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Climate-Resilient Infrastructure

ADAPTIVE DESIGN AND RISK MANAGEMENT

Committee on Adaptation to a Changing Climate

Edited by

Bilal M. Ayyub, Ph.D., P.E.

ASCE

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A list of available Manuals of Practice can be found at http://www.asce.org/bookstore.

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PREFACE

This manual of practice, *Climate-Resilient Infrastructure: Adaptive Design and Risk Management* (MOP 140), was prepared by a development team that includes members of the ASCE Committee on Adaptation to a Changing Climate between 2016 and 2018.

Some of the content has been outdated by recent events. For instance, the book contains references to ASCE Standard 7-10, which has been superseded by ASCE Standard 7-16. The differences between the two versions are not central for the purposes of this manual. Therefore, the Development Team decided to keep the references to ASCE 7-10.

In addition, President Donald Trump has canceled Executive Order 13690 and the federal flood risk management standard. The review undertaken by standards experts and the ASCE Blue-Ribbon Panel considered these changes, and the Development Team has responded to applicable comments.

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ACRONYMS

ADCIRC	Advanced Circulation Model
AEP	Annual exceedance probability
AMS	Annual Maxima Series
AR4	IPCC 4th Assessment Report
AR5	IPCC 5th Assessment Report
ARI	Average Return Interval
ARM	Adaptive Risk Management
ARRM	Asynchronous Regional Regression Model (cida.usgs.gov)
ASCE/SEI 24	*Flood Resistant Design and Construction*
ASCE/SEI 7	*Minimum Design Loads for Buildings and Other Structures*
ASD	Allowable Stress Design
BFE	Base Flood Elevation
CACC	Committee on Adaptation to a Changing Climate
CDF	Cumulative Density Function
CEM	US Army Corps of Engineer's Coastal Engineering Manual
CEQ	Council on Environmental Quality
CFS	Cubic feet per second
CI	Composite Index (Risk Rating)
CISA	Climate-Informed Science Approach
CMIP5	Coupled Model Intercomparison Project Phase 5
CMS	Cubic meters per second
COV	Coefficient of variation
CPT	Cone Penetration Test
csv	Comma separated values (file format)
CTA	ASCE Committee on Technical Advancement
DFE	Design Flood Elevation
DOE	Department of Energy
DOT	Department of Transportation

dpy	days per year
EMA	Expected Moments Algorithm
ENSO	El Niño Southern Oscillation
EO	Executive Order
EV1	Extreme-Value Type 1 (EV1) Gumbel (maximum) distribution
FBFE	Future Base Flood Elevation
FEA	Finite Element Analysis
FEMA	Federal Emergency Management Agency
FFRMS	Federal Flood Risk Management Standard
FHWA	Federal Highway Administration
FIRMs	Flood Insurance Rate Maps
FIS	Flood Insurance Study
FVA	Freeboard Value Approach
GCM	Global Climate Models
GEV	Generalized Extreme Value
GHG	Greenhouse gases
GMSL	Global mean sea level
GPM	Gallons per minute (gal./min)
HEC	USACE Hydraulic Engineering Center
HVAC	Heating, Ventilating, and Air Conditioning
IAM	Integrated Assessment Models
IBC	International Building Code
IDF	Intensity-Duration-Frequency
IPCC	Intergovernmental Panel on Climate Change (www.ipcc.ch)
ISO	International Organization for Standardization
LCCA	Life-Cycle Cost Analysis
LEED	Leadership in Energy and Environmental Design
LID	Low Impact Development
LiMWA	Limit of Moderate Wave Action
LPIII	Log-Pearson Type III Distribution
MACA	Multivariate Adaptive Constructed Analogs (maca.northwestknowledge.net)
MATLAB	MATrix LABoratory
MEOW	Maximum Envelopes of Water
MIT	Minimum Interevent Time
MIKE 21	Tool for coastal modeling by DHI (https://www.mikepoweredbydhi.com/products/mike-21, accessed 2/8/2018)
MLLW	Mean Low Low Water
MOM	Maximum of the MEOWs
MRI	Mean Recurrence Interval (same as ARI)

