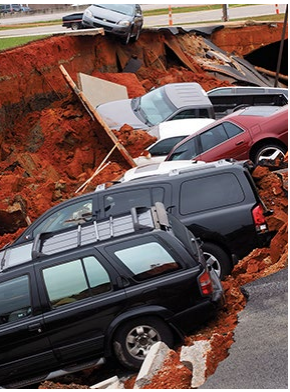
GSP 285 | Selected Papers from the Proceedings of Geo-Risk 2017

Geo-Risk 2017

Geotechnical Risk Assessment and Management





Edited by

Jinsong Huang, Ph.D.
Gordon A. Fenton, Ph.D., P.Eng.
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Preface

Interest and use of probabilistic methods and risk assessment tools in geotechnical engineering has grown rapidly in recent years. The natural variability of soil and rock properties, combined with a frequent lack of high quality site data, makes a probabilistic approach to geotechnical design a logical and scientific way of managing both technical and economic risk. The burgeoning field of geotechnical risk assessment is evidenced by numerous publications, textbooks, dedicated journals and sessions at general geotechnical conferences. Risk assessments are increasingly becoming a requirement in many large engineering construction projects. Probabilistic methods are also recognized in design codes as a way of delivering reasonable load and resistance factors (LRFD) to target allowable risk levels in geotechnical design.

This Geotechnical Special Publication (GSP), coming out of the Geo-Risk 2017 specialty conference held in Denver, Colorado from June 4-7, 2017, presents contributions in sessions: 1) Advances in the Applications of Theory and Practice of Statistics and Probability in Geoengineering, 2) Bayesian Updating for Geotechnical Applications, 3) Risk Assessment of Tunneling, 4) Risk Assessment and Management of Dams, and 5) Seismic Risk Assessment.

These contributions to Geotechnical risk assessment and management are very timely, and will provide a valuable and lasting reference for practitioners and academics alike.

The editors would like to thank all of the members of ASCE Geo Institute's Technical Committee on Risk Assessment and Management and the Engineering Practice of Risk Assessment and Management Committee (TC304) of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) for their ongoing support.

All the papers in this GSP went through a rigorous review process. The contributions of the reviewers are much appreciated.

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The Editors greatly appreciate the work of Ms. Helen Cook, Ms. Leanne Shroeder, Ms. Brandi Steeves, and Mr. Drew Caracciolo of the ASCE Geo-Institute for their administration of many important conference organizational issues, including management of the on-line paper submissions, the conference web site and sponsorship.

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Bayesian Probabilistic Asset Management Protocol for Infrastructure Systems: Example Application to a Flood Protection System

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Abstract

A Bayesian probabilistic asset management protocol was developed for risk management of a typical flood protection system. A major advantage of the proposed protocol is its ability to integrate and transform data from field inspections and other information sources into quantitative measures of risk for each system component to help prioritize decisions that reduce risk. While the example application is for a flood protection system subdivided into reaches with varying attributes, its underlying framework is highly versatile and can be applied to a broad spectrum of infrastructure assets and asset systems.

The protocol developed for the typical flood protection system uses risk assessment tools to identify reaches with potential risk and the possible measures to reduce that risk. The general approach adopted is to update a background failure probability with information from new observations specific to the reach being evaluated. The background and updated probabilities are termed prior and posterior probabilities, respectively. The prior probability of failure of a reach is determined using historical performance information and subject matter experts. Here, the prior probability of failure does not account for the current condition state or site-specific attributes of the reach being assessed. The posterior probability of failure incorporates new information by using Bayes theorem to combine the prior probability of failure and the likelihoods of observing the condition state for cases of reaches failing and not failing. The proposed protocol consists of three phases: (1) Development of a probability database consisting of prior probabilities and likelihoods; (2) Assessment of the current performance indicators for each reach; and (3)

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Determination of the updated probability of failure of each reach by combining new observations about the condition state of each reach with information stored in the probability database. The first phase, which is usually performed only once for a given system, starts with assigning potential modes of failure for the reaches. A given mode is then associated with performance indicators that each provide information on the condition state of the reach based on three levels of severity. The likelihoods of observing each level of severity in failure and non-failure conditions are determined using historical failure statistics supplemented with subject matter expert opinion. In some cases, this could be corroborated by available data such as design factors of safety, reliability indices, inspection reports, photographs, and construction records. In the second phase, data from field inspections and field instrumentation are used to assign a current condition assessment for each failure mode for each reach. Subsequently in the third phase, this condition assessment is combined with relevant information in the pre-populated probability database to calculate the posterior probability of failure using Bayes theorem. This revised estimate of probability of failure is then combined with the consequences of failure to provide a quantitative measure of risk for each reach. The posterior probability can be further updated as new information about the condition state becomes available.

INTRODUCTION

The concept of asset management is not new. It is an evolving idea that has been attracting the attention of many organizations that own, operate and/or maintain some type of infrastructure asset. Effective asset management involves making key strategic decisions throughout all phases of an asset's lifecycle that meet performance objectives with an optimal use of resources (Sarfi and Tao 2004). It is a philosophy and discipline through which organizations are enabled to deploy their resources more effectively to provide higher levels of customer service and reliability while also meeting financial objectives (Too 2010).

In infrastructure asset management, assets can have two basic types of value: capability value and consequence value. Both types of values have the common feature that they depend on the purpose for which the asset is being used. Capability has traditionally been the value of interest to engineers and is measured on a physical, not financial, scale (Amadi-Echendu et al. 2010). For example, the capability value of a floodwall might be measured by its probability of failure during a design storm event. Similarly, the capability value of a bridge approach might be measured by its probability of not meeting target serviceability requirements (for example differential settlement between the structure and the approaches). Throughout this paper, the term "failure" can refer to the condition where either serviceability or ultimate limit states are reached or exceeded. Consequence value, which is the value pertaining to the impacts incurred due to asset underperformance, could be for example measured as financial value, user comfort, and/or number casualties. The most common form of consequence value in asset management is financial value. Amadi-Echendu et al. (2010) state that financial value is measured on a monetary scale and can take several forms. If the aim is to determine if an asset should be retained,

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rehabilitated, or replaced, the present values of estimated future cash flows or the expected value from disposing the asset are relevant measures of financial value. If the aim is to determine the impact of the asset failing, the monetary consequence of failure is a relevant measure of financial value. For example, the financial value of a floodwall failing could be measured by the monetary damage due to a flood resulting from a storm event.

