize the kinetic energy by the initial potential energy of the N wave. We focus on hill spacing as the main design parameter, but consider additional factors in *SI Appendix*.

Wave amplitudes smaller than the hill height lead to significant reflection and reduction in total kinetic energy onshore (Fig. 4*A*). Fig. 4*A* also shows that the portion of reflected kinetic energy depends sensitively on hill spacing for tsunamis with small amplitudes compared to hill height. In this limit, the specific design of the hillscape has the largest impact on the overall protective benefit provided. The effect of park design becomes less pronounced as the tsunami amplitude increases. For the design event medium A/H, defined here as a tsunami with an amplitude that is comparable to hill height, the spread of onshore kinetic energy decreases relative to a small tsunami event and for a large tsunami, park design has only a marginal effect. These simulations show not only that the portion of kinetic energy reflected decreases notably for increasing tsunami amplitude, but also that park design is likely of limited value for optimizing the protective benefit against large tsunamis.

Fig. 4*B* shows the maximum inundation distance for different hill spacings and tsunami amplitudes. We find that mitigation hills reduce the maximum inundation distance only slightly and by a comparable degree for the vast majority of cases considered. The main reason is that the single line of hills considered here still allows significant flow between the hills that reaches similar inundation distances to those in the no-hills case. Interestingly, the reduction in maximum inundation distance is least pronounced for small tsunamis (small A/H) despite the reduced kinetic energy onshore (Fig. 4*A*), particularly at large hill spacing, $\Delta/2r = 2$. The idealized park design we study is thus not effective at controlling inundation distance.

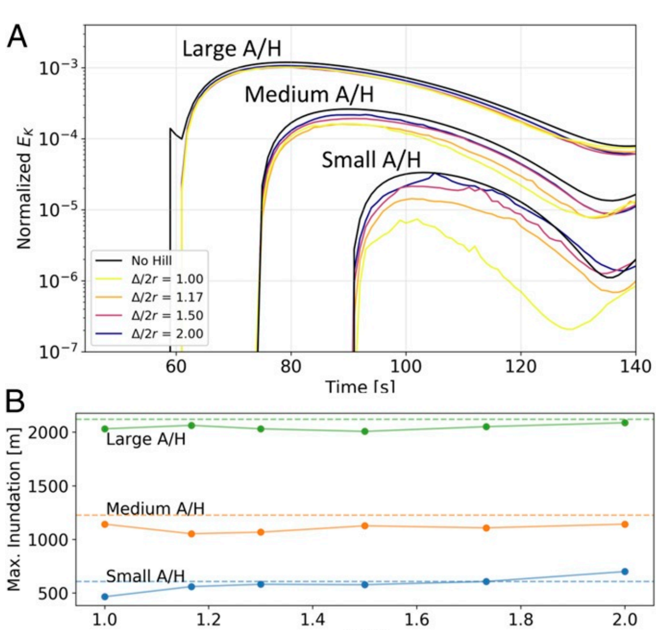

Fig. 4. (*A*) Total onshore kinetic energy normalized by initial potential energy. Shown is the comparison across wave amplitudes and obstacle spacings for the longest wave ($r_{obs}/\lambda = 0.006$). (*B*) Maximum inundation distance as a function of A/H for slope of 1/50. Shown is the comparison between simulations with hills (solid line) and with no hills (dashed line).

Fig. 4 begs the question of whether the difference in behavior is the consequence of the different initial potential energy of the wave or whether varying wave amplitude alters the onshore kinetic energy even when potential energy is unchanged. To investigate this, we model a range of initial conditions with constant potential energy, E_p, and variable A/λ. We hold E_p constant by increasing λ as A is decreased. By fixing the initial potential energy, we can isolate the effect of changing wave amplitude separate from the change to the potential energy available in the domain. These simulations, available in *SI Appendix*, show that the amplitude of the initial condition, rather than the potential energy, is controlling the onshore kinetic energy during inundation.

Potentially Adverse Effects of Tsunami Mitigation Parks. A close inspection of Fig. 4*B* shows that the maximum inundation distance may increase for runup through a hillscape compared to runup over a flat beach, particularly for relatively large hill spacings (e.g., $\Delta/2r = 2$). While the overall kinetic energy flux decreases, at least for small to intermediate tsunamis, the spatial variability increases. In fact, if flow is channelized by the presence of the hills, the destructive reach of the tsunami could increase and pose an additional risk to structures that would not otherwise be impacted. Based on our simulations, channelization is somewhat less pronounced for large tsunamis, because the majority of the flow overruns the hills (Fig. 4*A*).