NA-CORDEX	North American Coordinated Regional Climate Downscaling Experiment (na-cordex.org)
NARCCAP	North American Regional Climate Change Assessment Program (narccap.ucar.edu)
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988
NCA	National Climate Assessment (http://www.globalchange.gov/)
NCEI	National Centers for Environmental Information
NEPA	National Environmental Policy Act
NESDIS	National Environmental Satellite and Data Information Service
netCDF	Network Common Data Form
NEVA	Non-Stationary Extreme-Value Analysis
NFIP	National Flood Insurance Program
NGVD29	National Geodetic Vertical Datum of 1929
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration (www.noaa.gov)
NPCC	New York City Panel on Climate Change
NPV	Net Present Value
NS	Non-Stationary
NSIDC	National Snow and Ice Data Center
NWS	National Weather Service
NYCBC	New York City Building Code
NYCT	New York City Transit Authority
OM	Observational Method
PDF	Probability Density Function
PoR	Period of Record Practice on Adaptive Design and Risk Management
PWMs	Probability-Weighted Moments
RCP	Representative Concentration Pathway
RCP	Representative Concentration Pathway
RDM	Robust Decision Making
RDU	Raleigh-Durham International Airport
RegCM3	USGS Regional Climate Model Version 3 (regclim.coas.oregonstate.edu)
RISA-3D	Structural Engineering Software for Analysis and Design (http://risa.com/p_risa3d.html, accessed 2/8/2018)
RF	Radiative forcing
RL	Return Level
RP	Return Period
RSL	Regional Sea Level Rise
SAFB	Self-Activating Flood Barrier

SDOF	Single Degree of Freedom
SEI	Structural Engineering Institute
SFHA	Special Flood Hazard Area
SLOSH	Sea, Lake, and Overland Surge from Hurricanes (model)
SLR	Sea Level Rise
SOC	Soil Organic Carbon
SRES	Special Report on Emissions Scenarios
SREX	IPCC Special Report on Extremes
ST	Stationary
SWAN	Simulating Waves Nearshore
SWD	Still Water Depth
SWEL	Still Water Elevation Level
TAMP	Transportation Asset Management Plan
TL	Total Loss (Risk Quantification)
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
USGCRP	US Global Change Research Program http://www.globalchange.gov/
USGS	US Geological Survey
WBAN	Weather Bureau Army Navy station
WHAFIS	Wave Height Analysis for Flood Insurance Studies
WL	water level

CHAPTER 1
INTRODUCTION

1.1 PROBLEM DEFINITION, NEEDS, AND SIGNIFICANCE OF IMPACT

The climate science community informs us that extremes of climate and weather are changing from historical values and that the changes are driven substantially by emissions of greenhouse gases caused by human activities. The terminology of the climate science community is described in Appendix A, Terminology. Civil infrastructure systems traditionally have been designed, constructed, operated, and maintained for appropriate probabilities of functionality, durability, and safety while exposed to climate and weather extremes during their full service lives. Because of uncertainties in future greenhouse gas emissions and in the models for future climate and weather extremes, neither the climate science community nor the engineering community presently can define the statistics of future climate and weather extremes.

The Intergovernmental Panel on Climate Change (IPCC) concluded that warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia (IPCC 2014). The IPCC also concluded that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-twentieth century. Increases in atmospheric and ocean temperatures, droughts and wildfires, extreme precipitation and intensity in many areas, and global sea-level rise have already been observed. These trends are projected to continue into the future. While there is considerable evidence that the climate is changing, understanding the significance of climate change at temporal and spatial scales relevant to engineering practice is more difficult.

1.2 OBJECTIVE AND SCOPE

The purpose of this manual of practice (MOP) is to provide guidance for and contribute toward the development and enhancement of standards for infrastructure analysis and design, as well as the numerous regulation and building codes that refer to them, in a world in which risk profiles are changing (non-stationarity) and climate change is a reality but cannot be projected with a high degree of certainty. It also offers guidance to inform engineering decisions and introduces adaptive risk management before standards have been updated to account for more severe climate or weather extremes.

