School of Earth & Environment
FACULTY OF ENVIRONMENT
UNIVERSITY OF LEEDS

Risk-based design approach for the impact of climate change on critical infrastructure in the Caribbean

HERONA D. THOMPSON

SEPTEMBER 10, 2020

WORD COUNT: 15,000

This dissertation is submitted in partial fulfilment of the requirements for the degree of Master of Science in Engineering Geology

UNIVERSITY OF LEEDS

SCHOOL OF EARTH AND ENVIRONMENT

DECLARATION OF ACADEMIC INTEGRITY

To be attached to any essay, Dissertation, or project work submitted for assessment as part of a University examination.

I have read the University regulations on Cheating and Plagiarism, and I state that this piece of work is my own, and it does not contain any unacknowledged work from any other sources.

Name printed **Herona D. Thompson**

signed **Herona D. Thompson**

Date **September 10, 2020**

Programme of Study

MSc. Engineering Geology

School of Earth & Environment
FACULTY OF ENVIRONMENT
UNIVERSITY OF LEEDS

- Strike through all text that does NOT apply, ……… AND
- Circle all text that DOES apply, ……… AND
- Sign and date the foot of the page.

STATEMENT OF CONFIDENTIALITY STATUS.

For the hard-copy paper document:

- [✓ It contains no confidential material. Open access is allowed subject to normal University copyright restrictions]
- ~~It contains confidential material. Access is not permitted unless prior permission has been obtained from~~
- ~~It contains confidential material. Access restrictions must remain in place indefinitely~~
- ~~It contains confidential material. Access restrictions must remain in place for a period of~~ _______________ years ending on ____________________ (give date)

For any enclosures in paper or electronic form:

- It contains no confidential material. Open access is allowed subject to normal University copyright restrictions
- It contains confidential material. Access is not permitted unless prior permission has been obtained from
- It contains confidential material. Access restrictions must remain in place indefinitely
- It contains confidential material. Access restrictions must remain in place for a period of _______________ years ending on ____________________ (give date)

Print name Herona Thompson Signed **Herona Thompson**

ACKNOWLEDGEMENTS

Firstly, I would like to thank God for awarding me the opportunity to study in the U.K. I would like to specially thank The Caribbean Catastrophe Risk Insurance Facility (CCRIF SPC) for awarding a scholarship to pursue a MSc. in Engineering Geology at the University of Leeds, and for following-up with me through this difficult period.

I would like to thank my Supervisor, Prof. Barry Clarke for all the support, guidance and clarity he gave me while going through this process. I would like to thank Mr. Norman Harris and Ms. Nesha Nurse for providing insight on the geology and design process in Jamaica and Barbados. I would like to give a special thanks to Mrs. Dorothy Thompson and Ms. Racquel Wright for all the assistance and encouragement, along with other family members and friends that encouraged me, acted as a sounding board for my ideas on the study and helped me to cope during the COVID-19 pandemic. For all the wonderful friends I have made at Leeds, my classmates and flatmates who made my experience in the UK an enjoyable one and helped to keep me sane and gave insight during this trying time, I thank you. I would like to thank the St. Augustine Wrangthorn Church Group, Transformation Leeds and Leeds African Communities Network who made sure to always provide support to international students like myself while on government lockdown. I would also like to thank all my lecturers and staff in the MSc. Engineering Geology Programme for their classes, fieldtrips and labs, engagement and support with finding innovative means for us to learn more about Engineering Geology before and during the pandemic.

Finally, I would like to thank the persons reading and grading this dissertation in advance during this difficult and unprecedent time in the history of the world. The lockdown has had a great impact on us all.

I have learnt a lot while researching my topic. I hope this will help to give more insight on the Caribbean, the potential impact of climate change on critical infrastructure and geotechnical assets and Engineering Geology for the future.

ABSTRACT

Climate change is a major threat to critical infrastructure as well as efficient infrastructure spending and long-term planning. This has encouraged many fields, such as geotechnical design to finding solutions. Many scientists believe that current conventional geotechnical designs cannot manage the threat of climate change. Risk-based approaches, which incorporate risk assessments into all phases of the construction process, are being explored as an option. Three types of risk-based approaches are sustainable design, resilient design and adaptive design and are currently being used in geotechnical asset management. The Caribbean Region, which is extremely vulnerable to climate change, is interested in the survival of their critical infrastructure. However, little research has been done on the potential impact of climate change on the geotechnical assets at their critical infrastructure and the role of an Engineering Geologist.

