Global Environmental Change 40 (2016) 125–136

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

A method to estimate climate-critical construction materials applied to seaport protection

Austin Becker[a,*], Nathan T.L. Chase, PE[b], Martin Fischer, PhD[c], Ben Schwegler, PhD[c], Keith Mosher, MS[d]

[a] *Department of Marine Affairs, University of Rhode Island, Coastal Institute Room 213, 1 Greenhouse Road, Suite 205, Kingston, RI 02881,United States*
[b] *PE—RMC Water and Environment, 15510-C Rockfield Boulevard Suite 200, Irvine, CA 92618, United States*
[c] *Civil and Environmental Engineering, Stanford University, United States*
[d] *MS—Mosher Consulting/Stanford University, United States*

ARTICLE INFO

Article history:
Received 26 February 2016
Received in revised form 16 July 2016
Accepted 28 July 2016
Available online xxx

Keywords:
Climate adaptation
Demand estimation
Port protection
Sea level change
Coastal infrastructure resilience

ABSTRACT

Climate adaptation for coastal infrastructure projects raises unique challenges because global-scale environmental changes may require similar projects to be completed in many locations over the same time frame. Existing methods to forecast resource demand and capacity do not consider this phenomenon of a global change affecting many localities and the resulting increased demand for resources. Current methods do not relate to the most up-to-date climate science information, and they are too costly or too imprecise to generate global, regional, and local forecasts of "climate-critical resources" that will be required for infrastructure protection. They either require too much effort to create the many localized designs or are too coarse to consider information sources about local conditions and structure-specific engineering knowledge. We formalized the concept of a "minimum assumption credible design" (MACD) to leverage available local information (topography/bathymetry and existing infrastructure) and the essential engineering knowledge and required construction materials (i.e., a design cross-section template). The aggregation of the resources required for individual local structures then forecasts the resource demand for global adaptation projects. We illustrate the application of the MACD method to estimate the demand for construction materials critical to protect seaports from sea-level-rise-enhanced storm surges. We examined 221 of the world's 3,300+ seaports to calculate the resource requirements for a coastal storm surge protection structure suited to current upper-bound projections of two meters of sea level rise by 2100. We found that a project of this scale would require approximately 436 million cubic meters of construction materials, including cement, sand, aggregate, steel rebar, and riprap. For cement alone, ~49 million metric tons would be required. The deployment of the MACD method would make resource forecasts for adaptation projects more transparent and widely accessible and would highlight areas where current engineering knowledge or material, engineering workforce, and equipment capacity fall short of meeting the demands of adaptation projects.

1. Introduction

Scientists expect global sea level rise to range from 0.6 to 2.0 m by 2100 (Horton et al., 2014; Parris et al., 2012; Rahmstorf, 2010) and some project an upper bound of 4.3 m of rise by 2200 (Vellinga et al., 2008). Even a small amount of sea level rise can have major impacts on storm surge heights and associated flooding (NRC, 2010). Recent studies also found the number of strong (Cat 3–5) hurricanes in the Atlantic basin are likely to double in a warmed-climate scenario (Bender et al., 2010). These dramatic climate changes projected for 2100 and beyond may result in a worldwide competition for adaptation resources on a scale never seen before. Individuals and organizations will likely implement adaptation measures, such as constructing storm barriers to protect the world's major coastal seaports (NGIA, 2014). Such adaptation solutions are often discussed when decision makers think about long-term solutions to reduce risk from storm impacts (Blodget and Wile, 2012; Dronkers et al., 1990; Lonsdale et al., 2008). These types of projects will place simultaneous constraints on natural and manufactured resources, construction equipment, skilled labor, engineers, and project managers. Current estimating

---

* Corresponding author.
E-mail address: abecker@uri.edu (A. Becker).

http://dx.doi.org/10.1016/j.gloenvcha.2016.07.008
0959-3780/

methods are not adequate for global and regional estimates of the demand for basic resources like aggregate, sand, cement, specialty ships, and equipment like dredges, and coastal engineers. We call such resources "climate critical" and suggest that, occasionally, estimates of the demand for climate critical resources should be made to determine whether there are sufficient resources given the prevalent designs of protection structures.

Researchers have already generated estimates of the cost of adaptive structures for the U.S. (Aerts et al., 2014; Neumann et al., 2011) and at a global scale (Nicholls et al., 2010) for a wide variety of structures (Jonkman et al., 2013). These studies assume that the necessary resources will be available, should the funding be in place to carry out such projects. However, no such estimates of potential construction resource demand have been conducted to test this assumption against the projected supply.