In 2015, ASCE issued a report titled *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate* (ASCE 2015) that is free to the public for download (http://dx.doi.org/10.1061/9780784479193). Infrastructure includes buildings of all types and facilities for communications, energy generation and distribution, industry, transportation of all modes, waste management, water resources, and urban potable, storm, and wastewater.

This MOP builds on the 2015 report to

- Foster understanding and transparency of analytical methods necessary to update and describe climate, including possible changes in the frequency and intensity of weather and extreme events, for planning and engineering design of the built and natural environments
- Promote exploration of the value of adaptive design methods such as the observational method (OM) and adaptive risk management as a central tenet of a new paradigm for engineering practice, including standards that acknowledge the implications of climate change as well as the uncertainties inherent in projections of future weather and climate extremes

Engineers build durable infrastructure. The rights of way and footprints of the infrastructure have even longer-term influences. The planning and design of new infrastructure should, therefore, account for the climate of the future. Considering the impacts of climate change in engineering practice is analogous to including forecasts of long-term demands for infrastructure use as a factor in design. Although the scientific community agrees that climate is changing, there is significant uncertainty about the spatial and temporal distributions of the changes over the lifetimes of infrastructure designs and plans. The requirement that engineering infrastructure meets future needs with the uncertainty of future climate is a challenge to engineers.

Engineering practice recognizes and accounts for uncertainties in future conditions. These methods include designing for a flood or wind velocity of a particular magnitude, the use of safety factors or freeboard, and probabilistic and statistical methods. Engineers use statistical methods to quan-

tify uncertainty for empirical probability distributions used in engineering design. The assumption of stationarity implies that the statistical properties of extremes in future time periods will be similar to those of past time periods. Recent papers have noted that climate change undermines this assumption (Milly et al. 2008).

Infrastructure designs and plans, as well as institutions, regulations, and codes and standards to which they must adhere, will need to be adapted and even be adaptable to accommodate a range of future climate conditions. Secondary effects from a changing climate such as changes in land cover or use, resource availability, and demographics in population are similarly uncertain and require flexibility in infrastructure location and design. The standards, codes, regulations, zoning laws, and so on that govern infrastructure are often finely negotiated or delicately balanced legally, which often makes them slower to adapt. In addition, different stakeholders may exploit the uncertainties associated with climate change to argue for positions they prefer. This manual provides a review of most relevant engineering practices and discusses how engineers can consider climate change in their practice given the uncertainty of the future. Incorporating climate change into engineering practice will require engineering judgment to balance costs and potential consequences of failure.

Even without anthropogenic climate change, climate varies naturally on decadal and longer time scales, and the observed record is a relatively short time period compared to the potential range of climate variability. There are also multiple other sources of change and uncertainty—changes in demand for infrastructure and services, changes in land use, urbanization, population increase, and economic development in vulnerable areas such as floodplains, deserts, shorelines, and earthquake zones. Population and development may stress natural resources, such as increased groundwater depletion, surface water withdrawals, and deforestation. In addition, society and engineers are increasingly concerned about the natural environment. Potential responses by ecosystems, including changes in biodiversity or the abundance of component species, are particularly difficult to project with a high degree of certainty.

In recognition that historical observations cannot be relied on to adequately describe extreme conditions in the future as well as uncertainty associated with model projections at the project scale, *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate* (ASCE 2015) recommended that

- Engineers should communicate and collaborate with climate scientists to observe and model climate, weather, and extreme events. The purpose of the involvement is to improve the relevance of the modeling and observations for use in the planning, design, operation, maintenance, and renewal of the built and natural environment. It is only

when engineers work closely with climate scientists that the needs of the engineering community will be fully understood, limitations of the climate science community will be more transparent to engineers, and the uncertainties of the projections of future climate for engineering design purposes will be fully recognized.