This paper presents an asset management protocol developed for a typical flood protection system which uses risk assessment tools to identify reaches with potential risk and the possible measures to reduce that risk. While the example application is for a flood protection system subdivided into reaches with varying attributes, its underlying framework is highly versatile. It has the capacity to address both capability and consequences values of an asset and can be applied to a broad spectrum of infrastructure assets and asset systems. The reliance of the protocol on the Bayesian probability framework allows it to integrate rationally and formally the current condition state of an asset with historical information and expert opinion to obtain the capability value, more specifically the probability of failure, or alternately reliability. The current condition state is obtained from routine field inspection records, monitoring instrument readings, and/or in-situ test data. Ultimately, the protocol has the utility to combine the probability of failure with the consequences to obtain a monetary-value risk for each asset component. This paper focusses on the methodology to develop these probabilities and how they are seamlessly integrated with consequences.

STATE-OF-PRACTICE

There is a growing and dire need for the inclusion of a reliable and efficient asset management protocol into the state-of-practice for asset management in the United States due to the factors presented in Figure 1.

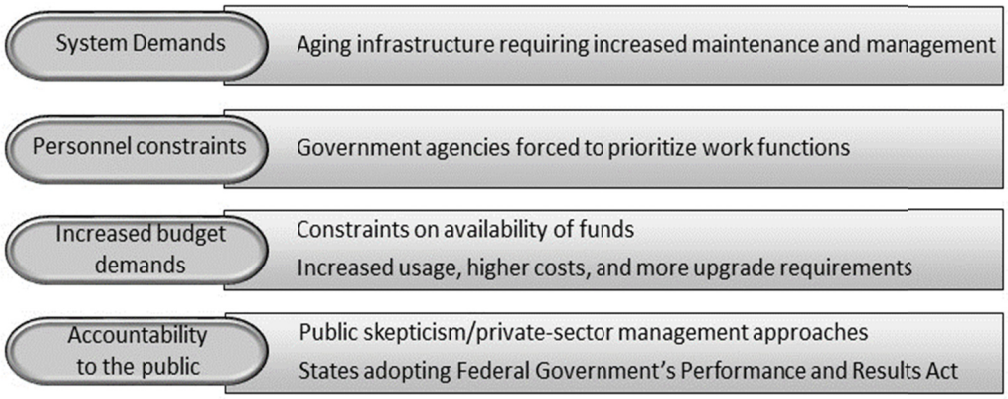


Figure 1. Factors Contributing to the Growing Need for Infrastructure Asset Management

Asset managers and engineers are frequently confronted with the problem of screening a large number of facilities to determine where funds can be deployed to achieve the greatest reduction in risk. In these situations, it is common that a large number of facilities must be

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investigated, but time and budget restrictions prevent performing such evaluations in a balanced, transparent manner. A procedure involving quantitative appraisal based on documented evidence is needed to prioritize facilities that need attention so that funds, which are often limited, can be used efficiently to optimize risk reduction. Additionally, the procedure must take into account not only the potential for failure but the possible consequences of failure. Typically, procedures used in current practice to address these problems employ simple weighted sum scores or sometimes a pair of simple scores for both probability and consequence of failure (Baecher and Christian 2013). One example of such a procedure is the simplified risk matrix, which has been and still is very much a significant part of the current state-of-practice. These procedures have been recommended by agencies and organizations such as the Environmental Protection Agency (EPA), Federal Highway Administration (FHWA), Government Accountability Office (GAO), and the Project Management Institute (PMI). Baecher and Christian (2013) indicate that these techniques violate fundamental measure-theoretic principles and often yield risk rankings that differ from what one would obtain from utility theories and probabilistic risk analysis. The reader is referred to Baecher (2008), Cox et al. (2005), and Cox (2007) for a more detailed treatment of the limitations risk scores and risk matrices.

PROTOCOL FOR A TYPICAL FLOOD PROTECTION SYSTEM

The concept adopted in the proposed protocol is similar to the method presented by Margo et al. (2009) in their paper on a levee screening tool developed for the U.S. Army Corps of Engineers (USACE), which is based on the work of Baecher (2008) and is similar to what was later presented by Baecher and Christian (2013). The described protocol overcomes the limitations in the simple weighted sum scores, for example risk scores and risk matrices, which currently dominate the current state-of-practice. The general approach is to update a background failure probability with information from new observations specific to the reach being evaluated. The proposed protocol consists of three phases: Phase 1 – Development of a probability database consisting of prior probabilities and likelihoods; Phase 2 – Assessment of the current performance indicators for each reach; and Phase 3 – Determination of the updated probability of failure of each reach by combining new observations about the condition state of each reach with information stored in the probability database. Collectively, the three phases correspond to nine steps to complete the protocol. Table 1 shows the phases and steps in the proposed protocol.

The first phase, which is usually performed only once for a given system, starts by defining reach types and assigning potential modes of failure for the reaches. A given mode is then associated with performance indicators that each provide information on the condition state of the reach based on three levels of severity (i.e. Low, Moderate, and Severe). The likelihoods of observing each level of severity in failure and non-failure conditions are determined using historical failure statistics supplemented with subject matter expert opinion. In some cases, this can be corroborated by available data such as design factors of safety, reliability indices, inspection reports, photographs, and construction records. In the second phase, data from

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periodic surveys, field inspections, and field instruments are used to assign a current condition state for each performance indicator. In the third phase, this condition assessment is combined with relevant information in the pre-populated probability database developed in Phase 1 to calculate the posterior probability of failure using Bayes' theorem. This revised estimate of probability of failure is combined with the consequences of failure to provide a quantitative measure of risk for each reach. The consequences are dependent on several factors including:

1. The pertinent domain of influence of the consequences. For example, the domain of interest could encompass consequences arising from underperformance of the asset (e.g. floodwall or levee) to infrastructure and property within the polder it protects or it could also be limited to damage or loss of the asset itself.
2. The size and scale of the storm event loading the asset.

The process of combining probability of failure and consequence of failure mentioned above completes the inclusion of both the capability and consequence values of an asset. It should be noted that the posterior probability can be further updated as new information about the condition state becomes available.

Table 1. General Steps in the Proposed Risk-Based Asset Management Protocol

Phase No.	Step No.	Step Description	Comments
1	1	Identify the types of reaches within the flood protection system	Steps 1 through 6 are only performed once for a given system
	2	Identify failure modes for each reach	
	3	Identify performance indicators for each failure mode	
	4	Develop three levels of severity for each performance indicator	
	5	Develop prior probabilities and likelihoods of observing each level of severity under the loading event of interest (e.g. the 500-year storm)	
2	6	Perform current condition assessment of the reach	Steps 6 through 9 are performed for each evaluation
3	7	Update probability of failure using information from condition assessments	
	8	Integrate probability of failure and failure consequences	
	9	Rank reaches based on monetary-value risk conditioned upon the loading event of interest‡	

Note: ‡ Risk can include using other measures of consequences (e.g. casualties, user comfort)

Specific details of each step shown in Table 1 are as follows:

Step 1: Identify the types of reaches within the flood protection system

This step involves studying the inventory of reaches within the perimeter of a flood protection system and developing categories of reach types in accordance with the type of structure. For a typical flood protection system, the following reach types were identified within a polder: (1) Levee; (2) Floodwall; (3) Floodwall on levee; (4) Pump station; and (5) Closure gate.

