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DESIGNING PORT INFRASTRUCTURE FOR SEA LEVEL CHANGE: A SURVEY OF U.S. ENGINEERS

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DESIGNING PORT INFRASTRUCTURE FOR SEA LEVEL
CHANGE: A SURVEY OF U.S. ENGINEERS

BY

BENJAMIN R. SWEENEY

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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OF
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ABSTRACT

Seaports are particularly vulnerable to the impacts of climate change due to their coastal location. With the potential threat of up to 2.5m in sea level rise by 2100, resilient port infrastructure is vital for the continued operation of ports. There are strong economic and social incentives for seaports to provide long-term resilience against climate conditions. For example, service disruptions can cost billions of dollars and impact the livelihoods of those who depend on the port. Engineers play a pivotal role in improving the resilience of ports, as they are responsible for designing port infrastructure that will be adequately prepared for future sea level change (SLC). However, incorporating SLC is a challenging task due to the uncertainty of SLC projections, the long service lives of port infrastructure, and the differing guidelines and recommendations for managing SLC. Through an online survey of 85 U.S. port and marine infrastructure engineers, this research explores the engineering community's attitude and approach to planning for SLC for large-scale maritime infrastructure projects. Survey findings highlight the extent that projects incorporate SLC, the wide range of factors that drive the inclusion of SLC, and the numerous barriers that prevent engineers from incorporating SLC into design. This research emphasizes that traditional engineering practices may no longer be appropriate for dealing with climate change design variables and their associated uncertainties. Furthermore, results call for collaboration among engineers, port authorities, and policy makers to develop design standards and practical design methods for designing resilient port infrastructure.

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PREFACE

This thesis was written in manuscript form because it will be submitted to the American Society of Civil Engineers (ASCE) Journal of Waterway, Port, Coastal, and Ocean Engineering.

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1. Introduction

Maritime infrastructure such as wharves, docks, and piers are particularly vulnerable to sea level change (SLC) due to their coastal location (Asoriotis and Benamara 2012). Observational data and calculated predictions confirm that sea level is changing (NRC 2012; Parris et al. 2012; IPCC 2013), and therefore, engineers of port and maritime infrastructure projects need to design structures to be more resilient by considering SLC throughout the design process (Esteban et al. 2011; Becker, Toilliez and Mitchell 2015). However, this can be a challenging task due to the uncertainty of SLC projections as well as differing guidelines and recommendations for managing SLC, especially at the local level (Becker, Toilliez and Mitchell 2015). Furthermore, incorporating SLC considerations in port engineering structures is especially critical, as these projects tend to have long working lifespans, in some case exceeding 100 years (Becker, Toilliez and Mitchell 2015). There are strong economic and social incentives for seaports to provide long-term resilience against climate conditions (Becker, Toilliez and Mitchell 2015). For example, service disruptions can cost billions of dollars (Haveman and Shatz 2006) and impact the livelihoods of those who depend on the port (Becker et al. 2013). Despite the need for more resilient port infrastructure, there is currently no standard nationwide guidance for incorporating SLC information into design (Toilliez 2018). Therefore, if SLC is to be incorporated into a project, engineers must make subjective decisions on what SLC information they will use and what guidance they will follow.

To better understand how different firms, organizations, and individual engineers incorporate SLC information into a design, the researchers conducted an

online survey of 85 port and marine infrastructure engineers. This exploratory survey addresses the following questions:

1. In what capacity are port infrastructure designers incorporating a sea level change projection into their design specifications for large-scale port engineering projects?
2. Where do incentives and disincentives originate for US engineering firms to incorporate sea level change into the design specifications of large-scale port engineering projects?
3. For engineering firms that are incorporating sea level change, what strategies are the port infrastructure designers in those firms implementing in the design specifications of large-scale port engineering projects to cope with the scientific uncertainty of sea level change?

By conducting a first-of-its-kind assessment of the current level at which engineers consider SLC in the design of port and marine infrastructure, points of intervention can be identified where collaboration can occur to effectively promote better resilience strategies. The baseline data resulting from this research can also be used for tracking how engineers change their approach to incorporating SLC into their designs over time.

2. Background

2.1 SLC threatens maritime infrastructure

Globally-averaged, near-surface temperature records from 1850-2016 provide undeniable evidence of a long-term warming trend (WMO 2018) while temperature and salinity data from 1958-2014 suggest increasing ocean heat content (Dieng 2017). As the temperature of the ocean increases, thermal expansion causes the average global sea level to rise (Dieng 2017). Recent scientific projections of global mean sea level rise (GMSLR) range from 0.3 to 2.5 meters by 2100 (IPCC 2013; Jevrejeva 2016; Sweet et al. 2017). However, regional and local scale SLC is less understood (Gregory et al. 2001). For example, SLC predictions vary widely across coastal regions of the United States. Parts of Alaska could witness a sea level decrease due to land uplift, while Louisiana may suffer a rise that exceeds global mean sea level rise projections.

The rate of SLC is uncertain because it is dependent on future greenhouse gas emissions (Church et al. 2013) and the complex mechanisms that control changes in sea level such as inputs from glaciers, changes in land water storage, and coastal erosion (Rahmstorf 2007; DeConto et al. 2016). The uncertainty of GMSLR is relatively minor over the next few decades (2040-2060), but increases substantially around 2080 (Church et al. 2013). These uncertainties need to be appropriately and transparently accounted for when planning for coastal hazards such as SLC (Stephens et al. 2017). Conversely, neglecting uncertainty about SLC projections can result in considerable underestimation of flood risks (Ruckert et al. 2017).

Infrastructure development and risk management decisions often come with long-term commitments that can be climate sensitive (Hallegatte 2009). For example, the engineered design life of port infrastructure is typically 30-50 years, but these structures will often have service lives that exceed 100 years (Becker, Toilliez and Mitchell 2015; Taneja 2010; UNCTAD 1985). Thus, many structures built today will have to cope with uncertain climate conditions in 2100. However, a survey of port administrators (Becker et al. 2012) found that capital planning cycles at ports are typically only 5 to 10 years. This mismatch between planning and infrastructure lifetime presents a concerning outlook on the ability for port infrastructure to adapt to a changing climate (Becker et al. 2012). Alternative design options are often investigated for port capital planning projects, but often the low-cost alternative is opted for, which can be attributed to difficulties in planning for uncertainty (Taneja 2010).

A 2012 survey conducted by the American Association of Port Authorities (AAPA) showed that U.S. ports and their private sector partners planned to spend at least \$46 billion in port-related improvements through 2016 (AAPA 2012). Remarkably, a follow up port infrastructure investment survey in 2016 found that U.S. ports and their private sector partners plan to spend nearly \$155 billion in port-related improvements (AAPA 2016). This shows that infrastructure spending from 2016-2020 is expected to triple that of 2012-2016. While portions of this investment will be dedicated to dredging and navigational improvements, the 2016 survey found that key investments are being planned for terminals, berths, piers, equipment, expansion, facility rehabilitation, and road and rail connections (AAPA 2016). Another recent

study shows that \$49 million at the Port of Houston has been invested to expand a container yard that will add 50 acres of storage; \$36 million has been invested at Washington's Port of Everett to make the port ready to receive more cargo brought in by larger ships; and several others including the Alabama Port Authority and Port of Wilmington are engaged in dredging plans to bring in larger ships, which will lead to more cargo, and ultimately lead to the need for port expansion and infrastructure investment (Nabers 2018).

Seaports and port infrastructure will be especially vulnerable to SLC because they do not have the option to relocate, as their functionality depends on their coastal location (Asoriotis and Benamara 2012). Researchers predict that rising sea levels will affect 79 European ports by the end of the century (Christodoulou et al. 2018). Officials from the Port of Virginia are expecting a foot and a half of sea level rise in the next 30 years, causing them to invest in raising electrical power stations and moving data servers farther away from the water's edge (Phillips 2019). Changes in sea level will also have a direct effect on other coastal hazards such as storm surge (Neumann et al. 2015). Therefore, seaports will need to make decisions about how to adapt to future climate conditions. Successful port adaptation and resilience strategies will require collaboration across various stakeholders from engineers, planners, financiers, insurers, scientists, port operators, shippers, regulators, and emergency responders (Becker et al. 2013). Each group of stakeholders has a role to play in port resilience and adaptation, and each face their own set of challenges to overcome.