- Practicing engineers, project stakeholders, and policy and decision makers should be informed about the uncertainty of the projections of future climate and the reasons for the uncertainty as elucidated by the climate science community. Because the uncertainty associated with future climate is not completely quantifiable, if projections of future climate are to be used in engineering practice, they require considerable engineering judgment to balance the costs of mitigating risk through adaptation against the potential consequences of failure.
- Engineers should develop a new paradigm for engineering practice in a world in which climate change may occur but cannot be projected with a high degree of certainty. When it is not possible to fully define and estimate the risks and potential costs and reduce the uncertainty in the time frame in which action should be taken, it may be feasible to use low-regret adaptive strategies to make a project more resilient to future climate and weather extremes.
- Critical infrastructure that is most threatened by changing climate in a given region of the country should be identified, and the public and decision makers should be made aware of this assessment. An engineering–economic evaluation of the costs and benefits of strategies for resilience of infrastructure should be undertaken.

1.3 WHY STANDARDS MATTER

Although Hurricane Katrina of 2005 affected major cities, flood resiliency for infrastructure and urban environments really came to the forefront with the damage caused by Hurricane Harvey in 2017 in the Houston metropolitan region (*New York Times* 2017). Land use and building practices contributed greatly to damages in the Houston area, but so did the 52 inches of rain that fell over four days, which was a rare event, perhaps influenced by modern-era climatic change. Since then, agencies and building owners have been trying to interpret the available codes and decide how to protect their assets against future storms. The results of this exercise are widely varied.

In general, transportation agencies are finding the current codes inadequate both in coverage and applicability for their assets, and thus they are navigating their way through writing their own standards or guides. Private building owners, with smaller-concentrated assets, are simply applying ASCE/SEI 7 (2010) and 24 (2014) in their pre–Hurricane Sandy based

on code-minimum levels. Whereas short-term actions are necessary, a comprehensive long-term campaign must be started to understand and reshape the available published guidance as it relates to dense urban environments.

Many engineers and scientists have been implementing Hurricane Sandy recovery and resiliency projects since 2012 and have a great deal of applied knowledge, including shortfalls, regarding the current codes. This MOP is intended to identify some of the current practices and knowledge gaps, offer guidance, suggest areas of further study and clarification, and be the springboard as a technical basis document for work on the next code development and revision cycles so that building owners are equipped with current guidance and agencies can become more unified by the research of experts in the field.

This book introduces the use of adaptive risk management including the observational method for achieving climate resilience of infrastructure. It has the added motivation that adaptive risk management would be considered for inclusion in currently used standards by the standards development community.

1.4 STRUCTURE OF MANUAL OF PRACTICE

This MOP has a varied style that includes a step-by-step guide in areas where technologies or methodologies are well established, suggested approaches in cases where several competing approaches are available, and leads based on research results for areas that are emerging. The manual is intended to eventually charter the way to changes to codes and standards.

The manual consists of the following chapters:

Chapter 1: Introduction
The first chapter sets the context, articulates the needs, provides objective and scope statements for the manual, lists topics warranting additional analysis, and defines users and uses of the manual.

Chapter 2: A Changing Climate: Problem Definition
This chapter summaries key drivers of climate variability and change and their effects on weather and climate extremes, as well as their relevance to existing ASCE standards.

Chapter 3: Observational Method
The third chapter describes the observational method and provides illustrative examples and a case study.

Chapter 4: Characterization of Extremes and Monitoring
This chapter focuses on methods for estimating extreme events, particularly related to precipitation, and suggests design methods and considerations

to address a changing climate. The chapter also offers guidance on monitoring methods and measures to enhance climate resilience.

Chapter 5: Flood Design Criteria

This chapter summarizes flood design criteria in relation to a changing climate. The chapter also provides guidance for developing project design flood elevations.

Chapter 6: Flood Loads

The sixth chapter covers computational methods of determining flood loads including hydrostatic loads and wave loads, among others.

Chapter 7: Adaptive Design and Risk Management

This chapter introduces adaptive design and adaptive risk management in the context of life-cycle engineering and economics.

Chapter 8: Data and Information Sources

This chapter provides leads to data and information sources related to climate change.

It should be noted that Chapter 3 provides a practical approach to adaptive risk management requiring no research beyond the use of existing standards and codes, whereas Chapters 4 and 5 guide the reader in approaches to research for estimating future climate or weather extremes. Chapter 3 is useful for practicing engineers who need to account for non-stationarity in a current project and for incorporation of the observational method in standards. Chapters 4 and 7 offer guidance to research the development of standards for more formal treatment of non-stationarity and adaptive risk management.