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Step 2: Identify failure modes for each reach

In this step, the following five failure modes associated with the five reach types were identified with a specific focus on failures leading to flooding:

- Failure Mode 1: Failure by global instability
- Failure Mode 2: Overtopping by waves or a combination of waves and surge with breach by surface erosion
- Failure Mode 3: Breach by erosion due to underseepage and throughseepage
- Failure Mode 4: Failure by structural and mechanical instability
- Failure Mode 5: Failure by operational or other circumstances.

Step 3: Identify performance indicators for each failure mode

In this step, performance indicators for all potential failure modes were identified. The performance indicators for each failure mode along with notes for determination of levels of severity are presented in the next step, i.e. Step 4.

Step 4: Develop three levels of severity for each performance indicator

This step involves determination of severity levels (Low, Moderate, and Severe) that can be observed for each performance indicator. Figures 2 and 3 provide illustrations of some performance indicators for Failure Modes 1 and 2, respectively. Tables 2 through 5 present the performance indicators for Failure Modes 1 through 4, respectively, and where possible, include comments, guidelines, and suggested references for assigning condition states (severity levels) corresponding to each performance indicator. Due to manuscript space limitations, these comments and guidelines are not meant to provide a comprehensive basis for condition assessments but rather serve to illustrate the asset management process of the protocol. The levels of severity and specific guidelines on how they are assigned based on field observations and/or monitoring and instrumentation data are determined using historical data, design information, recommendations in codes of practice and design guides, and expert opinion. Failure Mode 5 involves other potential extreme circumstances arising from the inherent randomness (aleatory uncertainty) or lack of fundamental knowledge (epistemic uncertainty) of processes involving components of the flood protection system and how they respond to loading events. Due to manuscript length limitations, this failure mode is not discussed further in this paper but the potential user of this risk protocol should be cognizant of its importance in assessing and managing risk. The reader is referred to Paté-Cornell (2012) for an introduction to the treatment of such uncertainties.

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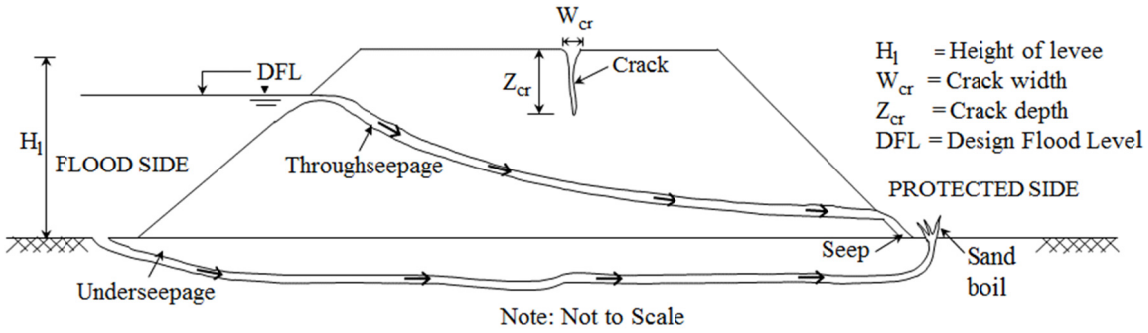


Figure 2. Illustration of Some Performance Indicators for Failure Mode 1 in a Levee

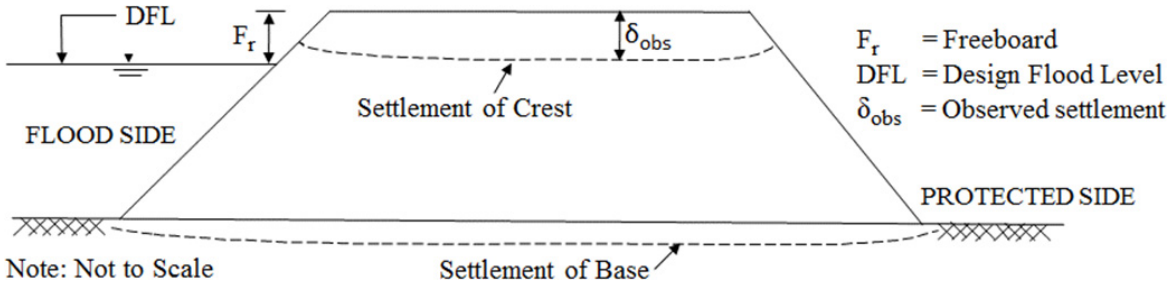


Figure 3. Illustration of Some Performance Indicators for Failure Mode 2 in a Levee

Table 2. Performance Indicators for Failure Mode 1

Performance Indicator(s)	Comments/Notes on Levels of Severity in Condition State (Refer to Figure 2 for definitions of symbols and acronyms)
Observed cracking in levee	Indications of a severe condition state include: (1) Cracks that extend below DFL; (2) $Z_{cr} \geq 2$ feet or $W_{cr} \geq 2$ inches; (3) Cross-crack differential settlements > 1 inch. Suggested reference: IDNR (2007).
Levee height	Greater H_l indicate potentially greater severity due to increased slope heights and loading on foundation soils.
Post-construction movements	Post-construction performance such as movements of the structure (e.g. sliding, overturning, and slope distress) indicate potentially increased severity.
Foundation materials composed of weak soils	The presence of weak soils (e.g. soft clays and silts, loose silty or clayey sands, organics) in foundation materials of structures and features indicate potentially increased severity.
Repair/maintenance history	*Historical records including records on repair/remedial work performed could give useful information on the susceptibility to failure.
Low design factor of safety (FOS) under extreme events	Low FOS under extreme events, specifically when the water level is at top of wall or levee, indicate increased susceptibility to global instability, particularly FOS for global stability < 1.1 under this condition.
Evidence of seepage	The presence of seeps and sand boils not associated with runoff indicates potentially increased severity.