Critical infrastructure of airports, seaports and energy facilities and their geotechnical assets were used to identify the potential impacts of climate change in the Caribbean. Geotechnical assets selected for investigation were pavements, embankments, fill and ground improvement and foundations. Sea-level rise scenarios of 1.5^{o}C, 2.0^{o}C and 3.0^{o}C were tested to identify the risk to twenty-four critical infrastructure located within 500m of the coastlines of Jamaica, Barbados and St. Lucia. These scenarios were used to generate risk matrices and identify risks to critical infrastructure and the geotechnical assets. Additionally, they were subsequently used to determine if current conventional design and/or risk-based approaches were more suitable.

The study has shown that both types of designs are applicable in the Caribbean, but the risk-based approaches are more suitable. Additionally, many uncertainties in the geotechnical, political, financial and environmental aspects would have to be considered in design. However, more research is needed, and the Engineering Geologist will have to play a greater role in design for the future.

TABLE OF CONTENTS

List of Tables

List of Figures

ACRONYMS, ABBREVIATIONS AND SYMBOLS

^{o}C	Degrees celsius
asl	Above sea level
bgl	Below ground level
C.C.	Climate Change
C.I.	Critical Infrastructure
$Ca(OH)_2$	Calcium hydroxide
$CaCO_3$	Calcium carbonate
CO_2	Carbon dioxide
EnGeol	Engineering Geologist
FHWA	Federal Highway Administration
ft	Feet
G.A.	Geotechnical Assets
G.A.M.	Geotechnical Asset Management
GHG	Greenhouse gases
H_2CO_3	Carbonic acid
H_2O	Water
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
km	kilometre
km^2	squared kilometre
L-A-R	Loads, Actions and Resistances
LRFD	Load Resistance Factor Design
LSD	Limit State Design
m	Metre
mm	millimetre
MPa	Megapascals
NRCS	U.S. Department of Agriculture Natural Resources Conservation Service
RCPs	Representative Concentration Pathways
SIDS	Small Island Developing States
U.K.	United Kingdom
U.S.	United States of America
UN	United Nations
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
Wm^{-2}	Watts per square metre
yr	Year

GLOSSARY

Terms	Definition
Actions	Permanent, transient or accidental loads and other forces that will affect the limit state of a structure.
Climate change	The alteration of long-term (~30-year) average weather conditions and trends caused directly or indirectly mainly by human activity through greenhouse gas emissions, and less so by natural climate variability such as volcanic eruptions and solar cycles. GHG's emissions lead to rising global temperatures which are altering the global atmosphere's composition (IPCC, 2013).
Critical infrastructure	Body of systems, networks and assets that are so essential that their continued operation, safety, reliability, preservation and protection are required for national security, economies, and the public's health and/or safety. (Haughn, n.d.; Mordor Intelligence LLP, 2020).
Dolos	Reinforced concrete block in a geometric shape used to build revetments for protection against hydraulic action of waves.
Geotechnical Asset Management	The management, monitoring and maintenance of geotechnical assets for the purpose of protecting or preserving infrastructure.
Geotechnical Assets	Engineered ground or designed ground solutions. These include earthworks, foundations, retaining walls, engineered/improved fill, subgrades, etc.
Geotechnical risks	Risk to construction and structure created by the site ground conditions and humans.
Ground	Soil, rock or fill.
Loads	Stresses imposed on the ground by structures.
Reconstructive Designs	Designs for removing and rebuilding structures.
Rehabilitative Design	Designs for repairing and upgrading structures in accordance with new standards, guidelines or requirements.
Resistance	The ground. Acts against the forces of actions and loads.
Risks	Quantified uncertainties with the possibility of actions and resulting outcomes
Thermo-hydraulic properties	Soil properties such as permeability and the coefficient of thermal expansion, thermal conductivity and heat capacity.
Uncertainties	Questionable and possibly unpredictable things.