Apart from a potential increase in the maximum inundation distance, flow channelization between the hills entails a local increase in the kinetic energy in the onshore zone (Fig. 5). This effect is not apparent in Fig. 4, because we are comparing the temporal evolution of total kinetic energy onshore in these cases. In Fig. 5, we plot the local difference in kinetic energy for a mitigation park with intermediate hill spacing ($\Delta/2r = 1.0$) compared to the no-hill case. In the absence of a park, the local kinetic energy is approximately constant in transects parallel to the shore. The presence of hills distorts that homogeneous distribution by redistributing the kinetic energy spatially. Shortly after impact it is particularly high between the hills, but then spreads out to the zone behind the hills. The zone behind the hills might also be preferentially impacted if the tsunami is large enough to overrun the hills (Fig. 5).

Ramifications for Mitigation Park Design. Hybrid solutions for mitigating coastal risk reflect the insight that gray approaches like sea walls and green solutions like vegetation provide different and potentially complementary protective benefits (45). Integrating green and gray approaches can thus create “multiple lines of defense” (46) against coastal hazards and provide better protection than one approach in isolation. The degree to which there is an added benefit from a hybrid approach hinges on the complementarity of protective benefits provided by its individual elements.

We show that the main protective benefit of tsunami mitigation parks is the partial reflection of wave energy. The park thus has a similar effect to a small wall at the coastline (see *SI Appendix* for a direct comparison). Combining a wall and hills in one park design would duplicate the protective benefit of reflection and therefore might not provide clear added value. Interestingly, existing tsunami defense designs such as the Morino project and the mitigation park at Constitución, Chile

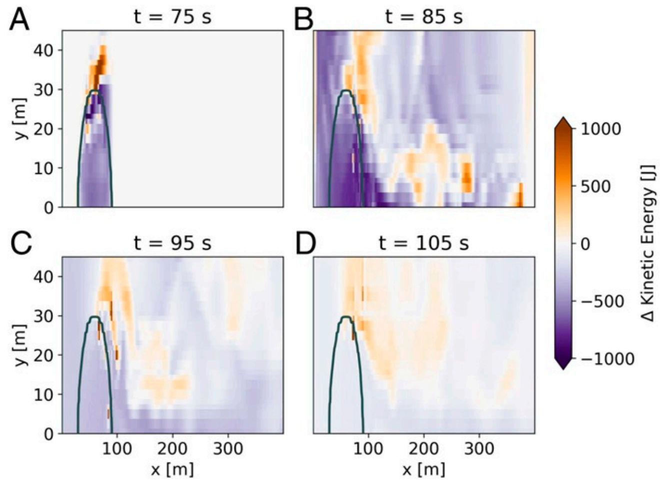

Fig. 5. Comparison of the local difference in kinetic energy for tsunami runup through a tsunami mitigation park compared to a planar beach for four temporal snapshots. Orange denotes zones of elevated kinetic energy compared to the no-hill case and purple highlights zones of reduced kinetic energy. (*A*–*C*) Local differences are highest upon tsunami impact on the hills (*A*) and then spread from the zone between the hills to behind the hills (*B* and *C*). As the flow continues onshore (*D*), the differences in kinetic energy decay.

(Fig. 1) typically combine walls and hills. Our simulations suggest that it may be sufficient to rely on the hills for reflection. Excluding walls from the park design could reduce expenses and reduce water pooling during rundown. Contrary to walls, tsunami mitigation parks also have additional protective benefits such as providing an evacuation zone for local residents as in the case of the greenbelt project in South Java shown in Fig. 1 and increasing the distance of dwellings and infrastructure from the coastline.

All current park designs we are aware of include vegetation, typically both on and between the hills, which adds a complementary protective benefit. Many previous studies have evaluated the protective benefits of coastal forests during tsunamis (2, 15, 20, 24, 47) and found that they can act to reduce inundation depth and flow speed both within and behind the vegetated zone (15, 20, 47). In the context of tsunami mitigation parks, vegetation could provide multiple complementary benefits. By elevating the basal friction, vegetation could slow down the flow and reduce runup (20). In *SI Appendix*, we show that this effect is small compared to the reduction in kinetic energy as a consequence of reflection. A more important protective benefit could be a stabilizing effect on the hillscape due to reduced erosion (15). Hills typically consist of erodible material and their shape will likely be altered by tsunami runup. Scour around hills (48) could rapidly change the spacing between the hills—an important parameter in determining onshore kinetic energy. Even complete erosion of the hills is possible, depending on their composition. For example, entire artificial dunes were removed by the 2011 Tohoku tsunami (49).