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Table 3. Performance Indicators for Failure Mode 2

Performance Indicator(s)	Comments/Notes on Levels of Severity in Condition State (Refer to Figure 3 for definitions of symbols)
Observed levee settlement and presence of compressible foundation soils	δ_{obs} in levees exceeding what is anticipated in the design and the presence of compressible foundation soils may indicate increased risk of overtopping accompanied by surface erosion breach if the levee is not raised prior to higher river or hurricane events.
Freeboard	A comparison of available F_r at the time of assessment to the amount required by design/regulations provides an indication of the potential susceptibility of the levee to be overtopped.
Repair/maintenance history	See * in Table 2.
Changes in coastal features	For a storm of given intensity, speed, size, central pressure, and approach angle, the resulting surge is influenced by shape characteristics of the coastal features including coastline shape and width and slope of the ocean bottom. Suggested references: NHC (2012, 2013); Pullen et al. (2007).
Levee surface material susceptibility to surface erosion	When armoring or grass cover are not present, the surface material is considered to be the levee embankment soils. §Levee soil erosion categories (Briaud 2008): (1) High erodibility – Sands and low plasticity silts; (2) Moderate erodibility – Low plasticity clays and high plasticity silts; (3) Low erodibility – High plasticity clays. Levee surface cover categories: (1) Armoring; (2) Poor grass cover (resistant to overtopping discharge rates, ODR ≤ 0.05 cfs); (3) Good grass cover (resistant to ODR ≤ 0.10 cfs); (4) No cover – exposed levee soil. For an overtopped floodwall, all forms of grass cover could classify as poor grass cover unless the wall height is low or the area is armored. Suggested references: Briaud et al. (2008), Briaud (2008), USACE (2000, 2010).
Levee geometry – floodside and landside slopes	Wave overtopping depends mainly on the geometry of the levee and characteristics of incoming waves. Berms can be effective in in reducing wave run-up and overtopping. Suggested references: FEMA (2005a); Schuttrumpf and van Gent (2003).
Observed cracking in levee	Cracks in a levee may be weak points for the initiation of surface erosion. They act as conduits with low resistance to flow and erosion. Suggested reference: IDNR (2007).
Evidence of surface erosion	Generally, eroded surfaces with depths exceeding 1 foot correspond to severe condition states. However, it is common practice to remediate eroded surface of this order of magnitude as part regular maintenance activities.
Presence of transitions and other obstructions	The presence of gates/other obstructions can be conducive to initiation of localized turbulence and surface erosion in adjacent unarmored areas.

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Table 4. Performance Indicators for Failure Mode 3

Performance Indicator(s)	Comments/Notes on Levels of Severity in Condition State (Refer to Figure 2 for definitions of symbols)
Susceptibility of levee soils to internal erosion	Refer to § in Table 3 for levee soil erosion categories.
Observed cracking in levee	Transverse cracking due to differential settlement or slope movement can contribute to concentrated leaks that could initiate or exacerbate seepage and lead to internal erosion. $Z_{cr} \geq 2$ ft could indicate a severe condition state. Suggested reference: Fell et al. (2003).
Evidence of seepage erosion	Some guidelines to assess the severity include the presence of: (1) Seeps and outflow of sediment laden water along the protected side of the levee (cloudy, turbulent outflow); (2) Sand boils and other sediments that are not associated with runoff; (3) Sinkholes and levee surface depressions.
Condition of levee seepage berms and presence of shallow sands	Information on the presence/condition of seepage berm should be used to assess the level of severity. The thickness of any low permeability layers underlying loose sand should also be considered.
Animal burrows	Animal burrows may cause hydraulic alterations which could potentially lead to internal erosion. Major hydraulic alterations include: (1) Shortening of seepage paths; (2) Piping. Suggested reference: FEMA (2005c, 2005d).
Sheetpile cutoff walls	Sheetpile cutoff walls can significantly reduce the potential for piping in sand strata in the foundation. If present, adequacy of the penetration depth (length) of the sheetpile wall could serve as an indicator of the susceptibility to this failure mode. Suggested reference: USACE (2000).
Corrosion potential of sheetpile cutoff walls, pipelines, and utilities	The use of corrosion protection and/or the presence of an adjacent cathodic system could reduce the susceptibility to this failure mode. Suggested reference: USACE (2000).
Manmade levee penetrations (pipelines, sewers, etc.)	Penetrations and the backfill surrounding them can create a preferential seepage path or hydraulic connection with the waterside and may contribute to internal erosion. In a structure experiencing settlement, penetrations may cause differential settlements leading to formation of cracks and cavities which in turn form potential pathways for seepage. Susceptibility to seepage is particularly acute from older penetrations which are prone to corrosion or collapse. Suggested reference: CDWR (2011); FEMA (2005b).
Repair/maintenance history	See * in Table 2.
Hydraulic gradients	High hydraulic gradients are a major factor causing the initiation of internal erosion. Generally, hydraulic gradients greater than 0.8 indicate potentially severe condition states. Suggested reference: Sherard et al. (1963).

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Table 5. Performance Indicators for Failure Mode 4

Performance Indicator(s)	Comments/Notes on Levels of Severity in Condition State
Observed post-construction floodwall tilt	Generally, observed tilts greater than 5 degrees indicate a potentially severe condition.
Floodwall material condition assessment	The condition assessment to determine potential levels of severity should include evaluation of corrosion, concrete cracking, honeycombing, concrete spalling, exposed rebar, and flaking steel.
Chances of levee/floodwall being hit by barge larger than design	The levels of severity can be determined based on the following barge traffic usage: (1) Floodside used as a regular barge channel; (2) Occasional barge traffic; (3) No barge traffic.
Condition/reliability of gate closure mechanisms	The levels of severity can be determined based on the following conditions of the closure mechanisms: (1) Inoperable/severely damaged; (2) Seems to work but with some damage; (3) In good working order/is well maintained.
Potential impact of differential settlement to pump station serviceability	Generally, differential settlements contributing to greater than acceptable distortions could indicate moderate to severe conditions states.
Condition of pumps at pump stations	The levels of severity can range from minimal to severe based on the condition of the pumps which could in turn range from being well maintained and in good working order to severely damaged or inoperable.
Repair/maintenance history	See * in Table 2.

Step 5: Develop prior probabilities and likelihoods of observing each level of severity

For the current application, the method begins with an estimate of the prior probability of failure for a given loading event (e.g. storm or hurricane) using available, but perhaps incomplete, information. The Bayesian method provides a useful approach when limited information is available so that decision makers can rely on judgments and expert opinion (Benjamin and Cornell 1970, Ang and Tang 1975, Margo et al. 2009). While the topic of elicitation of expert opinion is beyond the scope of this paper, the authors emphasize the importance of using qualified individuals and employing proper procedures to obtain these inputs from experts. For example, the facilitator of the expert elicitation process must understand the concepts of probability and risk, be aware of the biases that occur in judgment under uncertainty, and should be capable of resolving issues pertaining to breadth of opinion amongst experts. The reader is referred to Cooke (1991), Meyer and Booker (2001), O'Hagan et al. (2006), and USACE (2009) for guidelines on performing elicitation of expert opinion.