1 INTRODUCTION

1.1 Background

Climate change (C.C.) threatens efficient infrastructure spending and long-term planning. It is also the biggest threat now and in the future to critical infrastructure (C.I.) that have undergone increasing diversity, are more interrelated and interdependent and more expensive to build and maintain (Franco, 2020). Climate related disasters cost the world US$650 billion (2016-2018) and could cost US$7.9 trillion by 2050 (DiChristopher, 2019; Agence France-Presse, 2019). Thus, driving many disciplines, such as geotechnical engineering to finding solutions; one area this can be applied to is design.

The ground support and protection of C.I. are currently administered by conventional geotechnical design, where engineering geologists operate. Its purpose is to ensure that the ground and geotechnical assets (G.A.) are fit for purpose and are strong, safe, serviceable and durable (British Standards Institution (BSI), 2013). With relatively recent standardisation and global adoption of geotechnical design standards, their relevance and suitability need constant review (Eitner et al., 2002; Eggers, 2016). Designing structures to fulfil their design lives is one feature of design and must involve managing future developments and threats. However, recent research indicates conventional design may not be appropriate to handle C.C.'s threats, whether based upon their management, philosophy, applicability, or that some extreme climate hazards were not designed for or happen faster than standards are updated (Nicholson and Bruce, 1992; Weeks, 2013). Risk-based approaches are another type of design proposed to better manage ground uncertainties and impact of C.C. (Gibbs, 2012; Kannan, 2017). To prepare for the future, conventional design and risk-based approaches, and the role of the engineering geologist need to be reviewed against a probable future.

One of the most vulnerable regions in the world to C.C. is the Caribbean, namely the islands. Governments, investors, insurance companies and international development agencies are concerned with infrastructure, contemplating both the opportunities of developing the Blue Economy and the threats of C.C. to national and regional development (Caribbean Development Bank, 2018). The devastation caused during the 2017 Atlantic Hurricane Season, resulting in damages of over US$100 billion and counting, prompted the regional body, the Caribbean Community (CARICOM) to begin plans on creating the World's first Climate Resilient Region, with a goal to 'Build Back Better,' (Wilkinson et al., 2018; Morgan, 2018). Coastal C.I., namely transport (airports and seaports) and energy facilities were and are guided by conventional design. However, a risk-based design approach may be the better solution.

1.2 Justification

Ground engineering is contributing to solutions for C.C. through research and geotechnical asset management (G.A.M). Recent geotechnical and engineering geological studies have attempted to determine the potential impact of C.C. and climate variables to ground materials and properties and G.A. (Vahedifard et al., 2018; Tang et al., 2018; Chang et al., 2019; Vardon, 2019). Most studies are based on the climates of Europe and U.S. and use climate statistical trends, modelling, projections and scenarios. The U.S., U.K., Canada and New Zealand have also begun using a risk-based approach in managing and maintaining G.A. for transport C.I. through G.A.M (ARUP, 2010; Jared et al., 2018; Vessely et al., 2019; Kelsey, 2020; Spink, 2020).

Climate change scenarios may be a useful tool for planning and development. It can present potential impacts, identify uncertainties and risks and examine the preparedness and resilience of existing and future infrastructure. Recently, numerous studies have been conducted by international agencies, governments, and researchers on the vulnerability of Caribbean C.I. to C.C. (Nurse et al., 2014; Sjöstedt and Povitkina, 2017; Monioudi et al., 2018). However, little research has been done on the potential impact of C.C. on the ground or G.A. of C.I., as in the above studies and G.A.M. in the above countries. Additionally, the climate vulnerability studies have not mentioned the role of design in the process or the future role of the engineering geologist.

1.3 Purpose and Significance

This research aims to contribute to the discussion of geotechnical design and engineering geology for the future and provide a useful basis for studying the impact of C.C. on G.A. in tropical regions. The applicability and suitability of conventional design and risk-based approaches to potential future Caribbean C.C. scenarios will be examined. It will do this by investigating the potential impact of these scenarios on the C.I. of airports, seaports and energy facilities, their G.A. and the future role of the engineering geologist.

This study is significant because it could contribute to the study, potential use, and impact of risk-based design in the Caribbean and other Small Island Developing States (SIDS). It could also promote the importance of engineering geology to Caribbean governments, insurance companies, international funding agencies, infrastructure design consultants, geotechnical firms and universities.

1.4 Aims and Objectives

The aims and objectives are:

Aim 1: *To critically review current geotechnical design approaches for G.A. found at select C.I.*

Objectives:

1a) Identify current conventional design and the role of the Engineering Geologist as it relates to pavements, embankments, fill and ground improvement and foundations.