2.2 SLC uncertainty challenges engineers

Engineers and designers play a key role in increasing the climate resilience of seaports. They must consider not only their clients' needs, but also the needs of other stakeholders who depend on the infrastructure they design (Becker, Toilliez and Mitchell 2015). Since ports provide both private-sector profits and public services, stakeholders vary widely from shipping companies and insurers to local governments and local residents (Becker et al. 2013). The inadequate design of port infrastructure can have consequences for these stakeholders including physical damage to infrastructure and indirect damage to supply chains of goods and services (Becker et al. 2013). For engineers, the long service lives of port infrastructure coupled with uncertainty of regional SLC over the expected life of port infrastructure makes providing professional advice more challenging. Furthermore, a change in sea level can also have an effect on the geomorphology of a site, adding to that uncertainty (Becker, Toilliez and Mitchell 2015). SLC uncertainties, along with uncertainties of land cover and use, resource availability, and demographics in population in the future will require flexibility in infrastructure location and design (Olsen 2015). However, the standards, codes, and regulations that govern infrastructure are often slower to adapt to changes (Olsen 2015). This adds to the difficulty of answering the question: What level of SLC should engineers design for? Currently, there is no standard nationwide guidance for answering this question (Toilliez 2018) and there is a lack of design standards to guide this decision. There are several agencies and organizations such as the U.S. Army Corps of Engineers (USACE), National Oceanic and Atmospheric Administration (NOAA), and U.S. Department of Transportation Federal

Highway Administration (FHWA), as well as local and state governments that provide their own guidance, but use differing scales, projections, and uncertainties of SLC.

In planning, there is always a gap between what is known and what should be known, and in order to bridge this gap, flexibility is needed (Faludi 1977). However, engineers have traditionally operated under the assumption of stationarity, which assumes that natural systems fluctuate within an unchanging envelope of variability (Milly et al. 2008). Stationarity can be used to analyze numerous environmental hazards and design variables. Using flooding as an example, historic flood analysis can provide an estimation of the extent and intensity of flood scenarios and associate an exceedance probability to it (Merz and Thielen 2004). The usual procedure is to apply a flood frequency analysis to a given record of discharge data (Stedinger et al. 1993) and to transform the associated discharge to defined return periods (e.g., the 100-year event) with an estimated inundation extent and depth (Apel et al. 2009). The error associated with these estimations is acknowledged, but assumed to be reduced by additional regional and observations data (Milly et al. 2008). However, these natural systems no longer exist in an unchanging system because anthropic impacts have caused the Earth's climate to change (Milly et al. 2008). Studies have shown that even small changes in climate may result in large changes in storm events (Knox 2000). These climatic changes led Milley et al. (2008) to declare that stationarity is dead – it should no longer serve as a central, default assumption in risk assessment and planning.

This calls for a paradigm shift in planning, engineering, and design. Furthermore, to increase resilience in the built environment, new adaptive planning

and design strategies will be needed (Ahern 2011). Coming up with a successor is a daunting challenge due to complex patterns of change, significant uncertainties, and a constantly changing knowledge base from continual climate observation (Milley et al. 2008). Much of engineering practice is directed toward risk management, which has previously revolved around fixed specifications. For example, a building code may specify that the designer shall use a factor of safety of 1.7 in designing against live loads (ASCE 2013), which makes the engineer's job easier since some group of experts has done this probabilistic analysis work already (de Neufville 2004). Essentially, engineering does not typically design for a range of possibilities (de Neufville 2004). This is why incorporating and developing a new comprehensive approach to risk management and planning will be so challenging. There are numerous design variables that introduce some level of uncertainty, but SLC has an especially wide range of possibilities from 0.3m to 2.5m by the end of the century (Church et al. 2013; Stephens et al. 2017; Sweet et al. 2017).

2.3 Industry efforts address the SLC risks

Federal agencies recognize the need to incorporate climate change factors such as SLC into infrastructure design, but most design changes occur for structures that are being rebuilt after being damaged or completely destroyed (Savonis 2014). As of 2011, federal agencies such as USACE and the Environmental Protection Agency (EPA) pushed for the inclusion of SLC within the design of all federally funded projects, however, no mandates or policies have been issued (Headland et al. 2011). In 2015, the Obama administration issued Executive Order 13690 which proposed a new

Federal Flood Risk Management Standard. Under the new standard, infrastructure projects utilizing federal grants must abide by one of the following three design requirements: use data and methods informed by best-available climate science, build two feet above the 100-year flood elevation, or build to the 500-year flood elevation (White House 2015). This executive order provided some guidance on designing for SLC, however, in 2017, the Trump administration issued Executive Order 13807, which revoked these design requirements (White House 2017).

In lieu of design standards, the SLC challenges that ports face are on the radar of several industry leaders who are working on tools, providing guidance, and investing resources into helping ports become more resilient. For example, USACE has published technical guidance for adaptation to SLC (USACE 2014) and developed publicly available tools such as the Sea-Level Change Curve Calculator and the Sea Level Tracker. The Sea-Level Change Curve Calculator provides a way to visualize the USACE and other SLC scenarios for specific locations in the U.S. based off NOAA tide gauges. Furthermore, the COMET Program has recently produced an online educational tool that introduces the Sea-Level Change Curve Calculator and how it can be applied to scenario-based planning for SLC (COMET 2019). Not only does the lesson cover USACE resources, but also introduces the NOAA Sea Level Rise Viewer and NOAA's Sea Level Trends website where engineers and designers can access site-specific projections (COMET 2019).

Realizing that relative SLC at a given location should be an important component of site designs, members of the American Society of Civil Engineers (ASCE) Ports and Harbors Committee have also published recommendations to assist

engineers of marine civil works in the difficulties of designing for SLC (Becker, Toilliez and Mitchell 2015). Furthermore, ASCE's Committee on Adaptation to a Changing Climate developed a comprehensive manual of practice to aid engineers in the design of climate-resilient infrastructure (ASCE 2019). In addition to these valuable guidance tools, there are numerous other organizations and state and local governments that offer their own guidance and recommendations for designing for SLC (FHWA 2012; NRC 2012; "State of California Sea-Level Rise Guidance" 2018). With the abundance of information out there, the logical next step is to understand how port and marine infrastructure engineers utilize this information and in what capacity this information is being incorporated into design.

2.4 Related research on port stakeholder considerations of climate change impacts

Previous research suggests the importance (Becker et al. 2013; Becker, Toilliez and Mitchell 2015) and the difficulty (Milly et al. 2008; Ahern 2011; Olsen 2015) of designing more resilient infrastructure, but there is little understanding of the current state of the practice. Surveys have targeted port directors and other port operations personnel to gauge climate change planning efforts more generally (Bierling and Lorented 2008; Becker et al. 2012). While port directors play a role in planning for SLC, port engineers often make final determinations about how to incorporate SLC into infrastructure designs. Thus, the survey described in this paper focuses on engineers and their decision making processes to assess how SLC is currently considered in the design of port and marine infrastructure.

3. Methods

3.1 Participants

The survey targeted engineers from consulting firms, port authorities, and government agencies who have any experience working on a wide variety of port infrastructure projects in different coastal regions of the U.S. The sample approach focused primarily on members of ASCE's Coasts, Oceans, Ports, and Rivers Institute (COPRI). Participation was voluntary, and no compensation provided. The Institutional Review Board (IRB) of the University of Rhode Island approved this study.

After distributing the survey, 85 useable responses were received. The majority of all respondents work for private consulting firms (60) while those working for port authorities (16) and government agencies (9) make up the remainder of the respondents. Of the 85 responses, 62 respondents voluntarily provided the name of the organization they work. From these responses, 31 different private consulting firms and 11 different port authorities were represented, providing a broad state of the current practices for designing port infrastructure for SLC across the United States. There were nine private consulting firms represented which had more than one respondent for the firm; six firms with two respondents, two firms with three respondents, and one firm with four respondents.