The acquisition of new information can be applied using Bayes' Theorem to obtain an updated (or posterior) estimate of the probability of failure under the given loading event (Hartford and Baecher 2004). For example, given some background rate of levee failure due to embankment instability (or prior probability), and given that levees with longitudinal cracking are more likely to experience failure by global instability, then an observation of longitudinal

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cracks on a levee may increase the estimated probability that the cracked levee will fail. Bayes' Theorem combines the prior probability and likelihoods using the following basic expression:

Posterior Probability $\propto$ Likelihood of Observations x Prior Probability

For the case of the global instability failure mode where a levee has experienced severe cracking, the terms in the basic expression of Bayes' Theorem given above are defined as follows:

- Posterior Probability is the probability of failure by global instability given severe cracking has been observed.
- Likelihood of Observation is the probability of the observation of severe cracking given failure. This could also be expressed as the percentage of levees that fail by global instability that would have been assessed to have severe cracking prior to failure.
- Prior Probability is the probability of failure without specific or sufficient information including the case when using available, but incomplete, information.

The following sections within Step 5 present mathematical results that may not be familiar to all readers. The mathematics are presented here for completeness but the concepts are better understood by the example application and calculations presented later in this paper. The application of Bayes' Theorem in the protocol provides a means to infer the probability of levee failure based on the engineering assessment of the performance indicators for several failure modes. For the purposes of the methodology presented in this paper, it is convenient to begin with the form of Bayes' Theorem shown in Equation (1):

$$\mathrm{P(f|E,O)} = \frac{\mathrm{P(f|E)P(O|E,f)}}{\sum_i \mathrm{P(f_i|E)P(O|E,f_i)}} \tag{1}$$

where $\mathrm{P(f|E,O)}$ is the posterior probability of failure under the loading event of interest E given an observation O, $\mathrm{P(f|E)}$ is the prior probability of failure under the loading event E without specific or sufficient information, $\mathrm{P(O|E,f)}$ is the probability of the observation O given failure under the loading event E, and $\sum_i \mathrm{P(f_i|E)P(O|E,f_i)}$ is a normalizing constant for all possible system response outcomes, including failure and non-failure. It should be noted that the mathematics presented herein deals with failure or non-failure of a reach under a given loading event of interest. For example, if the loading event of interest, E is the 500-year storm, $\mathrm{P(O|E,f)}$ is the probability of the observation O given failure of the reach under the 500-year storm. At this point, two steps are performed to simplify the calculations:

- Since all calculations in the proposed protocol are performed for probabilities associated with the given event of interest, the term E designated for the loading event in Equation (1) is eliminated for convenience of notation resulting in Equation (2):

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$$P(f|O) = \frac{P(f)P(O|f)}{\sum_i P(f_i)P(O|f_i)} \quad (2)$$

- The probability of failure, f, given the observation, O, is divided by the probability of non-failure, $\bar{f}$, given the same observation, O. This ratio is called the Likelihood Ratio and is presented in Equation (3):

$$\frac{P(f|O)}{P(\bar{f}|O)} = \frac{P(f)\,P(O|f)}{P(\bar{f})\,P(O|\bar{f})} \quad (3)$$

According to Baecher (2008), the term $P(f)/P(\bar{f})$ in Equation (3) is the odds in favor of failure of the reach when there is no specific information or in the case where the information available is insufficient. Baecher (2008) went on to define odds as the sort of measure that everyone is familiar with from, say, the track, for example "2:1 in favor," "a hundred-to-one against," and so forth. More precisely, this term is the prior odds, sometimes loosely called the base rate or ratio of base rates. The second term in Equation (3),

$$LR = \frac{P(O|f)}{P(O|\bar{f})} \quad (4)$$

is the Likelihood Ratio (LR), which is the weight of evidence contained in the observations. So, the updated odds, i.e. after the observation, $P(f|O)/P(\bar{f}|O)$ equals the prior odds multiplied by the Likelihood Ratio. In the case where there are multiple observations for a given failure mode, the Likelihood Ratio (LR) becomes the Joint Likelihood Ratio and can be computed as the joint likelihood of the observations using Equation (5):

$$LR = \frac{P(O_i, \ldots . O_n|f)}{P(O_i, \ldots . O_n|\bar{f})} = \frac{P(O_1|f)P(O_2|O_1,f)}{P(O_1|\bar{f})P(O_2|O_1,\bar{f})} \ldots \ldots \frac{P(O_n|O_{n-1}, \ldots . O_1,f)}{P(O_n|O_{n-1}, \ldots . O_1,\bar{f})} \quad (5)$$

where *n* is the number of observations (in this case, the number of performance indicators) for a given failure mode.

In the desirable and simplified approach adopted in this protocol, the performance indicators (i.e. observations) are assumed to be mutually independent, and the Joint Likelihood Ratio reduces to the simple product given in Equation (6):

$$LR = \prod_i \frac{P(O_i|f)}{P(O_i|\bar{f})} \quad (6)$$

As shown by Margo et al. (2009),

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$$\frac{P(f|O_i, \ldots . O_n)}{P(\bar{f}|O_i, \ldots . O_n)} = \frac{P(f)}{P(\bar{f})} \prod_i \frac{P(O_i|f)}{P(O_i|\bar{f})} \quad (7)$$

$$P(f|O_i, \ldots . O_n) = \frac{\frac{P(f)}{P(\bar{f})} \prod_i \frac{P(O_i|f)}{P(O_i|\bar{f})}}{1 + \frac{P(f)}{P(\bar{f})} \prod_i \frac{P(O_i|f)}{P(O_i|\bar{f})}} \quad (8)$$

The Likelihood Ratios for all structure types (e.g. levees, floodwalls, closure gates, pump stations) included in the overall assessment of the flood protection system must be obtained for all performance indicators within each failure mode.