1b) Examine the advantages and disadvantages of conventional design, and the treatment of C.C.

1c) Examine three types of risk-based approaches
and compare conventional design and risk-based approaches.

Aim 2: *To determine the potential risks of C.C. to select Caribbean C.I. and their ground conditions by 2100.*

Objectives:

2a) Identify potential future C.C. threats to the Caribbean.

2b) Identify airports, seaports and energy facilities within 500m of the coastline of three Caribbean countries, the hazards that currently affect them and their ground conditions.

2c) Create two risk matrices to determine the risk of SLR scenarios to:
  i. The C.I.
  ii. The G.A. at these C.I.

Aim 3: *To determine the potential impact and application of these designs to the future scenarios.*

Objectives: 3a) Determine how both types of designs can be applied to these future scenarios for existing and new C.I.

3b) Identify the uncertainties and issues that need to be addressed in these designs.

3c) Identify the potential role of the engineering geologist in designs for the future scenarios.

1.5 Dissertation Outline

This dissertation consists of six chapters:

Chapter 1: Introduces the background, aims and objectives, justification, purpose and significance of this research.

Chapter 2: Presents the research strategy, data collection, process of analysis and limitations surrounding the methodology.

Chapter 3: Presents the findings of Aim 1 on the review of current designs.

Chapter 4: Presents the findings of Aim 2 on the future risks of C.C. to C.I. and their ground conditions in the Caribbean.

Chapter 5: Discusses the suitability and application of current designs to the future risks.

Chapter 6: The conclusions and recommendations for future research.

A review of the relevant literature will be incorporated into Chapters 3-5.

2 METHODOLOGY

Various stages were used to assess whether conventional designs or risk-based approaches are suitable for use in the Caribbean. Figure 2-1 outlines the entire process and the relevant sections followed by limitations.

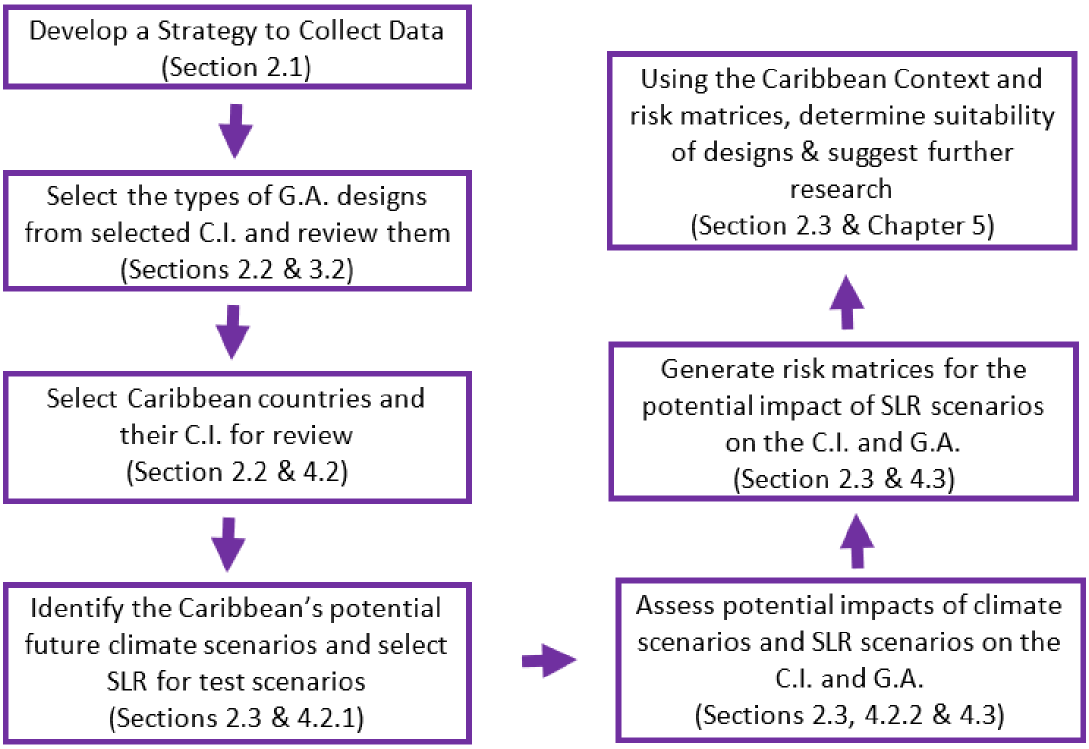


Figure 2-1: Flowchart outlining the methodology.