This manual also includes four appendixes on Terminology (Appendix A), ASCE Standards and Climate Change (Appendix B), Methodology for L-Moment and Other Statistical Computations (Appendix C), and Adaptation Technologies (Appendix D).

1.5 TOPICS WARRANTING ADDITIONAL ANALYSIS

Three areas are identified: (1) direct effects of increasing temperatures, (2) wildfires, and (3) adaptive design implementation. Other areas also could be added to this list.

1.5.1 Direct Effects of Increasing Temperatures

The impacts of increasing temperatures caused by climate change on society are well established (IPCC 2014, USGCRP 2014). Direct effects are ubiquitous and include impacts to agriculture, ecosystems, human health (e.g., to vulnerable populations and workers), economics of energy, facilities, and infrastructure. Additional work to analyze methods for minimizing

impacts from increasing heat, including the reduction of urban heat island effects, are warranted.

1.5.2 Wildfires

Although a clear trend of increased wildfires has not yet been established (Short et al. 2015), the average extent of area burned by wildfires each year appears to have been increasing since the 1980s (MTBS 2016), with severe wildfires in 2017. Recent research suggests that human-caused climate change contributed to an additional 4.2 million hectares of forest fire area from 1984 to 2015, nearly doubling the forest fire area expected in its absence (Abatzoglou and Williams 2016). Many environmental impacts associated with climate change can affect wildfire severity, extent, and frequency, including changes in precipitation, temperature, and drought. Additional analysis and development are needed for methods to reduce the financial, environmental, and health costs associated with wildfires.

1.5.3 Adaptive Design Implementation

Although adaptive design (including the observation method) offers an opportunity to increase the resilience of infrastructure while minimizing long-term regret, there are presently implementation challenges related to systematic frameworks within the agencies leading the largest infrastructure projects. Additional understanding of relevant financial, operational, budgetary, bureaucratic, and construction-related factors involved in implementing a cost-effective adaptive design is warranted.

1.5.4 Scale Disconnect

It should be noted that scale disconnect is a considerable concern that is addressed herein and elsewhere in the manual. Chapter 2 provides climate change information mostly from Global Climate Models (GCMs). The chapters that follow provide examples of specific tools for how to evaluate future extremes at the local level. Going from global to local scale creates this disconnect. For example, in Chapter 4, the Intensity-Duration-Frequency (IDF) technique is described assuming that GCMs are appropriate for this sort of analysis in the future. Although it does acknowledge that GCMs are currently "highly uncertain and models exhibit large intermodel variability," it should be noted that they are improving rapidly with a steady increase in reliability on rainfall statistics. There is improvement, but it is unrealistic to assume GCMs alone are the only appropriate approach for this sort of analysis. Raw GCM precipitation data are generated at large spatial scales that do not capture local processes and should

not be used directly, especially to evaluate place-specific extremes needed at the scale of much of our infrastructure.

1.5.5 Other Areas

IPCC forecasts that droughts in already dry regions will become more severe, as provided in Table 2-1 of Chapter 2. Droughts will create challenges for maintaining adequate water supplies for agriculture, cooling of power plants, transportation, and human consumption. Also, the desiccation of vegetation will increase the risk of wildfires that will be hazardous to infrastructure. Standards and recommended practices will be needed for landscaping to reduce exposures of infrastructure to wildfire effects and for increasing the fire resistance of roofing and cladding for infrastructure.

1.6 USES AND USERS

This book is intended to guide practitioners and developers of ASCE standards in the incorporation of adaptive risk management to deal with the uncertainties of future climate and weather extremes. The incorporation of adaptive risk management in standards will take some time. For instance, research with the climate or weather science community is needed to estimate the most likely and most severe future climate and weather extremes for 50 to 100 years and beyond for service lives of infrastructure projects and systems. Engineers responsible now for the design, construction, operation, and maintenance of infrastructure also can use this manual to implement adaptive risk management for decisions needed before standards are updated to incorporate adaptive risk management.

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