For a given failure mode, the prior odds can be determined using the annual probability of failure, $P_{an}(f)$ which is obtained using either or a combination of historical data, expert opinion, and other pertinent information that is available. One example would be to use the relationships between Factor of Safety and Annual Probability of Failure based on level of engineering developed by Silva et al. (2008). When eliciting expert opinion on prior probabilities of failure, the person conducting the elicitation must make the time frame i.e. the specified time interval, clear to the experts. The flood protection reach will be assessed for a specified time period, T years. Therefore, the probability of the reach failing within the specified time period T years, $P_T(f)$ is given by

$$P_T(f) = 1 - [1 - P_{an}(f)]^T \quad (9)$$

The probability of the reach not failing in T years, $P_T(\bar{f})$ is given by

$$P_T(\bar{f}) = 1 - P_T(f) \quad (10)$$

Some performance indicators, such as the maintenance and repair history, contribute to several failure modes, so the failure modes may not be completely independent. However, they are likely to be positively correlated, that is, say an embankment with a large probability of failure in one mode probably has a large probability of failure in the other modes as well. In that case, it is conservative to assume that the modes of failure are independent, and the overall probability of failure from all modes is given by Equation (11):

$$p_{f,overall} = 1 - (1 - p_1)(1 - p_2)(1 - p_3)(1 - p_4) \quad (11)$$

The subscripts correspond to the modes of failure. It should be noted that Steps 1 through 5 (Phase 1 of the protocol) only need to be performed once. The information gathered through these steps is stored in a spreadsheet. The subsequent steps can be performed using this

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spreadsheet where the required calculations are automated based on input values provided by the user with information gathered in Steps 6 through 9.

Step 6: Perform current condition assessment of the reach

For a selected reach, perform an assessment to determine the current condition state. This could be done by means of reviews of historical inspection reports and risk protocol-specific field inspections (when warranted) using the performance indicators and predefined levels of severity as guidelines to determine the current condition state of the reach. The condition state is observed in the field and is assigned to the reach by making the appropriate selection in the spreadsheet developed in Steps 1 through 5. For example, if severe cracking is observed, the observation is translated into the corresponding Likelihood Ratio which is the ratio of the probabilities of making the observation of severe cracking given failure and non-failure states, respectively, as given in Equation (6).

Step 7: Update probability of failure using information from condition assessment

Using the information from Steps 5 and 6, an updated probability of failure of the reach which incorporates new information contained in the observations is obtained. This probability of failure is reflective of the current condition state of the reach.

Step 8: Combine probability of failure and failure consequences

Once the overall probability of failure is obtained from Step 7, some measure of consequences for risk quantification of the reach is calculated as the product of the probability and the consequence of failure. The consequence of failure could be estimated from assessments of the monetary damage that would be incurred if the reach were to fail. For a flood protection system, this would be obtained by performing inundation studies followed by economic analyses to evaluate the consequence. At the end of this, the risk, which combines probability of failure with some quantitative measure of failure consequences, is obtained for a given reach under a given loading event of interest.

Step 9: Rank reaches based on monetary-value risk

The reaches of the flood protection system can be ranked based on the risk corresponding to a benchmark event, say the 500-year storm. Based on this ranking, reaches in given polders that are in greater relative need of closer inspection, instrumentation and monitoring and/or rehabilitation can be identified. For a given reach, the types of monitoring, instrumentation and/or rehabilitation measures can be selected based on the probability of failure for the individual failure modes. In other words, once the overall ranking is obtained, critical failure modes within the reach can be identified for follow-up action.

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EXAMPLE APPLICATION FOR ONE REACH

This section presents the calculations performed to determine the probability of failure of an example reach by global instability under the 500-year storm event given that a set of hypothetical observations pertaining to the performance indicators have been preassigned. The example presented herein is for a levee reach located within a polder.

Likelihood Ratios

The Likelihood Ratios are obtained from a subject matter expert elicitation process. In the example, the performance indicators for failure by global instability are:

1. Cracking of the earth embankment
2. Levee height
3. Post-construction movement
4. Strength of foundation soils
5. Repair/maintenance history
6. Design Factor of Safety for global instability during extreme events
7. Observed seepage

Table 6 shows the Likelihood Ratios associated with cracking for three conditions states (Severe, Moderate, and Low). For the purpose of this example, the guidelines to assign these condition states based on field observations are assumed to have been predetermined. Similar tables for the remaining six performance indicators have been omitted from the example due to manuscript length restrictions. However, the final calculations to determine the probability of failure of the reach by global instability will include entries for the remaining performance indicators accompanied by the necessary input values so that the user is able to follow the computations which account for all performance indicators.

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Table 6. Typical Expert Elicitation for Observation of Cracking as an Indicator of Failure by Global Instability

No.	Question Addressed	Source	Value	
Questions for levees that did fail under the 500-year storm				
(1)	What percentage of levees that fail (f) by global instability would have been assessed to have severe cracking ($S_{cracking}$)?	Expert elicitation	44%	Total Percentage = (44 + 36 + 20)% = 100%
(2)	What percentage of levees that fail (f) by global instability would have been assessed to have moderate severity of cracking ($M_{cracking}$)?	Expert elicitation	36%	
(3)	What percentage of levees that fail (f) by global instability would have been assessed to have low severity or no cracking ($L_{cracking}$)?	Expert elicitation	20%	
Questions for levees that did not fail under the 500-year storm				
(4)	What percentage of levees that did not fail ($\bar{f}$) by global instability would have been assessed to have severe cracking ($S_{cracking}$)?	Expert elicitation	18%	Total Percentage = (18 + 33 + 49)% = 100%
(5)	What percentage of levees that did not fail ($\bar{f}$) by global instability would have been assessed to have moderate severity of cracking ($M_{cracking}$)?	Expert elicitation	33%	
(6)	What percentage of levees that did not fail ($\bar{f}$) by global instability would have been assessed to have low severity or no cracking ($L_{cracking}$)?	Expert elicitation	49%	
Likelihood Ratios from Expert Elicitation				
Likelihood Ratio for $S_{cracking}$, $P(S_{cracking} \mid f)/P(S_{cracking} \mid \bar{f})$			0.44/0.18 = 2.44	
Likelihood Ratio for $M_{cracking}$, $P(M_{cracking} \mid f)/P(M_{cracking} \mid \bar{f})$			0.36/0.33 = 1.09	
Likelihood Ratio for $N_{cracking}$, $P(L_{cracking} \mid f)/P(L_{cracking} \mid \bar{f})$			0.20/0.49 = 0.41	

Posterior Probability of Failure for the Example Likelihood Ratios

Table 7 summarizes the Likelihood Ratios from Table 6 and also presents Likelihood Ratios for the remaining six performance indicators. The Likelihood Ratios for these six performance indicators were obtained using the same process presented in Table 6. Table 7 also shows in the last column an example of observed condition assessments of each of the seven indicators.