Results showed that 59% of respondents had over 15 years of experience, 81% self-identified as a project manager or someone who makes final design decision on projects at their organization, and 68% reported spending more than half of their time

working on port infrastructure projects as opposed to working on other, non-port related, infrastructure projects.

Respondents were also asked to indicate their experience across different geographic regions. There were 46 respondents (54%) that indicated having experience in more than one geographic region. The region with the greatest number of respondents was the Gulf Coast (42), followed by Alaska (38), then the Southeast (36) and Mid-Atlantic (36), Northwest (33), Southern California (31), Northern California (30), Northeast (26), Hawaii (20), and with the least respondents, Great Lakes (18).

3.2 Procedure

In September 2018, the survey was first distributed to all members of COPRI's Ports and Harbors Committee through SurveyMonkey, a web service for conducting surveys. This approach allowed the researchers to easily reach a population spread across the U.S. The survey was also incorporated into the COPRI October 2018 newsletter, posted to the "Environmental, Coasts, Oceans and Water Infrastructure" forum within ASCE Collaborate, posted to the Coastal List (Center for Applied Coastal Research 2019), and shared on LinkedIn through SLC Subcommittee members' profiles. Furthermore, a snowball sampling (Atkinson and Flint 2001) approach was also employed where recipients of the survey were asked to distribute the survey among their professional networks in order to ensure a robust sample size that represents the nationwide engineering practices of designing port infrastructure

for SLC. Through these outlets, researchers believe they reached a representative portion of practicing port infrastructure engineers in the U.S.

3.3 Measures

The online survey instrument (Appendix 3A) was developed with a five-person project steering committee consisting of members from COPRI's Sea Level Change Subcommittee. The 20-item survey was designed for practicing engineers in the U.S. and estimated to take 10-15 minutes to complete. The survey was broken down into four sections: general information about the respondent, the capacity in which SLC is being considered in design, how SLC is being incorporated into design, and perceived barriers to incorporating SLC into design. To validate the survey for the intended audience, the survey was pilot tested by other members of the Ports and Harbors Committee (i.e., retired professional engineers, engineering professors, and regulatory engineers).

Nine out of the 20-items are presented in this paper in order to answer the three research questions. The nine questions are as follows: *In the past 5 years, about how many port infrastructure projects have you played a role in engineering and/or designing?* (Q6); *Of the port infrastructure projects you have worked on over the past 5 years, about how many have incorporated sea level change?* (Q7); *For which types of structures does your organization incorporate/consider sea level change during the design phase?* (Q8); *Does your organization use a policy/planning document that communicates how future sea level change should be incorporated into port infrastructure design projects?* (Q10); *What factors cause your organization to add a*

sea level change design component to a project? (Q12); When incorporating future sea level change into the design of port infrastructure, where does your organization obtain sea level change projections from? (Q13); How confident are you in the accuracy of the sea level change projections that are being incorporated into projects your organization designs? (Q14); In cases where sea level change is not incorporated into the design of port infrastructure projects, what are the potential reasons why? (Q17); and, From the list above, what are the three most common reasons why sea level change may not be incorporated into a project? (Q18). Of these nine questions, Q8, Q10, Q12, Q13, and Q17 allowed respondents to provide qualitative data through an *Other* text box or *Comments* text box. Furthermore, at the end of the survey, respondents were asked to provide general comments regarding the survey and/or designing port infrastructure for SLC.

Likert scales were used in the creation of some survey questions. Q8, Q12, and Q13 used a frequency Likert scale with response options of *Never*, *Rarely*, *Sometimes*, *Often*, and *Always*. Each of these three questions required responses for a series of sub-items. For example, Q8 listed out 17 different types of port infrastructure, Q12 presented respondents with five different scenarios, and Q13 had eight different sources of sea level data. Each sub-item in each question required the Likert scale. Q14 used a level of confidence Likert scale with options of *Not at all confident*, *Little confidence*, *Neutral*, *Fairly confident*, and *Very confident*. Q14 listed the same eight different sources of sea level data.

3.4 Data cleaning

In total, 118 responses to the survey were received, and 85 of the responses were useable. There were 12 respondents that indicated having no professional engineering and/or design experience working on port infrastructure projects, and 21 responses with no questions answered for the final three out of four sections of the survey. Therefore, those 33 responses were excluded. Partially incomplete responses, however, were included in the analysis.

As discussed in Section 3.3, Likert scales were used in four of the nine survey questions addressed in this paper. Due to scarcity of the data for some of the Likert scale response options, the data was bifurcated. For Q8, Q12, and Q13 which used a frequency Likert scale, response options *Never* and *Rarely* were grouped, as were *Often* and *Always*, thus leaving three groups, including the third as *Sometimes*. Similarly, for Q14 which used a level of confidence Likert scale, response options *Not at all confident* and *Little confidence* were grouped, as were *Fairly confident* and *Very confident*, with *Neutral* as the third group. For Q10, which asked about whether or not the respondent's organization had a formal document that communicates how SLC should be incorporated into design, responses options were grouped for simplified analysis. Those who responded *Yes, and we use it for all projects*; *Yes, and we use it for some projects*; and *Yes, but we rarely use it* were placed in one group ("Have Policy Document"). Those who responded *No* or *I am not sure* were placed in another group ("Don't Have Policy Document or Not Sure").

4. Results and Discussion

The results and discussion section describes survey respondents' perceptions of the state of the practice for designing port infrastructure for SLC, including organizational policies, sources of scientific data on SLC, SLC implications for design life, and reasons that projects do or do not consider SLC. This section uses the results of the survey to provide evidence with respect to the three research questions.

4.1 Capacity in which SLC is incorporated into design specifications

The first broad question the survey intended to answer was: In what capacity are port infrastructure designers incorporating a SLC projection into their design specifications for large-scale port engineering projects? This question aims to identify the current level at which engineers consider SLC and to produce baseline data to track how the state of the practice changes in the future. Appendix 2 provides a list of structure types that this survey considered "large-scale."

Respondents were asked the total number of port infrastructure projects they worked on in the past five years and the number of those projects that had incorporated SLC. On average, respondents played a role in designing 11.1 (SD: 9.9) port infrastructure projects in the past five years. Further analysis suggests that on average, 43% (SD: 39%; Median: 30%) of port infrastructure projects that respondents worked on over the past five years have incorporated SLC. Because engineers with more SLC design experience may have been more likely to respond to this survey and skew the results, 43% may not be an accurate nationwide indicator of the capacity in

which port infrastructure design incorporates SLC. It is likely that 43% is optimistic due to the potential sample bias.

To better understand the organizational level approaches to designing for SLC, respondents were asked if their organization has a policy or planning document that communicates how future SLC should be incorporated into port infrastructure projects. As shown in Figure 1a, 64% of respondents indicated that their organization did not have a policy or planning document, with only 29% having a document, and of those respondents, 9% use it for all projects, 16% use it for only some projects, and 4% use it rarely. The remaining 7% were unsure whether their organization had a SLC design document.

The responses to this question were then used to assess whether or not the organization having a policy or planning document had an effect on the number of projects that incorporated SLC (Figure 1b). There were 25 respondents (18 of which represented private consulting firms) in the “Have Policy Document” group and 60 in the “Don’t Have Policy Document or Not Sure” group. Within each group, the average percent of SLC incorporated projects that respondents worked on in the past five years was calculated. A difference between the two groups was found where the average percentage of projects that have incorporated SLC is 30% higher for respondents that work for an organization with a policy document (Mean: 65%; SD: 35%; Median: 67%) than those who do not (Mean: 35%; SD: 36%; Median: 20%).

Figure 1 - (a) Utilization of a policy document that guides SLC design decision making; (b) The effect of a policy document on the frequency of incorporating SLC into design

One explanation of this difference is that engineers who work for an organization with a formal document have been specifically informed on how to approach designing for SLC, which might give them confidence to recommend design changes to a client or an in-house design team. Additionally, document provides solid ground for the engineer to stand on when making these recommendations. Conversely, engineers without the documented support from their organization may be less willing to take the personal and professional risk that comes with making subjective decisions on how to incorporate SLC into a project. If an organization has not formally outlined how to design port infrastructure for SLC, it is potentially less likely that their engineers will incorporate SLC because they do not have the necessary protocols or tools to do so. Without a formalized or even knowledge of a formalized document, practitioners must wade through the differing guidance produced by various agencies.