Attempting a global estimate of climate-critical resources, which are typically under private control, necessarily raises a question of cumulative effects—which any one actor acting in self-interest would not necessarily consider. The built-in incentive of cost-efficient operations for most seaport managers virtually guarantees that all the actors will delay construction until the last responsible moment (Becker et al., 2013). In this light, we are reminded of the assumptions made by individual actors in the "credit risk business" pre-2008 and the assumptions made by individual actors planning for climate adaptation today. In the case of the credit risk market, actors assumed that individual risk was trivial because of the enormity of the global market. They did not consider that the cumulative effect of all the individual risks could actually deplete the global market, which, in hindsight, is exactly what happened. In our case, every city or seaport may estimate their own individual resource demand, correctly assuming the trivial strains each may place with respect to the global market. This assumption may be faulty because it does not consider that the cumulative effect of the individual projects could be large.

Estimating construction resources on a global and regional scale poses unique challenges, the most obvious of which is the site-specific nature of infrastructure design. Resource-demand estimates for necessary materials would normally emerge from individual designs of required adaptation structures, such as breakwaters and flood walls. Best practice engineering design methods require extensive site data, compliance with local standards and regulations, and multi-stakeholder performance criteria (Goda, 2000; del Estado, 2002; Thoresen, 2003). On a global scale, however, estimating construction resources required by individual designs would be a gargantuan task. For example, for a large infrastructure project such as developing a coastal defense system for a single port, the cost of a preliminary engineering design is typically on the order of 1–5% of the capital cost for construction (specific figures are generally proprietary, but see for example (WOFM, 2015; TCRP, 2010)). Following Hurricane Katrina, five years were required for a design-build approach to complete the 1.8-mile long Inner Harbor Navigation Canal Surge Barrier in New Orleans at a cost of approximately $1.1b (USACE, 2013), representing thousands of labor hours of skilled planners, engineers, scientists, and technicians. Assuming that 1% of this cost was required to complete a preliminary design and cost estimate, at an average professional staff fee of $200/h this would represent 55,000 h (which equates to 26 staff working full-time for a year).

While sufficiently accurate for budgeting and decision-making for individual projects, the method of forecasting resource demands from conceptual engineering designs of individual protection structures is too time-consuming to complete a global estimate. In our example of seaport protection, this effort includes agreement on forcing functions (i.e., wave energy, surge heights, tidal ranges), geotechnical design, design lifespans, and maintenance criteria in addition to condition assessment of existing structures (USACE, 2008). At the other end of the spectrum of estimating methods, conceptual, order-of-magnitude estimating methods reduce a structure to one or a few variables only (e.g., length of the protection structure) leaving out variables that are critical to estimate resource demand (e.g., depth of the structures and optimal alignment) (Hinkel et al., 2012). While quick, this method leads to results that are too inaccurate for a credible prediction of resource demands for adaptation structures. In summary, existing global demand estimation techniques are either too costly to apply or too inaccurate to understand the potential scale of this construction challenge. Against this background of current engineering practice, researchers seeking a global-scale estimate of construction resources face the tradeoff between simplifying assumptions and accuracy.

We show here a novel technique that addresses this tradeoff. We call the technique "minimum assumption credible design" (MACD). The intuition behind the approach is to combine engineering knowledge with easily available local data to minimize the effort required to design a structure that could protect an area while improving the accuracy of global estimates of materials required for adaptation structures. The approach relies on a MACD for coastal protection structures to estimate an order-of-magnitude demand of construction materials. The remainder of the paper explains the MACD approach by applying it to estimate the materials required to protect the world's most important seaports.

2. Port adaptation and sea level rise

The MACD approach is best described by explaining its application for a specific resource prediction challenge. We selected the estimation of the materials required to protect the most important seaports as the application area. We first highlight the importance of protecting these seaports and then describe the MACD method.

2.1. Why seaports?

In its most recent report, the Intergovernmental Panel on Climate Change (IPCC, 2014) found that over US$3 trillion in port infrastructure assets in 136 of the world's largest port cities are vulnerable to weather events and that, "ports will be affected by climate changes including higher temperatures, SLR, increasingly severe storms, and increased precipitation" (p. 675). As projected changes in sea level and storm intensity progress through this century and beyond, many coastal decision makers, particularly those with responsibility for port operations and development, will likely implement transformational adaptation strategies (Esteban et al., 2014; Kates et al., 2012) such as one of three major adaptation solutions: *elevate*, *defend*, or *retreat* (Aerts et al., 2014; Cheong, 2011; Kates et al., 2012). *Elevating* a port typically entails filling the port lands to raise them above the floodplain, reconstructing facilities at the new elevation, and designing a system to accommodate the difference in heights between the water level and the port infrastructure (MSPA, 2007). *Defending* a port entails construction of a coastal protection solution, such as a caisson breakwater, often with floodgates or locks to allow for the passage of ships (Dircke et al., 2012). In areas where adjacent land is not available for development, seaports can expand by filling in submerged land to a sufficient elevation that will also protect existing infrastructure. *Retreat* will likely be the option of last resort because adjacent hinterland areas are typically not vacant or available for relocation, and regional economies depend heavily on their local port. Unless a protected deep river or estuary is available, most seaports will likely either occupy their current location or be abandoned, perhaps in favor of consolidation into a