Despite the multiple protective benefits of tsunami mitigation parks, there are also risks associated with the approach. Maybe most importantly, its protective benefits are limited to small and intermediate tsunamis. In this limit, strategic design that maximizes reflection has the largest potential to maximize the protective benefit, but our analysis suggests that it is likely ineffective at extending the protective benefits of the park to large tsunamis (Fig. 4*A*). An additional concern is that while hills reduce total kinetic energy onshore, they redistribute that kinetic energy, and hence the risk associated with tsunami impact, in a spatially heterogeneous way. It is possible that certain locations, particularly in the vicinity of the hills, might be exposed to a higher risk than without a park. The design ramification of this finding is that placing the structure or community in need of protection directly behind the park could increase its risk, particularly for large-amplitude tsunamis. A potentially promising alternative would be to consider a sequence of increasingly smaller, staggered hills to dampen flow speeds and reduce channelization or to complement the park with other risk mitigation interventions.

Here, our aim is to gain general insights into the design criteria that would be worthwhile to evaluate when planning a tsunami mitigation park. The sensitive dependence of the protective benefit on both wave properties and park design highlights that a meaningful evaluation of the risks and benefits must be done on a site-by-site basis. For example, if the site does not experience frontal wave impact but rather lateral or multidirectional flow, reflection might be reduced. Similarly, the wave form impacting a far-field community might no longer be well described by the N wave considered here but resemble a bore instead and our analysis does not apply in this limit.

Methods

We use $\mathbf{x}$ to denote the position vector and $\mathbf{u} = \mathbf{u}(t, \mathbf{x})$ for the flow velocity. The height of the free surface relative to the bathymetry is $h = h(t, \mathbf{x})$. The water surface level hence consists of two separate components, the dynamic evolution of the free surface, $\eta(t, \mathbf{x})$, and the imposed bathymetry, $H_b(\mathbf{x})$, such that $h = \eta(t, \mathbf{x}) - H_b(\mathbf{x})$, keeping in mind that $H_b(\mathbf{x})$ is negative below the geoid. We solve the 2D viscous nonlinear shallow water equations with NUMA2D, a high-order discontinuous Galerkin solver, which has been developed since 2002, benchmarked, and used extensively for ocean modeling as reviewed in *SI Appendix*. We note that the main strength of the shallow-water approximation lies in resolving the large-scale dynamics of runup and that our model does not accurately resolve the physical processes contributing to dissipation when the tsunami impacts the hills such as wave breaking, runup over sedimentary or vegetated surfaces, or turbulence generation.

We solve the shallow-water equations, reformulated as

$$h_t + \nabla \cdot (h\mathbf{u}) = \delta \nabla \cdot (\mu_{SGS} \nabla h), \quad [1]$$

$$(h\mathbf{u})_t + \nabla \cdot \left(h\mathbf{u} \otimes \mathbf{u} + \frac{g}{2}(h^2 - H_b^2)\mathbf{I} \right) + g\eta \nabla \cdot (H_b \mathbf{I}) = \nabla \cdot (\eta \mu_{SGS} \nabla \mathbf{u}) - n^2 g \frac{\mathbf{u}|\mathbf{u}|}{h^{1/3}}, \quad [2]$$

where $\mathbf{I}$ is the 2×2 identity matrix, $\delta = 1$ is a binary switch to activate the stabilization term, $g = 9.81$ ms^{-2} is the acceleration of gravity, n is the Manning friction coefficient, and μ_{SGS} is the dynamic dissipation coefficient defined in ref. 50 and discussed in detail in *SI Appendix*. By construction, the dynamic numerical dissipation only contributes to the dissipation of the high-wave-number energy buildup in the proximity of sharp fronts without altering the large-scale flow dynamics. The coefficient μ_{SGS} is zero where the water surface is smooth and increases in the vicinity of wave fronts.