2.1 Strategy and Data Collection

An online desk-study of relevant qualitative and quantitative secondary data was used for this project. This included relevant government statistics, geology, soil, hazard vulnerability and susceptibility maps; environmental impact assessments and vulnerability reports of the selected C.I. to C.C., and reports from regional and international and regional agencies regarding climate change in the Caribbean and the vulnerability of C.I. to C.C. Software tools from credible organizations were used to generate maps, charts and test scenarios in the Caribbean. Primary data were gathered from online interviews with practicing geologists Mr. Norman Harris (Jamaica) and Ms. Nesha Nurse (Barbados) to validate the secondary information on their island's geology and treatment of design and maintenance.

2.2 Selection of C.I., designs and sites to be tested

Figure 2-2 outlines the process of selecting the G.A. and current designs reviewed in Chapter 3. Based on the Caribbean's political/colonial history with European nations, foreign development and investment, and proximity to the U.S., it was assumed that many of the coastal C.I. were and will be designed and built using their codes and standards. European and relevant U.S. standards were used as the guide for conventional geotechnical design. Journal articles, books, case studies and geotechnical reports and standards were used to compare designs in Chapter 3.

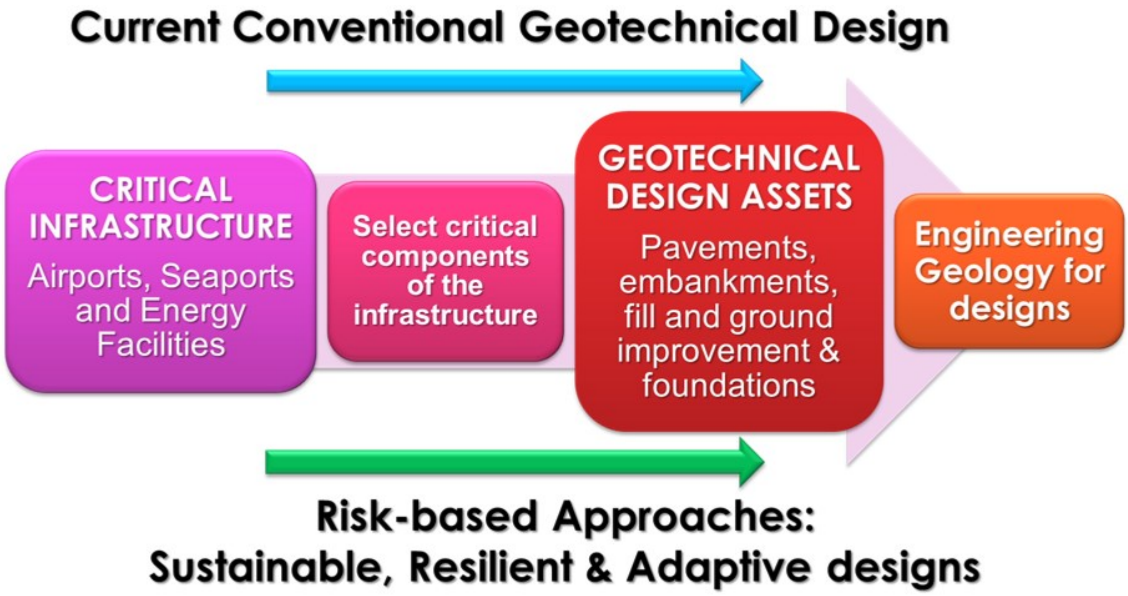


Figure 2-2: Process for selecting the G.A. and designs discussed in Chapter 3.

Subsequently, 24 coastal C.I. comprising airports (5), seaports (6) and energy facilities (13 - 9 power plants, 2 oil terminals, 1 LNG terminal and 1 oil refinery) across three countries (Jamaica – Montego Bay and Kingston, St. Lucia and Barbados) were selected for the analysis in Chapter 4 as displayed in Figure 2-3.