Having a policy or planning document at the organization level could also become a selling point for the organization in competing with other private consulting

firms for a contract. Port authorities are beginning to require SLC considerations in the design and redesign of port infrastructure more frequently. In 2018, for example, the Port Authority of New York and New Jersey (PANYNJ) sent out a request for proposal (RFP) for the replacement of numerous wharf structures, which required the bid to provide best practice wharf design concepts that take into account sea level rise (PANYNJ 2018). As these projects and practices become more prevalent, private consulting firms that have a clear and specified approach to designing for SLC could have an advantage.

Researchers also examined the capacity in which SLC was incorporated across different types of port infrastructure projects. Respondents were asked how frequently their organization considers and/or incorporates SLC into the design of 17 different types of port infrastructure. To make comparisons between structure types that are similar in functionality, the 17 infrastructure types were grouped into six different subgroups: protection structures, berthing structures, cargo storage structures, connectivity infrastructure, electoral and operations, and water flow structures. Appendix 2 contains the descriptions of each structure type.

Figure 2 shows how often respondents believed their organization incorporates SLC for each structure type. The researchers grouped responses into three frequency categories. The y-axis shows the percentages of responses for each category. The structure type is on the x -axis, and the number of respondents with design experience for each structure type (n) is indicated in parenthesis next to or below the structure type.

Figure 2 – Types of structures – broken down by functional category – for which respondents acknowledged considering or incorporating SLC during the design phase, and how often the design for these structures considered or incorporated SLC

Structure types that are the closest to, and in most cases directly abutting, the waterfront had the highest percentage of either always or often incorporating SLC in their design. This applies to *Protection Structures* (berms, breakwaters, and seawalls) and *Vessel Berthing Structures* (dock structures and wharf structures). Conversely, port hinterland connections such as roads and railways, which are typically located further away from the waterfront, had two of the four highest percentages for either rarely or never incorporating SLC. Understandably, these findings suggest that the closer to the water a structure is located, the more likely the design of that structure will incorporate SLC.

4.2 Incentives and disincentives for incorporating SLC into design

The second research question inquired about: where do incentives and disincentives originate for U.S. engineering firms to incorporate SLC into the design specifications of large-scale port engineering projects? First, this section discusses the variety of factors that can act as an incentive to incorporate SLC and how the decision can originate from several different stakeholders. Conversely, for projects that do not incorporate SLC, this section then addresses the disincentives that prevent engineers from incorporating SLC and how the development of regulatory design standards can alleviate several barriers identified by respondents.

4.2.1 Incorporating SLC into design is motivated by a variety of factors

To better understand the driving forces behind designing port infrastructure for SLC, respondents were asked what factors cause their organization to add a SLC design component to a project. Realizing that for any given project, the decision to incorporate SLC could originate from any, or even a combination of these factors, respondents were asked to indicate how often each factor plays a role in causing SLC to be incorporated into a project (Figure 3).

Figure 3 – Potential factors that may cause port infrastructure engineers to incorporate SLC into the design specifications of port infrastructure projects. There was no standout factor that always drives the incorporation of SLC into design

Client requirements, engineering recommendations, and regulation requirements were the three leading factors that respondents suggest drive the incorporation of SLC in port infrastructure. However, the Often/Always group had the greatest percentage of respondents for four of the five factors. Incorporating SLC based on a life cycle cost/benefit analysis was the only exception. In this case, Never/Rarely (35%) was the most common response, but only by 1% over the Often/Always group (34%).

Simplifying the five factors listed, one factor is client dependent (*Client requirement*), one factor is regulatory dependent (*Regulation requirement*), and the other three factors are in the hands of the engineers (*Engineer makes recommendation to the client*, *Design alternative presented to the client*, and *SLC is incorporated based on life cycle cost/benefit analysis*). Responses to this question suggest that none of the three groups are leading the effort to incorporate SLC. Furthermore, responses suggest

the decision to incorporate SLC could originate from different stakeholders from project to project.

Although there were only slight variations in the responses, and there were no factors that stood out as being the least likely driver of SLC consideration, *Incorporating SLC based on a life cycle cost/benefit analysis* had the greatest percentage of respondents that said it was either *Never* or *Rarely* a driving factor. Perhaps engineers are not conducting a life cycle cost/benefit analysis, which would indicate a lack finances or incentives to execute long term planning, or engineers *are* conducting a life cycle cost/benefit analysis, but the results of the analysis suggest it would be more cost effective to ignore SLC. Further investigation into the use of life cycle cost/benefit analysis, long term planning from the engineering perspective, and design life challenges would shed more light on why this particular factor appears to play a very limited role in the decision to incorporate SLC into port infrastructure design. Additionally, although regulation was only the third most common factor, it is possible that regulation may be the leading factor in some geographic regions, such as California (“State of California Sea-Level Rise Guidance” 2018), but a non-existent factor in other regions, such as the Gulf Coast.

To gauge how engineers determine the level of SLC they need to design for, respondents were asked from where their organization obtains SLC projections (Figure 4). As mentioned in Section 2.2, numerous organizations have produced SLC projections with varying rates. Therefore, engineers must make decisions on which projections they will rely on. According to respondents, the most frequently used source of SLC projection data was NOAA (65%), followed by USACE (49%).

Although the third most commonly used source was state or local organizations (40%), there were an equal percentage of respondents who rarely or never use state or local projections (40%). For five out of the seven sources shown in Figure 4, at least half of the respondents indicated either sometimes, often, or always using that particular source. Therefore, outside of the fact that NOAA and USACE are the most relied upon sources, these findings highlight that there is very little, if any, standardization across the approach taken by different organizations to incorporate SLC into design. It appears that any one organization could use different sources of SLC projections for any particular project. This could be due to different clients requesting the use of different SLC data, but it could also suggest that there is a lack of consistency across planning for SLC.

Figure 4 – Respondents indicated relying most frequently on NOAA and USACE to obtain SLC projection data when their organization is designing port infrastructure for SLC

For each of the possible sources of SLC data, respondents were asked how confident they were in the accuracy of the SLC projections that are being incorporated

into projects that their organization designs. Not only are NOAA and USACE the most relied up sources to obtain SLC data, they are also the sources that respondents were the most confident in (Figure 5). In general, respondents were relatively confident in the accuracy of projections from all of the sources listed. For each SLC projection source identified, 12% or less of respondents reported little or no confidence in the accuracy of projections. Although additional survey results show that respondents begin to lose confidence in SLC projections as project design life increases (Results Appendix 4D: Figure 12), engineers represented in this sample are generally confident in these projections.

Figure 5 – Respondents acknowledged that they were the most confident in the accuracy of SLC projections from NOAA and USACE compared to other sources of SLC projection data

4.2.2 Lack of design standards were a key barrier to incorporating SLC into design

To assess the barriers to incorporating SLC into infrastructure designs, the survey listed 14 different potential barriers and asked respondents to select which

barriers they have encountered during their professional career. The 14 barriers were derived from findings from previous studies and the institutional knowledge of the engineers who helped design the survey. Becker, Toilliez and Mitchell (2015) address the lack of nationwide guidance, and Stephens et al. (2017) discusses the challenges of dealing with uncertain SLC projections. As previously mentioned in Section 3.3, the researchers established a five-person project steering committee consisting of members from COPRI's Sea Level Change Task Committee. The steering committee was influential in developing this list of potential barriers and ensuring survey questions and response options were valid for the intended audience. An additional five industry professionals also pilot tested the survey and were asked to provide feedback on the questions and response options.

Of the 70 respondents to this question, 36 indicated that *having no standards* was a reason for not incorporating SLC. A *lack of project funding* and the *client not wanting to incorporate SLC* were tied as the second most commonly acknowledged barriers. Furthermore, 17 of the respondents indicated that there were other barriers that they felt prevented SLC from making it into final design which were not included the list provided within the survey. Other barriers included *site constraints*, *raising certain structures for future conditions renders them unusable during current tidal conditions*, and *difficulty incorporating SLC for retrofit, rehab, and upgrade projects on structures that were not originally designed for SLC*. Figure 6 shows that every barrier listed was seen as a potential barrier by at least 10 respondents. These findings suggest engineers felt that numerous barriers prevent SLC from being incorporated into design.