To initiate the tsunami, we use Carrier's description of an N wave (40),

$$\eta = 2(a_1 \exp\{-\hat{k}_1 (x - \hat{x}_1)^2\} - a_2 \exp\{\hat{k}_2 (x - \hat{x}_2)^2\}), \quad [3]$$

with $\hat{x}_1 = 1{,}000 + 0.5151125\lambda$, $\hat{x}_2 = 1{,}000 + 0.2048\lambda$, $\hat{k}_1 = 28.416/\lambda^2$, $\hat{k}_2 = 256/\lambda^2$, $a_1 = A$, and $a_2 = A/3$. The free parameters in our simulations are the wavelength, λ, and the amplitude, A, of the initial wave. An example of the Carrier wave initial condition and offshore propagation behavior for $A = 15$ and $\lambda = 2{,}000$ is shown in Fig. 2. We use free-slip, no-penetration boundary conditions on all four boundaries, meaning that the component of the velocity vector perpendicular to the boundary is set to zero and the tangential component is unaltered.

To quantify the energy flux onshore, we derive the energy flux from the shallow-water equations (Eqs. **1** and **2**) as detailed in *SI Appendix*. The derivation yields

$$\mathbf{f} = \mathbf{u}\left[\frac{gh^2}{2} + hq\right], \quad [4]$$

where $q = \mathbf{u} \cdot \mathbf{u}/2$. The energy flux described by Eq. **4** is a vector quantity with direction given by the flow velocity vector and it has units of $m^4 \cdot s^{-3}$. In the analysis of our model results we integrate across the width of the domain at a fixed location and normalize by the width of the domain. For a location of x_s and a domain of width Y,

$$\mathbf{F}(t, x = x_s) = \frac{1}{Y}\int_0^Y \mathbf{f}(t, x = x_s, y)dy. \quad [5]$$

We can now isolate the kinetic, $\mathbf{F}_k$, and potential, $\mathbf{F}_p$, components,

$$\mathbf{F}_p = \frac{1}{Y}\int_0^Y \mathbf{u}\left(\frac{gh^2}{2}\right)dy, \quad [6]$$

$$\mathbf{F}_k = \frac{1}{Y}\int_0^Y \mathbf{u}(hq)dy \quad [7]$$

and compare their relative magnitudes.

All codes needed to reproduce our main results through the open-source package GeoClaw are available as a GitLab repository from the SIGMA research group at Stanford University: http://zapad.stanford.edu/sigma/pnas-2020_tsunami-mitigation-parks. A detailed readme file provides instructions.

ACKNOWLEDGMENTS. We acknowledge helpful discussions with Oliver Fringer, Bruce Jaffe, Sergio Maldonado, Brian Tucker, and Veronica Cedillos, as well as help with graphics from Ian Avery Bick. This project was supported by the School of Earth, Energy and Environmental Sciences at Stanford University; the NSF Graduate Research Fellowship Program; and the Computational Geoscience Fellowship from Stanford University's School of Earth, Energy and Environmental Sciences. F.X.G. acknowledges support from the Office of Naval Research through Grant PE-0602435N.