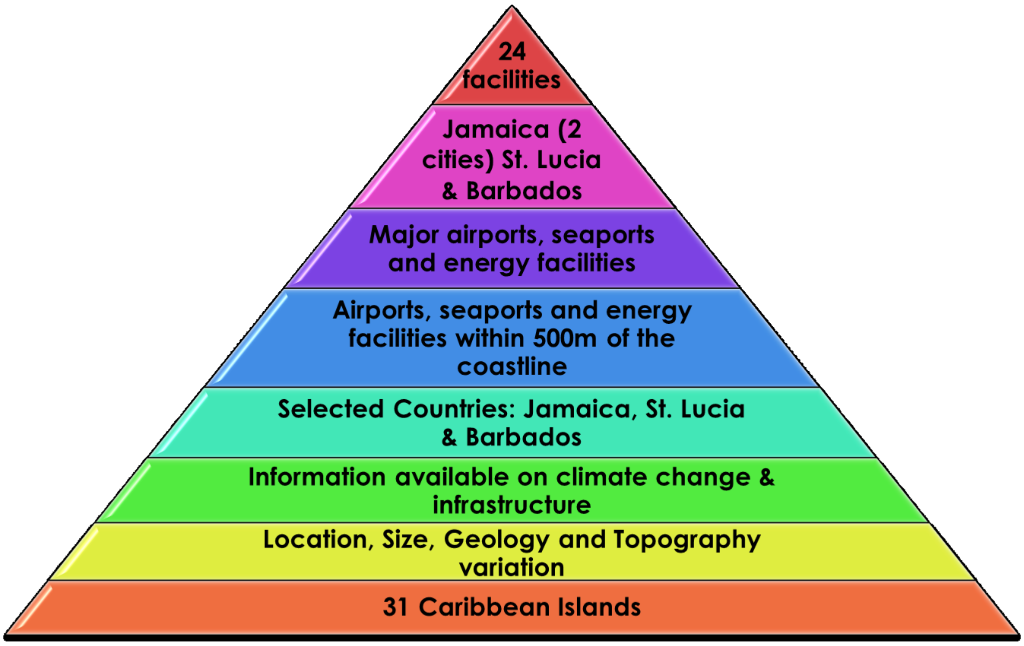


Figure 2-3: Pyramid diagram of the selection process for countries and C.I.

2.3 Scenarios and generating risk assessments

The author’s inexperience with climate modelling and wind analysis were originally considered for selecting the test scenarios. Additionally, initial reviews of the ground and topographic parameters at selected sites were unsuitable for slope analysis. Out of all the manifestations of C.C, SLR scenarios, which will be used, have been regarded as having both a very high degree of confidence in the detection of observed impacts, and a very high degree of confidence in attribution to C.C. drivers within tropical small islands (Nurse et al., 2014). A free KML file on SLR relative to global temperatures from the tool *Surging Seas: Mapping Choices* by Climate Central was used. According to Climate Central (2020), their Caribbean data is a high accuracy elevation dataset for low-lying coastal areas with ~30m in horizontal resolution. Figure 3-3 outlines the process of generating scenarios to risk matrices. Chapter 4 provides additional information on generating risk matrices from observations.

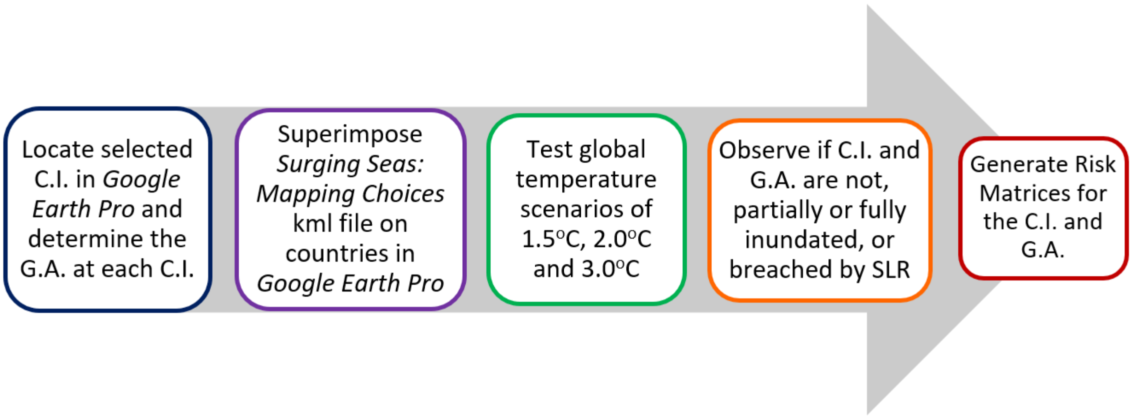


Figure 2-4: Process of testing SLR scenarios to generate risk matrices.