Figure 6 – Potential reasons why SLC may not be incorporated into the design of port infrastructure projects. Responses were ranked from left to right in descending order of the total number of respondents who confirmed that the potential reason provided in the survey was in fact a barrier that can prevent SLC from being incorporated into design

The only barrier that more than half of respondents (36) acknowledged was *No standards*. Regulatory standards and codes remove the burden on engineers to make their own subjective decisions when determining how to incorporate SLC and make other barriers less relevant. For example, design standards would override the client’s decision, which respondents saw as both a major barrier in SLC design and as a primary driving factor in the decision to design for SLC. The results show that the client clearly has a majority of the decision making power, but standards provide consistency in SLC design specifications. Additionally, *Lack of project funding* would no longer hinder the incorporation of SLC. One respondent noted, “*Lack of planning or vision for surrounding facilities being modified for sea level change has caused accommodating for sea level change to be the first item removed from scope of project to meet funding.*” When funding is limited, SLC can be low on the priority list. However, as another respondent alluded, removing SLC from the scope of a project would not be an option if there are regulatory design standards in place, stating, “*The cost differential cannot be justified, especially when it is not a regulatory compliance issue.*”

As mentioned in Section 2.3, federal regulation has had some success under Executive Order 13690. Until it was revoked, EO 13690 provided clear flood protection requirements for designing infrastructure. Although SLC is projected to be highly varied across coastal regions of the U.S., these requirements provided flexibility and allowed owners and engineers to select one of three options: use best available climate science, design for the 1-percent-annual-chance flood (100-year flood) plus an additional two feet, or design for the 0.2-percent-annual-chance flood (500-year flood). This flexibility alleviates some of the financial stress by not forcing a specific action onto an owner. Of course, some ports have a greater institutional capacity to cope with these requirements, but providing different options minimizes any strategic advantage one port would have over another when requiring all U.S. ports to address increased flood risk.

Restablishing EO 13690 would be a positive approach toward improving the resilience of seaports nationwide. However, as discussed in Section 2.2, the concept of stationarity and utilizing 100-year flood or 500-year flood events to guide design is an outdated one. Due to climatic changes, the return period probability for storm events is no longer what it once was. The entire globe is witnessing more intense storm events and more frequent high intensity storms, so it can no longer be accurately predicted what a 100-year storm brings in terms of flood extent and depth.

ASCE has a unique role to play in the development and improvement of regulatory standards and codes. ASCE has proven to be a leader in the development of flood resistant design standards through ASCE/SEI 24-14 (ASCE 2014). ASCE 24 is the industry standard for flood-resistant design and construction, and has been adopted

by several building codes (Ayyub 2019). However, ASCE 24 does not adequately address the implications that SLC can have on design flood elevations (ASCE 2014). An updated version of ASCE 24 that does account for SLC would be a significant benefit toward implementing regulatory design standards across the nation. Just as EO 13690 was developed with input from the engineering community, any future federal regulation should also be crafted in a collaborative setting. In Canada, the engineering profession believes that engineering codes, standards, and work practices should consider climate change, and that federal and provincial governments must collaborate with the engineering profession on climate change policies for the benefit of the public (Engineers Canada 2013).

Alternatively to federal regulations, states could take it upon themselves to increase the resilience of their port infrastructure. In the context of seaports, state transportation agencies could establish and enforce regulatory design standards. Some states have already deemed their current codes and standards inadequate to prepare infrastructure for a changing climate and wrote their own standards (Ayyub 2019). For example, in California, Executive Order S-13-08 was issued in 2008 which directed state agencies to plan for SLC. This led the California Department of Transportation to develop guidance on incorporating SLC into transportation infrastructure projects (Caltrans 2011).

4.3 SLC uncertainty challenges are minimized by avoiding long-term design decisions

The final research question asked: For engineering firms that are incorporating SLC, what strategies are the port infrastructure designers in those firms implementing in the design specifications of large-scale port engineering projects to cope with the

scientific uncertainty of SLC? Some respondents indicated designing port infrastructure in a way that can accommodate future upgrades to keep pace with SLC (Results Appendix 4D), but results ultimately suggest that SLC uncertainty has not been a major consideration due to relatively short design lives, where uncertainty is not as significant as it is toward the end of the century. Therefore, strategies to cope with uncertainty have not been widely developed or implemented.

Figure 7 – Respondents ranked the three most common reasons why SLC may not be incorporated into a port infrastructure project. *Client does not want to incorporate SLC into the design* was the reasons that received the greatest number of most common votes

From Figure 7, respondents perceived the *client not wanting to incorporate SLC* (count=14) as the most common barrier. *Design life not extending far enough into the future to consider SLC* was the second most common barrier (count=8). This suggests that since these structures often have relatively short design lives, the projected sea levels at the end of their design lives are not significant enough to warrant incorporating into design specifications. However, respondents also commented on the difficulties of incorporating SLC for retrofit, upgrade, or expansion projects that involve structures not originally designed for future SLC. As one responded stated, “*The biggest hurdle is in retrofit wharf construction. The costs are*

prohibitively huge to raise marine deck structures.” Another wrote, “So much of the work is retrofit of existing docks that generally it doesn’t make financial sense to raise.” And a third reported, “It is hard to accommodate significant sea level rise with existing large marine terminals (multiple thousand feet of wharf, 200+ acres, rail, etc.) – it is not financially feasible.” This raises attention on how new infrastructure is designed, and highlights the importance of new infrastructure incorporating SLC. Furthermore, these findings call into question port planning time frames and the rigid methodology of designing structures for a specified lifetime or “design life” rather than the structure’s “service life” (Figure 8).

<p><i>Design Life</i> - The theoretical period of time during which engineers expect a structure to be fully operational.</p> <p><i>Service Life</i> – The period of time in which the structure is actually in use, from construction completion to failure.</p>

Figure 8 – Definitions of “design life” and “service” life from the engineering perspective of determining the age of infrastructure assets

Design life of port infrastructure varies depending on structure type, but typically ranges from 30-50 years. However, it is not uncommon for some port infrastructure to have service lives that exceed 100 years (Becker, Toilliez and Mitchell 2015). This is a concerning disconnect when designing port infrastructure for SLC. For example, new infrastructure designed for the projected sea levels of 2050 could likely remain in service beyond 2050. Therefore, the design may be inadequate for the change in sea level between 2050 and the end of its service life. Alternatively, the structure could be repaired, retrofit, or upgraded at the end of its design life, but as

respondents said, it is often more difficult to design for higher sea levels after initial construction. The significant uncertainties in SLC rates combined with the uncertainties of service life make designing for SLC challenging. Nevertheless, designing port infrastructure for a theoretical design life hinders the opportunity for ports to be more resilient in the future.

4.4 Recommendations

To improve the resilience of port infrastructure in the long term, the engineering community needs to reconsider traditional engineering practices that involve designing for a specific design life. An alternative approach is Life Cycle Cost Analysis (LCCA). Engineers designing for the impacts of climate change have become increasingly reliant on this approach. ASCE's Structural Engineering Institute (SEI) advocates for the use of LCCA design practices by stating, "Structural engineering is undergoing a profound change towards a life-cycle oriented design philosophy where the classical point-in-time design criteria are extended to account for more comprehensive time-variant performance indicators over the entire service life" (Biondini and Frangopol 2017). A study conducted by ICF International, Inc. also highlights the benefits of this approach where the authors support LCCA by saying, "This methodology can be used to support decision making regarding climate change adaptation alternatives under compounded uncertainty. In addition, this methodology can be used to determine which adaptation design alternative is the most consistently resilient across the range of climate change and disaster event scenarios" (Rodehorst et

al. 2018). This could be a potential way forward for engineers of port and marine infrastructure to navigate the challenges of designing for SLC.