1. F. Danielsen *et al.*, The Asian tsunami: A protective role for coastal vegetation. *Science* **310**, 643 (2005).
2. K. Harada, F. Imamura, "Effects of coastal forest on tsunami hazard mitigation–A preliminary investigation" in *Tsunamis*, K. Satake, Ed. (Springer, 2005), pp. 279–292.
3. B. Chatenoux, P. Peduzzi, Impacts from the 2004 Indian Ocean tsunami: Analysing the potential protecting role of environmental features. *Nat. Hazards* **40**, 289–304 (2007).
4. A. M. Kerr, A. H. Baird, Natural barriers to natural disasters. *BioScience* **57**, 102–103 (2007).
5. M. F. Olwig *et al.*, Using remote sensing to assess the protective role of coastal woody vegetation against tsunami waves. *Int. J. Rem. Sens.* **28**, 3153–3169 (2007).
6. R. Cochard *et al.*, The 2004 tsunami in Aceh and southern Thailand: A review on coastal ecosystems, wave hazards and vulnerability. *Perspect. Plant Ecol. Evol. Systemat.* **10**, 3–40 (2008).
7. A. M. Kerr, A. H. Baird, R. S. Bhalla, V. Srinivas, Reply to using remote sensing to assess the protective role of coastal woody vegetation against tsunami waves. *Int. J. Rem. Sens.* **30**, 3817–3820 (2009).
8. N. Mukherjee *et al.*, From bathymetry to bioshields: A review of post-tsunami ecological research in India and its implications for policy. *Environ. Manag.* **46**, 329–339 (2010).
9. J. L. Bayas *et al.*, Influence of coastal vegetation on the 2004 tsunami wave impact in west Aceh. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 18612–18617 (2011).
10. A. Muhari, M. Mück, S. Diposaptono, H. Spahn, Tsunami mitigation planning in Pacitan, Indonesia: A review of existing efforts and ways ahead. *Sci. Tsunami Hazards* **31**, 244–267 (2012).
11. V. Santiago-Fandiño, H. Tanaka, M. Spiske, *Tsunamis and Earthquakes in Coastal Environments* (Springer, 2016).
12. E. Rudianto *et al.*, "Ecosystem-based tsunami disaster risk reduction in Indonesian coastal areas" in *Tsunamis and Earthquakes in Coastal Environments*, V. Santiago-Fandiño, H. Tanaka, M. Spiske, Eds. (Springer, 2016), pp. 31–46.
13. F. Dahdouh-Guebas *et al.*, How effective were mangroves as a defence against the recent tsunami? *Curr. Biol.* **15**, R443–R447 (2005).
14. K. Kathiresan, N. Rajendran, Coastal mangrove forests mitigated tsunami. *Estuarine Coast. Shelf Sci.* **65**, 601–606 (2005).
15. G. Gelfenbaum, D. Vatvani, B. Jaffe, F. Dekker, "Tsunami inundation and sediment transport in vicinity of coastal mangrove forest" in *Coastal Sediments' 07*, N. C. Kraus, J. D. Rosati, Eds. (American Society of Civil Engineers, 2007), pp. 1117–1128.
16. D. M. Alongi, Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuarine Coast. Shelf Sci.* **76**, 1–13 (2008).
17. F. Y. Teo, R. A. Falconer, B. Lin, "Modelling effects of mangroves on tsunamis" in *Proceedings of the Institution of Civil Engineers-Water Management*, A. Ab. Ghani, N. A. Zakaria, R. A. Falconer, Eds. (Thomas Telford Ltd, London, 2009), vol. 162, pp. 3–12.
18. S. Y. Teh, H. L. Koh, P. L. F. Liu, A. I. M. Ismail, H. L. Lee, Analytical and numerical simulation of tsunami mitigation by mangroves in Penang, Malaysia. *J. Asian Earth Sci.* **36**, 38–46 (2009).
19. H. Yanagisawa *et al.*, The reduction effects of mangrove forest on a tsunami based on field surveys at Pakarang Cape, Thailand and numerical analysis. *Estuarine Coast Shelf Sci.* **81**, 27–37 (2009).
20. H. Yanagisawa, S. Koshimura, T. Miyagi, F. Imamura, Tsunami damage reduction performance of a mangrove forest in Banda Aceh, Indonesia inferred from field data and a numerical model. *J. Geophys. Res.* **115**, C06032 (2010).
21. H. Ismail, A. A. Wahab, N. E. Alias, Determination of mangrove forest performance in reducing tsunami run-up using physical models. *Nat. Hazards* **63**, 939–963 (2012).
22. N. Tanaka, Y. Sasaki, M. I. M. Mowjood, K. B. S. N. Jinadasa, S. Homchuen, Coastal vegetation structures and their functions in tsunami protection: Experience of the recent Indian Ocean tsunami. *Landsc. Ecol. Eng.* **3**, 33–45 (2007).
23. N. Tanaka *et al.*, Developing effective vegetation bioshield for tsunami protection. *Civ. Eng. Environ. Syst.* **26**, 163–180 (2009).
24. K. Iimura, N. Tanaka, Numerical simulation estimating effects of tree density distribution in coastal forest on tsunami mitigation. *Ocean Eng.* **54**, 223–232 (2012).