The results from Chapters 4 and 5 were used to determine the application and suitability of designs (Figure 2-4) and any gaps/areas for further research.

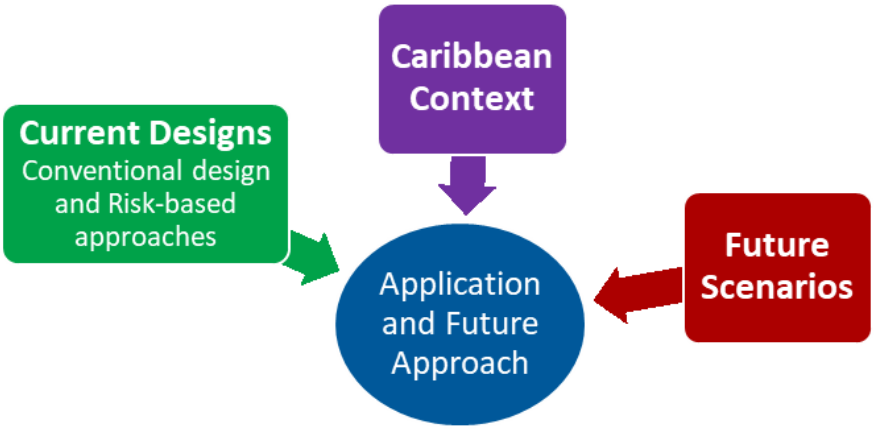


Figure 2-5: Approach to determining the application and suitability of designs.

2.4 Limitations

As research was conducted during the 2020 COVID-19 pandemic, data availability and credibility were limited. Furthermore, C.I. are important for national security, so the availability and quality of published data from each country was limited and varied. Attempts were made to interview someone with geological/design experience from St. Lucia, but this proved unsuccessful. Due to the word count limit of this research some of the sources could not be included in the reference page. Repetition of sources was limited to two mentions in the report and references were included based on their level of importance and added value.

Limitations in the analysis existed in the accuracy of the SLR projections on the KML file (based on data from 2015 and the non-inclusion of regional isostacy data) and the use of visual observations to generate risk matrices (see Section 4.4.2 for more details).

3 CURRENT DESIGNS

This Chapter address Aim #1: To critically review current geotechnical design approaches for G.A. found at selected C.I.

3.1 Conventional Design

Geotechnical design is the third part of the linear construction project process (Figure 3-1) and is governed by the:

i. Purpose, type and requirements of the structure,
ii. Structure's age (new/existing)
iii. Budget, time and effort
iv. Type of contract (design-build or design-bid-build), and
v. **Conventional Design** - Codes of practice/standards and guidelines

3.1.1 European and U.S. Designs

Conventional design includes standards and guidelines for investigations, testing and design. Relevant testing standards include the *ISO/TC 182 Geotechnics* Standards used in Europe *and ASTM International* standards used in the U.S. Relevant investigation and design standards include:

i. European Standards - *Eurocode 7: Geotechnical Design* (BSI, 2007; BSI, 2013),
ii. Guidelines made by U.S. government agencies such as the Federal Highway Administration (FHWA), U.S. Department of Agriculture Natural Resources Conservation Service (NRCS), U.S. Army Corps of Engineers (USACE), and U.S. Department of the Interior Bureau of Reclamation (Eitner et al., 2002).

All design standards recognize Engineering Geology in stages 2-3 of the construction process (Figure 3-1). Exemptions include the NRCS guidelines which requires engineering geology investigations at all stages in construction - applying the "total engineering geology approach", and the USACE which places a greater weighting on sourcing construction materials and the environmental impact (Keaton, 2013).