The results of this survey also present new opportunities for future research that addresses climate change adaptation and resilience for seaports. The inconsistencies in approaching SLC design challenges and the lack of SLC design standards highlighted in this paper calls for collaboration among the engineering community, port authorities, and regulating bodies to improve the resilience of port infrastructure. Developing design standards collaboratively can help engineers overcome the barriers that currently prevent them from incorporating SLC. With design standards in place, many of the other barriers acknowledged by respondents would no longer exist. Therefore, further exploration and discussion is required to determine the most effective approach to implementing design standards. Should regulation be implemented at the federal level? Should states be the ones to develop their own design standards? Should standards be applied based on design life? Should standards be specific to the type of infrastructure? These questions deserve further dialogue as SLC becomes an increasing threat to port infrastructure.

Also, the opportunity exists for private consulting firms that have a policy or planning document for SLC design to share resources, tools, and best practices with other members of the engineering community. Organizations such as ASCE have proven to be great facilitators of this type of knowledge sharing. Given the massive amounts of infrastructure spending that ports are planning in the next five years, ensuring that these investments are sustainable and resilient to future environmental conditions should be a top priority.

5. Limitations of Research

This was the first nationwide survey of port and marine infrastructure engineers regarding the practice of designing port infrastructure that is resilient to SLC. The sample originated with members of COPRI who have port infrastructure design experience, and expanded through snowball sampling. There were at least 31 different private consulting firms and 11 different port authorities represented in this sample, but there are clearly port infrastructure engineers at other consulting firms and port authorities across the country. It is difficult to determine the total number of consulting firms in the U.S. that work on port infrastructure projects, and therefore, it is difficult to gauge what portion of the entire population responded to the survey. Survey recipients who did not respond may not be interested in SLC design issues. Therefore, responses may be skewed toward engineers who are aware of the challenges brought by SLC and who have more experience designing port infrastructure projects for SLC.

The researchers designed the survey to gauge the general state of the practice across the U.S. Therefore, the results are not indicative of engineering practice within specific regions, and are not indicative of engineering practice outside of the U.S. SLC impacts will vary, resulting in SLC design challenges to become a greater priority in some regions. The survey was not designed to identify the location of port infrastructure projects that respondents have worked on. Since 46 respondents acknowledged having experience in multiple different geographic regions, results

cannot determine the location of each project a respondent worked on, therefore, responses could not be analyzed separately based on geographic location.

A sample of engineers within specified geographic regions would provide findings for further comparison. This survey was designed for engineers working for private consulting firms, port authorities, and government agencies. As a result, the researchers may have overlooked potential differences in SLC design approaches between these groups. Separate surveys that target each group individually could reveal differences in approach to designing for SLC. While additional details of engineering practices need to be explored in this area, the researchers feel that this study provides informative baseline data where key issues in the resilient design of port infrastructure can be identified and addressed.

Bifurcated Likert scales used for presenting results is also a limitation of the survey and data collected. Although data analysis was conducted with and without bifurcating the data and results were similar in each instance, results had only slight variations when the data was bifurcated. However, due to the similarity in results of the non-bifurcated data and the data that was bifurcated as discussed in Section 3.3, the researchers believe that bifurcating the data in this way was acceptable.

Potentially gathering a more international dataset or even tailoring the survey to specific audiences or stakeholders, this could provide more future variability in the outcomes.

6. Conclusion

SLC design decisions made today have long-term impacts on the resilience of port infrastructure. Engineers must consider SLC and climate change impacts when designing port infrastructure to ensure that ports can continue to serve their essential role in the global economy in the coming decades. In serving the public interest, engineers are uniquely qualified and positioned to ensure port infrastructure is resilient for future sea level scenarios. However, adequately designing port infrastructure for SLC is a challenging task due to the uncertainty of SLC projections and the long service lives of port infrastructure. The inconsistencies revealed by this study suggest that the incentive to incorporate SLC into design is inconsistent from project to project, as are the barriers that prevent incorporating SLC into design. Furthermore, SLC projection data varies across NOAA, USACE, IPCC, state and local organizations.

To overcome these challenges, the engineering community needs to develop systematic and practical methods for incorporating SLC into design decisions. Engineers have the opportunity to work with both port authorities and regulatory bodies to help improve resilience efforts through knowledge sharing of successful design strategies, the development of design standards, and transitioning away from the traditional frameworks that engineers have operated within. Only 29% of respondents indicated that their organization had an internal policy or planning document that communicates how to design for SLC. Knowledge sharing between organizations could promote the adoption of formal guidelines and lead to more consistency in the engineering community's approach. Findings also suggest that the

lack of design standards in this area leads to engineers and their clients disregarding SLC more frequently. Regulatory design standards would alleviate some challenges, but the development of such standards needs more robust dialogue between engineers and regulators. Lastly, designing port infrastructure for a theoretical point in time can leave structures at risk to SLC beyond its design life. Future retrofit and upgrade projects can ensure structures are resilient throughout their service lives, but as respondents noted, it is much more difficult to incorporate SLC as an afterthought. Engineers can help improve the resilience of port infrastructure by transitioning to a life cycle cost analysis design approach, which is better suited to address the uncertainties that climate change introduces.

Appendix 1: Appendix Introduction

The appendixes below describe the aspects of this study in greater detail. They provide greater detail on different types of port infrastructure, life cycle cost analysis design, additional methods, and additional results obtained from the survey. We also provide a copy of the survey instrument.

Appendix 2: Defining Port Infrastructure

This appendix provides more information on what the researchers considered “large-scale” port infrastructure projects, as well as the different types of port infrastructure that were listed in question eight of the survey: *For which types of structures does your organization incorporate/consider sea level change during the design phase?* Table 1 provides definitions for each structure type.

Table 1 – Definitions of structure types used in the survey instrument

Structure Type	Definition
Wharf structures	The place at which ships tie up to unload and load cargo. The wharf typically has front and rear loading docks (apron), a transit shed, open storage areas, truck bays, and rail tracks
Dock structures	Structure built along, or at an angle from, a navigable waterway so that vessels may lie alongside to receive or discharge cargo
Open cargo storage areas	Unshedded where cargo is left while awaiting to be loaded onto a ship or picked up for inland distribution
Landside road connections	Roads originating and ending at the port for the transportation of cargo to and from the port by truck
Landside rail connections	Railroad tracks originating and ending at the port for the transportation of cargo to and from the port by truck train
Operating buildings	Buildings that contain the operations of the port and maintain the day to day functionality of the port
Cargo storage buildings	Covered buildings where cargo is left while awaiting to be loaded onto a ship or picked up for inland distribution
Data centers	Dedicated space within a building, or a group of buildings used to house computer systems and associated components such as telecommunications
Electrical/data transmission systems	Systems that move electrical energy and/or data throughout the interconnected lines within the port

Electrical gear	General electrical equipment that the port relies on for day to day operations
Storm water utilities	Control devices and systems for the management of the quantity and quality of stormwater (sometimes combined with sanitary facilities)
Fresh water utilities	Structures designed for improving the quality of water to make it more acceptable for a specific end-use such as drinking or industrial water supply
Sanitary facilities	Facilities designed and constructed for the safe disposal of human waste
Breakwaters	Structures constructed near the coasts to protect an anchorage or berthing site from the effects of both weather and longshore sediment transport
Seawalls	Wall or embankment erected to prevent the sea from encroaching on or eroding an area of land
Berms	Level space, shelf, or raised barrier, usually made of compacted soil or other materials
Flood gates	Adjustable gates used to control water flow in flood barriers, reservoir, river, stream, or levee systems
<i>Definitions provided by Port of New Orleans <https://www.portnola.com/> and Wikipedia</i>	

Appendix 3: Additional Methods

This appendix provides additional information on the survey and methods used for data analysis. This appendix also includes a copy of the survey instrument.

Appendix 3A: Copy of Online Survey Instrument

U.S. Coastal Port Infrastructure Design Practices

Consent

The University of Rhode Island Department of Marine Affairs, in partnership with the Ports and Harbors Committee of the American Society of Civil Engineers, invites you to take part in a research study to gauge the port and marine infrastructure engineering community's attitude and approach to planning for sea level change. Please read the following before agreeing to be in the study. Questions will be asked about if/how sea level change is incorporated into large-scale engineering projects. There are no known risks, benefits or compensation.