25. N. Tanaka, K. B. S. N. Jinadasa, M. I. M. Mowjood, M. S. M. Fasly, Coastal vegetation planting projects for tsunami disaster mitigation: Effectiveness evaluation of new establishments. *Landsc. Ecol. Eng.* **7**, 127–135 (2011).
26. N. Tanaka, "Effectiveness and limitations of vegetation bioshield in coast for tsunami disaster mitigation" in *The Tsunami Threat-Research and Technology*, N.-A. Morner, Ed. (InTech, 2011), pp. 161–178.
27. N. B. Thuy, N. Tanaka, K. Tanimoto, Tsunami mitigation by coastal vegetation considering the effect of tree breaking. *J. Coast Conserv.* **16**, 111–121 (2012).
28. E. A. Okal *et al.*, Field survey of the Camaná, Perú tsunami of 23 june 2001. *Seismol. Res. Lett.* **73**, 907–920 (2002).
29. H. M. Fritz *et al.*, Insights on the 2009 South Pacific tsunami in Samoa and Tonga from field surveys and numerical simulations. *Earth Sci. Rev.* **107**, 66–75 (2011).
30. K. Goto *et al.*, New insights of tsunami hazard from the 2011 Tohoku-oki event. *Mar. Geol.* **290**, 46–50 (2011).
31. M. Rueben *et al.*, Optical measurements of tsunami inundation through an urban waterfront modeled in a large-scale laboratory basin. *Coast. Eng.* **58**, 229–238 (2011).
32. J. L. Irish *et al.*, Laboratory experiments of tsunami run-up and withdrawal in patchy coastal forest on a steep beach. *Nat. Hazards* **74**, 1933–1949 (2014).
33. N. Goseberg, T. Schlurmann, "Non-stationary flow around buildings during run-up of tsunami waves on a plain beach" in *34th International Conference on Coastal Engineering, ICCE 2014*, P. Lynett, Ed. (Coastal Engineering Proceedings, 2014) vol. 34, p. currents.21.
34. S. Thomas, J. Killian, K. Bridges, Influence of macroroughness on tsunami loading of coastal structures. *J. Waterw. Port Coast. Ocean Eng.* **141**, 04014028 (2014).
35. P. Lin, A numerical study of solitary wave interaction with rectangular obstacles. *Coast. Eng.* **51**, 35–51 (2004).
36. P. J. Lynett, Effect of a shallow water obstruction on long wave runup and overland flow velocity. *J. Waterw. Port Coast. Ocean Eng.* **133**, 455–462 (2007).
37. A. Apotsos, B. Jaffe, G. Gelfenbaum, Wave characteristic and morphologic effects on the onshore hydrodynamic response of tsunamis. *Coast. Eng.* **58**, 1034–1048 (2011).
38. S. Tadepalli, C. Synolakis, The run-up of N-waves on sloping beaches. *Proc. Math. Phys. Eng. Sci.* **445**, 99–112 (1994).
39. Morino Project, Project summary (2019). https://morinoproject.com/english. Accessed 13 April 2019.
40. G. F. Carrier, T. T. Wu, H. Yeh, Tsunami run-up and draw-down on a plane beach. *J. Fluid Mech.* **475**, 79–99 (2003).
41. S. Koshimura, T. Oie, H. Yanagisawa, F. Imamura, Developing fragility functions for tsunami damage estimation using numerical model and post-tsunami data from Banda Aceh, Indonesia. *Coast Eng. J.* **51**, 243–273 (2009).
42. A. Suppasri *et al.*, Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami. *Nat. Hazards* **66**, 319–341 (2013).
43. A. Suppasri, I. Charvet, K. Imai, F. Imamura, Fragility curves based on data from the 2011 Tohoku-oki tsunami in Ishinomaki city, with discussion of parameters influencing building damage. *Earthq. Spectra* **31**, 841–868 (2015).
44. A. Muhari, K. Imai, D. Sugawara, F. Imamura, "A method to determine the level 1 and level 2 tsunami inundation areas for reconstruction in eastern Japan and possible application in pre-disaster areas" in *Post-Tsunami Hazard*, V. Santiago-Fandiño, Y. A. Kontar, Y. Kaneda, Eds. (Springer, 2015), pp. 133–155.
45. K. K. Arkema *et al.*, Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Ann. N. Y. Acad. Sci.* **1399**, 5–26 (2017).
46. J. A. Lopez, The multiple lines of defense strategy to sustain coastal Louisiana. *J. Coast. Res.* **2009**, 186–197 (2009).
47. H. Matsutomi, E. Yamaguchi, K. Naoe, K. Harada, Damage to reinforced concrete buildings and coastal trees due to the 2011 off the pacific coast of Tohoku earthquake tsunami. *Coast. Eng. Proc.* **1**, 51 (2012).
48. S. Tonkin, H. Yeh, F. Kato, S. Sato, Tsunami scour around a cylinder. *J. Fluid Mech.* **496**, 165–192 (2003).
49. B. Richmond *et al.*, Erosion, deposition and landscape change on the Sendai coastal plain, Japan, resulting from the March 11, 2011 Tohoku-oki tsunami. *Sediment. Geol.* **282**, 27–39 (2012).
50. S. Marras, M. A. Kopera, E. M. Constantinescu, J. Suckale, F. X. Giraldo, A residual-based shock capturing scheme for the continuous/discontinuous spectral element solution of the 2d shallow water equations. *Adv. Water Resour.* **114**, 45–63 (2018).