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Table 7. Typical Likelihood Ratios for Global Instability

			Base Failure Rate	0.001
Performance Indicator	Likelihood Ratios (LR)			Condition Assessment of the Reach
Cracking	$S_{cracking}$	$M_{cracking}$	$L_{cracking}$	$M_{cracking}$ (LR = 1.09)
	2.44	1.09	0.41	
Levee Geometry – Height	S_{height}	M_{height}	L_{height}	S_{height} (LR = 1.50)
	1.50	1.17	0.50	
Post-construction Movement	S_{mvmt}	M_{mvmt}	L_{mvmt}	S_{mvmt} (LR = 2.75)
	2.75	1.17	0.20	
Strength of Foundation Soils	$S_{found\text{-}soil}$	$M_{found\text{-}soil}$	$L_{found\text{-}soil}$	$S_{found\text{-}soil}$ (LR = 2.25)
	2.25	1.17	0.40	
Repair/maintenance history	S_{repair}	M_{repair}	L_{repair}	S_{repair} (LR = 2.00)
	2.00	1.17	0.50	
Design Factor of Safety (FOS) for global instability during extreme events	$S_{FOS\text{-}Global}$	$M_{FOS\text{-}Global}$	$L_{FOS\text{-}Global}$	$M_{FOS\text{-}Global}$ (LR = 1.00)
	2.75	1.00	0.30	
Observed Seepage	$S_{Seepage\text{-}Global}$	$M_{Seepage\text{-}Global}$	$L_{Seepage\text{-}Global}$	$S_{Seepage\text{-}Global}$ (LR = 2.00)
	2.00	1.00	0.60	

Note: S = high level of severity, M = moderate level of severity, L = low level of severity.

Inserting the corresponding likelihood ratios from Table 7 and using the prior probability of 0.001, one obtains from Equation 7,

$$P\left(f_{global} \mid \text{Cracking, Levee Height, Movement, Soil Strength, } FOS_{global}\text{, Seepage}\right)$$

$$= \frac{\frac{0.001}{(1-0.001)}(1.09)(1.50)(2.75)(2.25)(2.00)(1.00)(2.00)}{1+\frac{0.001}{(1-0.001)}(1.09)(1.50)(2.75)(2.25)(2.00)(1.00)(2.00)}$$

$$= \frac{\frac{0.001}{0.999}(1.09)(1.50)(2.75)(2.25)(2.00)(1.00)(2.00)}{1+\frac{0.001}{0.999}(1.09)(1.50)(2.75)(2.25)(2.00)(1.00)(2.00)}$$

$$= 0.0389$$

The result (0.0389) is significantly higher than the prior value of 0.001, so it is possible that this particular reach may warrant further investigation. The process performed for this reach could be performed for all reaches within a polder or the entire flood protection system, depending on the scope of the priorities that need to be established. The remaining reaches could consist of other

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structures including levees, floodwall on levees, floodwalls, pump stations, and closure gates. The assessment shown in the example is generally repeated at some frequency to track the changes in the probabilities of failure. Overall, the approach would be useful in developing management strategies to minimize risks.

CONCLUSIONS

A probabilistic asset management protocol, developed for typical flood protection systems, was presented in this paper. The protocol addresses five key structure types (represented as reaches) present within the flood protection system. Out of the five failure modes identified, performance indicators for four failure modes were established for these structures. Due to manuscript length limitations, potential performance indicators for the fifth failure mode were not included in this paper. Some guidelines to assign observable severity levels were then developed for the established performance indicator so that the condition state of the reach at any given time could be determined in a consistent and reliable manner. These condition states were then converted into probabilistic expressions using information obtained from subject matter expert opinion. Using these expressions, the probability of the reach failing under a benchmark storm event, say the 500-year storm, was determined using Bayes' Theorem. Subsequently, the probability of failure was combined with the consequence of failure to get the monetary-value of risk. When the monetary-value risk for all reaches are computed, reaches of the flood protection system can be ranked based on the risk corresponding to the benchmark event. Based on this ranking, reaches in greater relative need of closer inspection, instrumentation and monitoring and/or rehabilitation can be identified. For a given reach, the types of instrumentation and/or rehabilitation measures can be selected based on the probability of failure for the individual failure modes. In other words, once the overall ranking is obtained, critical failure modes within the reach can be identified for follow-up action.

The following are the key benefits of the protocol: (1) It has the capability to integrate and convert data from routine field inspection records, monitoring instrument readings, and/or in-situ test data into a quantitative risk ranking that can be updated with time; (2) It has the utility to address both capability and consequence values of an asset. Ultimately, the protocol provides for the seamless integration of probability of failure with the consequence of failure to obtain a monetary-value risk for each asset component; (3) It can be tailored to address a broad definition of failure, i.e. as the underperformance of an asset. For example, underperformance could be addressed from the perspective of serviceability or ultimate limit states. (4) While the example application presented in this paper was for a flood protection system subdivided into reaches with varying attributes, its underlying framework is highly versatile. It can be applied to a broad spectrum of infrastructure assets and asset systems. For example, the protocol can be tailored for asset management of a transportation corridor which includes bridges and bridge approaches, pavements, retaining walls, and slopes.

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REFERENCES

Amadi-Echendu, J.E., Willett, R., Brown, K., Hope, T., Lee, J., Mathew, J., Vyas, N., and Yang, B-S. (2010). "What Is Engineering Asset Management?" *Definitions, Concepts and Scope of Engineering Asset Management*, J.E. Amadi-Echendu, K. Brown, R. Willett, and J. Mathew, eds. Springer-Verlag, London, 3-18.

Ang, A. H-S. and Tang, Wilson H. (1975). *Probability Concepts in Engineering Planning and Design, Volume 1 – Basic Principles*. John Wiley and Sons, NY.

Baecher, G. B. (2008). "Constructing Additive Risk-Rating Scales." Occasional Paper 2008-01, The Water Collaborative at the University of Maryland, July 31st.

Baecher, G. B. and Christian, J. T. (2013). "Screening Geotechnical Risks." *Foundation Engineering in the Face of Uncertainty*, J. L. Withiam, K-K. Phoon, and Mohamad Hussein, eds., Geotechnical Special Publication 229, ASCE, Reston, VA, 215-224.

Benjamin, J.R. and Cornell, C.A. (1970). *Probability, Statistics, and Decision for Civil Engineers*. McGraw-Hill Book Company.

Briaud, J.-L., Chen, H.-C., Govindasamy, A.V., and Storesund, R. (2008). "Levee Erosion by Overtopping in New Orleans during the Katrina Hurricane." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Reston, VA, 134(5), 618-632.

Briaud, J.-L. (2008). "Case Histories in Soil and Rock Erosion: Woodrow Wilson Bridge, Brazos River Meander, Normandy Cliffs, and New Orleans Levees." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Reston, VA, 134(10), 1425-1447.

CDWR (California Department of Water Resources). (2011). "Chapter 4 – Levee Status." <www.water.ca.gov/cvfmp/docs/FCSSRDec2011_Section4.pdf> (Jun. 19, 2013).

Cooke, R.M. (1991). *Experts in Uncertainty – Opinion and Subjective Probability in Science.* Oxford University press, New York.