Your participation and responses will be strictly confidential. In aggregate, the responses may be used to help track how firms and other organizations change their approach to incorporating sea level change into their designs over time and will be incorporated into research papers and presented at academic and industry conferences.

The decision to participate in this study is entirely up to you. You may refuse to take part in the study at any time without affecting your relationship with the investigators of this study or the University of Rhode Island (URI). Your decision will not result in any loss of benefits to which you are otherwise entitled. You have the right not to answer any single question, as well as to withdraw completely from the survey at any point during the process; additionally, you have the right to request that the researchers not use any of your responses. If you agree to be in this study, it will take you approximately 15 minutes to complete this survey.

You have the right to ask questions about this research study and to have those questions answered, during or after the research, by contacting Austin Becker from the Department of Marine Affairs at URI, at (401) 874-4192.

Additionally, you may contact the URI Institutional Review Board (IRB) if you have questions regarding your rights as a research participant, questions, complaints or concerns which you do not feel you can discuss with the investigator. The University of Rhode Island IRB may be reached by phone at (401) 874-4328 or by e-mail at researchintegrity@etal.uri.edu. You may also contact the URI Vice President for Research and Economic Development by phone at (401) 874-4576.

If you would like to keep a copy of this document for your records, please print or save this page now. You may also contact the researcher to request a copy.

By clicking "Continue" below to be taken to the survey, you indicate that you have read and understood the above and volunteer to participate in this study.

Respondent Profile and General Information

Before taking this survey, please read the following definitions.

Sea level change:

For the purposes of this survey, sea level change refers to the net sea level change resulting from both the change in ocean volume (eustatic sea level), and land subsidence (isostatic sea level).

U.S. Coastal Port Infrastructure:

For the purposes of this survey, port infrastructure refers to all hard infrastructure assets necessary for carrying out of all port services, as well as man-made vertical/sloping structures within the U.S. Examples of port infrastructure include, but is not limited to, wharves, docks, piers, revetments, open cargo storage areas, landside road and rail connections, operating buildings, cargo storage buildings, data centers, electrical/data transmission systems, electrical gear, storm water utilities, wastewater utilities, breakwaters, seawalls, berms, and flood gates.

1. Do you have any professional engineering and/or design experience working on port infrastructure projects?

- ☐ Yes
☐ No

2. How many years of professional engineering and/or design experience do you have working on port infrastructure projects?

3. Over the past 5 years, roughly how much of your time has been spent working on port infrastructure projects?

0% 100%

4. What type of organization do you currently work for?

- ☐ Private Design Firm/Consulting Firm ☐ Government Agency
- ☐ Port Authority
- ☐ Other (please specify)

5. Are you or were you a project manager or someone who makes final design decisions on projects at your organization?

- ☐ Yes ☐ No

Comment (Optional)

U.S. Coastal Port Infrastructure Design Practices

Sea Level Change Design Considerations

6. In the past 5 years, about how many port infrastructure projects have you played a role in engineering and/or designing?

7. Of the port infrastructure projects you have worked on over the past 5 years, about how many have incorporated sea level change?

8. For which types of structures does your organization incorporate/consider sea level change during the design phase?

	Never	Rarely	Sometimes	Often	Always	I don't have experience with this structure type
Wharf structures	☐	☐	☐	☐	☐	☐
Dock surfaces	☐	☐	☐	☐	☐	☐
Open cargo storage areas	☐	☐	☐	☐	☐	☐
Landside road connections	☐	☐	☐	☐	☐	☐
Landside rail connections	☐	☐	☐	☐	☐	☐
Operating buildings	☐	☐	☐	☐	☐	☐
Cargo storage buildings	☐	☐	☐	☐	☐	☐
Data centers	☐	☐	☐	☐	☐	☐
Electrical/data transmission systems	☐	☐	☐	☐	☐	☐
Electrical gear	☐	☐	☐	☐	☐	☐
Storm water utilities	☐	☐	☐	☐	☐	☐
Fresh water utilities	☐	☐	☐	☐	☐	☐
Sanitary facilities	☐	☐	☐	☐	☐	☐
Breakwaters	☐	☐	☐	☐	☐	☐
Seawalls	☐	☐	☐	☐	☐	☐
Berms	☐	☐	☐	☐	☐	☐
Flood gates	☐	☐	☐	☐	☐	☐
Other flood mitigation measures (Please specify below)	☐	☐	☐	☐	☐	☐

Other flood mitigation measures

9. In your experience, how likely are the design specifications of port infrastructure projects to incorporate sea level change in the following geographic locations?

	Never	Rarely	Sometimes	Often	Always	I don't have experience with projects in this area
Northeast US (Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut)	☐	☐	☐	☐	☐	☐
Mid-Atlantic US (New York, New Jersey, Pennsylvania, Delaware, Maryland, Virginia)	☐	☐	☐	☐	☐	☐
Southeast US (North Carolina, South Carolina, Georgia, Atlantic Coast of Florida)	☐	☐	☐	☐	☐	☐
Pacific Northwest US (Oregon and Washington State)	☐	☐	☐	☐	☐	☐
Northern California (North of Monterey, CA, including Monterey, CA)	☐	☐	☐	☐	☐	☐
Southern California (South of Monterey, CA)	☐	☐	☐	☐	☐	☐
Alaska	☐	☐	☐	☐	☐	☐
Hawaii	☐	☐	☐	☐	☐	☐
Gulf Coast US (Texas, Louisiana, Mississippi, Alabama, Gulf Coast of Florida)	☐	☐	☐	☐	☐	☐
Great Lakes US	☐	☐	☐	☐	☐	☐
International	☐	☐	☐	☐	☐	☐

10. Does your organization use a policy/planning document that communicates how future sea level change should be incorporated into port infrastructure design projects?

- ☐ Yes, and we use it for all projects
 ☐ No
- ☐ Yes, and we use it for some projects
 ☐ I am not sure
- ☐ Yes, but we rarely use it

Comment (Optional)

11. Does your organization typically design port infrastructure in a way that can accommodate future upgrades to keep pace with sea level change?

☐ Never

☐ Often

☐ Rarely

☐ Always

☐ Sometimes

Comment (Optional)

U.S. Coastal Port Infrastructure Design Practices

Incorporating Sea Level Change into Design

12. What factors cause your organization to add a sea level change design component to a project?

	Never	Rarely	Sometimes	Often	Always	I don't know
Client states that design should consider future sea level change and/or climate change in the RFP	☐	☐	☐	☐	☐	☐
Engineer at our firm recommends to the client that future sea level change should be incorporated into the design	☐	☐	☐	☐	☐	☐
Engineer at our firm presents an alternative design option to the client that considers sea level change	☐	☐	☐	☐	☐	☐
Regulation requires sea level change to be incorporated	☐	☐	☐	☐	☐	☐
Sea level change is incorporated based on a life cycle benefit/cost analysis	☐	☐	☐	☐	☐	☐
Other (please specify below)	☐	☐	☐	☐	☐	☐

Other

13. When incorporating future sea level change into the design of port infrastructure, where does your organization obtain sea level change projections from?

	Never	Rarely	Sometimes	Often	Always
National Oceanic and Atmospheric Administration (NOAA)	☐	☐	☐	☐	☐
US Army Corps of Engineers (USACE) sea level change curve calculator	☐	☐	☐	☐	☐
International Panel on Climate Change (IPCC)	☐	☐	☐	☐	☐
National Research Council (NRC)	☐	☐	☐	☐	☐
State projections	☐	☐	☐	☐	☐
Local projections	☐	☐	☐	☐	☐
University/academic research	☐	☐	☐	☐	☐
Projections are calculated in-house based on historical water level data trends	☐	☐	☐	☐	☐
Other (please specify below)	☐	☐	☐	☐	☐

Other

14. How confident are you in the accuracy of the sea level change projections that are being incorporated into projects your organization designs?

	Not at all confident	Little confidence	Neutral	Fairly confident	Very confident	N/A (I don't use projections from this source)
National Oceanic and Atmospheric Administration (NOAA)	☐	☐	☐	☐	☐	☐
US Army Corps of Engineers (USACE) sea level change curve calculator	☐	☐	☐	☐	☐	☐
International Panel on Climate Change (IPCC)	☐	☐	☐	☐	☐	☐
National Research Council (NRC)	☐	☐	☐	☐	☐	☐
State projections	☐	☐	☐	☐	☐	☐
Local projections	☐	☐	☐	☐	☐	☐
University/academic research	☐	☐	☐	☐	☐	☐
Projections calculated in-house based on historical water level data trends	☐	☐	☐	☐	☐	☐
Other (specified from the question above)	☐	☐	☐	☐	☐	☐

15. Even if you use/have used more than one of the sea level change projection sources listed in questions 13 and 14, generally how confident are you in the accuracy of those sea level change projections being used for structures with the following design lives?

	Not at all confident	Little confidence	Neutral	Fairly confident	Very confident	I don't incorporate sea level change for projects with this design life
20 year design life	☐	☐	☐	☐	☐	☐
30 year design life	☐	☐	☐	☐	☐	☐
50 year design life	☐	☐	☐	☐	☐	☐
100 year design life	☐	☐	☐	☐	☐	☐
Greater than 100 year design life	☐	☐	☐	☐	☐	☐

Please note for question 16: The following question asks about different sea level change curve scenarios. Sea level change curves are often displayed on a graph and are based on future greenhouse gas emission possibilities (e.g. low emission scenario, intermediate emission scenario, high emission scenario). Different sources may use a different range of emission scenarios.

An example is provided below that uses high, intermediate-high, intermediate-low, and low emission scenarios.

Modified NOAA sea level projection curves (Modified from Parris et al., 2012)

16. For structures with the following design lives, what sea level change curve scenarios (if any) do you typically use when incorporating sea level change into the project's design specifications?

	Low Scenario	Intermediate Scenario	High Scenario	Other (please specify below)	I don't incorporate sea level change for projects with this design life
20 year design life	☐	☐	☐	☐	☐
30 year design life	☐	☐	☐	☐	☐
50 year design life	☐	☐	☐	☐	☐
100 year design life	☐	☐	☐	☐	☐
Greater than 100 year design life	☐	☐	☐	☐	☐

Other

U.S. Coastal Port Infrastructure Design Practices

Not Incorporating Sea Level Change into Design

17. In cases where sea level change is *not* incorporated into the design of port infrastructure projects, what are the potential reasons why? (Check all that apply)

☐ Sea level change is too politically sensitive	☐ Client does not want to incorporate sea level change into the design
☐ Design life of projects do not extend far enough into the future to consider sea level change	☐ Lack of project funding for incorporating sea level change
☐ There is no nationwide guidance	☐ Too much uncertainty with sea level change projections
☐ There is no state guidance	☐ Land use at ports is always changing, so projects aren't designed with long term considerations
☐ There is no local guidance	☐ Probability of sea level change values are not high enough to take action on
☐ Lack of consistent guidance from a primary source	☐ There are no standards
☐ Differing guidance from multiple sources	☐ There are no codes
☐ Other (please specify)	

18. From the list above, what are the three most common reasons why sea level change may not be incorporated into a project?

First	<div></div>
Second	<div></div>
Third	<div></div>

19. Do you personally support or oppose incorporating future sea level change into port infrastructure projects with the following design lives?

	Strongly oppose	Somewhat oppose	Neutral	Somewhat support	Strongly support
20 year design life	☐	☐	☐	☐	☐
30 year design life	☐	☐	☐	☐	☐
50 year design life	☐	☐	☐	☐	☐
100 year design life	☐	☐	☐	☐	☐
Greater than 100 year design life	☐	☐	☐	☐	☐

20. Indicate which (if any) of the following changes you anticipate to occur in the near future?

☐ Regulatory changes to base flood elevations	☐ Clients will require sea level change to be incorporated into the design of port infrastructure more often
☐ Change of standards with respect to future sea level change	☐ I do not anticipate any changes
☐ Change of codes with respect to future sea level change	
☐ Other (please specify)	

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Additional Information

21. What is the name of the firm/organization that you work for? *The researcher will keep this information confidential, but will be important for this study to understand how many different firms participated.

22. Please provide any general comments you have with regards to this survey and/or designing port infrastructure for sea level change.

23. If you are interested in participating in future dialogue on sea level change design implications for port infrastructure, please enter your name and email address below. By entering your name and email address, your answers will still remain confidential.

Name

Email

On behalf of the ASCE Ports and Harbors Committee and the University of Rhode Island, thank you very much for taking the time to fill out this survey!

Please contact if you have any questions.

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Appendix 3B: Survey Analysis

In the survey, five questions required respondents to answer on a 1 – 5 scale, which included (1) *Never*, (2) *Rarely*, (3) *Sometimes*, (4) *Often*, and (5) *Always*. For some questions, a sixth response option was provide for *I don't know* or *I don't have experience with projects in this area*. These questions were used to gauge the frequency or likelihood of different design decisions and how often SLC was incorporated into projects. The five questions were:

- Question 8: *For which types of structures does your organization incorporate/consider sea level change during the design phase?*
- Question 9: *In your experience, how likely are the design specifications of port infrastructure projects to incorporate sea level change in the following geographic locations?*
- Question 11: *Does your organization typically design port infrastructure in a way that can accommodate future upgrades to keep pace with sea level change?*
- Question 12: *What factors cause your organization to add a sea level change design component to a project?*
- Question 13: *When incorporating future sea level change into the design of port infrastructure, where does your organization obtain sea level change projections from?*

Responses to these questions were analyzed in two ways. First, the researchers treated the five primary response options separately in the analysis. Secondly, from the five primary response options, three groups were created: One group for *Never* and

Rarely, a second group for *Sometimes*, and a third group for *Often* and *Always*. After comparing the two analyses, no clear difference in the analysis emerged. Therefore, in the interest of simplicity, ease of understanding the responses, and generating comprehensible figures, results were presented using the three groups of *Never/Rarely*, *Sometimes*, and *Always/Often*.

Similarly, two questions asked respondents to indicate their confidence in SLC projections based on a 1 – 5 scale, which included (1) *Not at all confident*, (2) *Little confidence*, (3) *Neutral*, (4) *Fairly confident*, and (5) *Very confident*. The two questions were:

- Question 14: *How confident are you in the accuracy of the sea level change projections that are being incorporated into projects your organization designs?*
- Question 15: *Even if you use/have used more than one of the sea level change projection sources listed in questions 13 and 14, generally how confident are you in the accuracy of those sea level change projections being used for structures with the following design lives?*

Responses to these questions were also analyzed in two ways. First, the researchers treated the five primary response options separately, and then placed responses into three groups: One group for *Not at all confident* and *Little confidence*, a second group for *Neutral*, and a third group for *Fairly confident* and *Very confident*. After comparing the two analyses, no clear difference in the analysis emerged. Therefore, results were presented using only the three groups.

Appendix 4: Additional Results

This appendix provides additional results collected from the survey. These results expand on the findings outlined in the main text.

Appendix 4A: Respondent Geographic Experience

Figure 9 - Breakdown of the different geographic regions where respondents have professional design experience

Appendix 4B: Likelihood of Projects Incorporating SLC Based on Respondent Experience in Different Geographic Regions

Figure 10 - Likelihood of projects incorporating SLC based on respondent experience in different geographic regions

Appendix 4C: Frequency of Organizations Designing Infrastructure in a Way that Can Accommodate Future Upgrades to Keep Pace with SLC

Figure 11 – Are respondents designing infrastructure in a way that can accommodate future upgrades to keep pace with SLC?

Appendix 4D: General Confidence in SLC Projections Based on Design Life

Figure 12 - General confidence in SLC projections based on design life

Appendix 4E: Usage of Different SLC Projection/Emission Scenario Curves Based on Design Life

Figure 13 - Utilization of different SLC emission scenario curves based on design life

Appendix 4F: Personal Level of Support for Incorporating SLC into Design

Figure 14 - Personal support for incorporating SLC into design

Appendix 4G: Anticipated Changes in Engineering Practices in the Near Future

Figure 15- Anticipated changes for the port infrastructure engineering field in the near future

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