Cox, L.A., Djangir, G., and Huber, W. (2005). "Some Limitations of Qualitative Risk Rating Systems." *Risk Analysis*, 25(3), 651-661.

Cox, L.A. (2008). "What's Wrong with Risk Matrices." *Risk Analysis*, 28(2), 497-511.

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Fell, R., Wan, C.F., Cyganiewicz, J. and Foster, M. (2003). "Time for Development of Internal Erosion and Piping in Embankment Dams." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Reston, VA, 129(4), 307-314.

FEMA (Federal Emergency Management Agency). (2005a). "Section D.4.5 Wave Setup, Runup, and Overtopping." 〈http://www.fema.gov/library〉 (Feb. 19, 2013).

FEMA (Federal Emergency Management Agency). (2005b). *Technical Manual: Conduits through Embankment Dams, Best Practices for Design, Construction, Problem Identification and Evaluation, Inspection, Maintenance, Renovation, and Repair.* U.S. Department of Homeland Security.

FEMA (Federal Emergency Management Agency). (2005c). *Technical Manual for Dam Owners, Impacts of Animals on Earthen Dams, FEMA 473.* U.S. Department of Homeland Security.

FEMA (Federal Emergency Management Agency). (2005d). *Dam Owner's Guide to Animal Impacts on Earthen Dams, FEMA L-264.* U.S. Department of Homeland Security, September.

Hartford, D. N.D. and Baecher, G.B. (2004). *Risk and Uncertainty in Dam Safety.* Thomas Telford Publishing, London.

IDNR (Indiana Department of Natural Resources). (2007). *Indiana Dam Safety Inspection Manual Part 3.* Division of Water, Indianapolis.

Margo, D., Harkness, A., and Needham, J. (2009). *Levee Screening Tool.* United States Society on Dams Conference, Nashville, TN.

Meyer, M.A. and Booker, J.M. (2001). *Eliciting and Analyzing Expert Judgment – A Practical Guide.* American Statistical Association, Alexandria, VA and Society for Industrial and Applied Mathematics, Philadelphia, PA.

NHC (National Hurricane Center). (2012). "Storm Surge Overview." 〈http://www.nhc.noaa.gov/surge〉 (Feb. 19, 2013).

NHC (National Hurricane Center). (2013). "Introduction to Storm Surge." 〈http://www.nhc.noaa.gov/ssurge/surge_intro.pdf〉 (Feb. 19, 2013).

O'Hagan A., Buck, C.E., Daneshkhah, A., Eiser, R.J., Garthwaite, P.H., Jenkinson, D.J., Oakley, J.E., and Rakow, T. (2006). *Uncertain Judgments – Eliciting Experts' Probabilities*. John Wiley & Sons, West Sussex, England.

Paté-Cornell, E. (2012). "On "Black Swans" and "Perfect Storms": Risk Analysis and Management When Statistics Are Not Enough." *Risk Analysis*, 32(11), 1823-1833.

Pullen, T., Allsop, N.W.H., Bruce, T., Kortenhaus, A., Schuttrumpf, and van der Meer, J.W. (2007). *European Overtopping Manual (EurOtop), Wave Overtopping of Sea Defenses and Related Structures: Assessment Manual.*

Sarfi, R. and Tao, M. (2004). "Asset Management – Realizing a practical strategy." *Energy Pulse: Insight, Analysis and Commentary on the Global Power Industry.*

Schuttrumpf, H. and van Gent, M.R.A. (2003). "Wave Overtopping at Seadikes." *Coastal Structures 2003*, 431 – 443.

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Sherard, J.L., Woodward, R.J., Gizienski, S.F., and Clevenger, W.A. (1963). *Earth and Earth-Rock Dams, Engineering Problems of Design and Construction.* John Wiley & Sons.

Silva, F., Lambe, T.W., and Marr, W.A. (2008). "Probability and Risk of Slope Failure," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Reston, VA, 134(12), 1691-1699.

Too, E.G. (2010). "A Framework for Strategic Infrastructure Asset Management." *Definitions, Concepts and Scope of Engineering Asset Management*, J.E. Amadi-Echendu, K. Brown, R. Willett, and J. Mathew, eds. Springer-Verlag, London, 31-64.

USACE (U.S. Army Corps of Engineers). (2000). *Design and Construction of Levees – EM 110-2-1913*, Department of the Army, Washington, D.C.

USACE (U.S. Army Corps of Engineers). (2009). *Technical Guide for Use of Expert Opinion Elicitation for U.S. Army Corps of Engineers Risk Assessments.* Dam Safety Risk Management, Department of the Army, Washington, D.C.

USACE (U.S. Army Corps of Engineers). (2010). *Hurricane and Storm Damage and Risk Reduction System Design Elevation Draft Report Version 4.0*, USACE New Orleans District.

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Characterizing Unknown Trend Using Sparse Bayesian Learning

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Abstract

This paper addresses the problem of characterizing the statistical uncertainties associated with the estimation of a depth-dependent trend function using *limited* site-specific geotechnical data. Specifically, the statistical uncertainties associated with the following elements of the problem are considered: (1) the functional form of the trend function, (2) the parameters of the trend function (e.g., intercept and gradient), and (3) the random field parameters, namely standard deviation (σ) and scale of fluctuation (δ). The problem is resolved with a two-step Bayesian framework. In Step 1, a set of suitable basis functions that parameterize the trend function is selected using the sparse Bayesian learning. In Step 2, an advanced Markov chain Monte Carlo method is adopted for the Bayesian analysis. The two-step approach is shown to be consistent in the well-defined sense that the resulting 95% Bayesian confidence interval (or region) contains the actual trend (or actual σ & δ) with a chance that is close to 0.95.

INTRODUCTION

One of the purposes of site investigation is to obtain information on the vertical spatial distribution of geotechnical parameters. The amount of information collected in a site investigation is limited when compared to the volume of soil. Hence, statistical uncertainty is particularly important in the geotechnical context. This means that the parameters used to characterize the vertical spatial distribution, such as the trend function (t), standard deviation (σ), and scale of fluctuation (SOF) (δ), cannot be estimated with complete certainty. The statistical uncertainty in some of these parameters has been explicitly addressed in Ching et al. (2016a). They considered a vertical spatial distribution with a constant trend = μ. They concluded that the Markov chain Monte Carlo (MCMC) is consistent in the well-defined sense that the chance that the actual value of (μ,σ,δ) is within the 95% Bayesian confidence region is close to 0.95. Ching et al. (2016b) further considered a vertical spatial distribution with a linear trend = $a + b \times z$ (z is the depth; a and b are the intercept and gradient). They further considered a common scenario where the trend function is obtained by regression and the de-trended data is adopted to

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