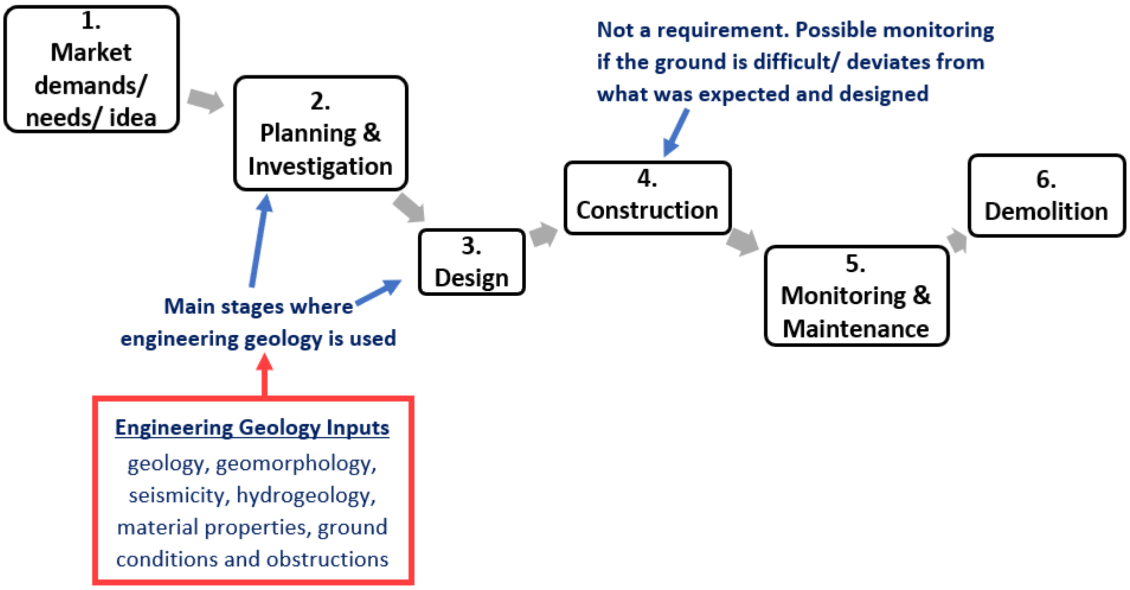


Figure 3-1: General construction project process. Engineering geology inputs are in blue text.

3.1.2 Engineering Geologist's (EnGeol) role in design

Their role varies by contract type, involvement in the design process (conceptual/detailed/remediation or fixing design problems) and cost allocated to their services. They clarify or reduce geotechnical risks (Figure 3-2) and uncertainties that may affect the project, environment, stakeholders and society. Their role centres on the inputs of Figures 3-1 and 3-3. Using Eurocode 7, this means doing the desk study, ground investigation, and ground interpretation (ground model and geotechnical report with design parameters).

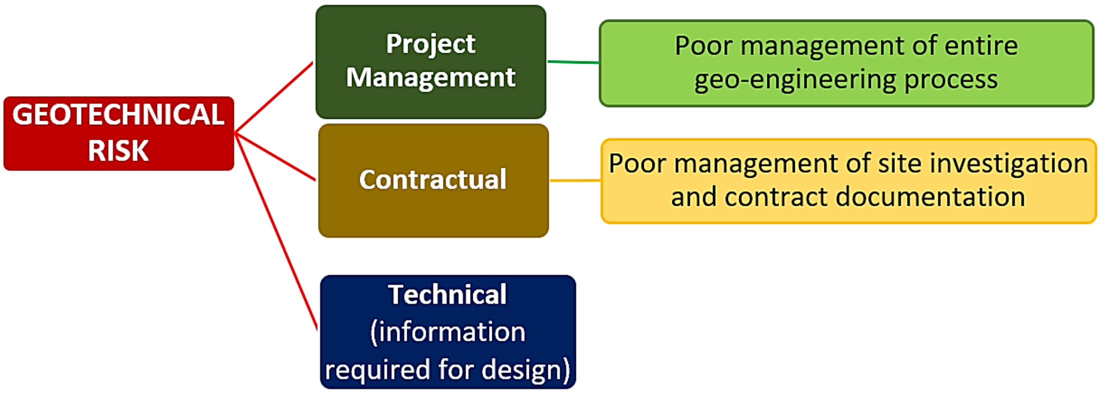


Figure 3-2: Locations of geotechnical risk in a project. Some are outside the scope of the EnGeol. Adapted from Baynes (2010).

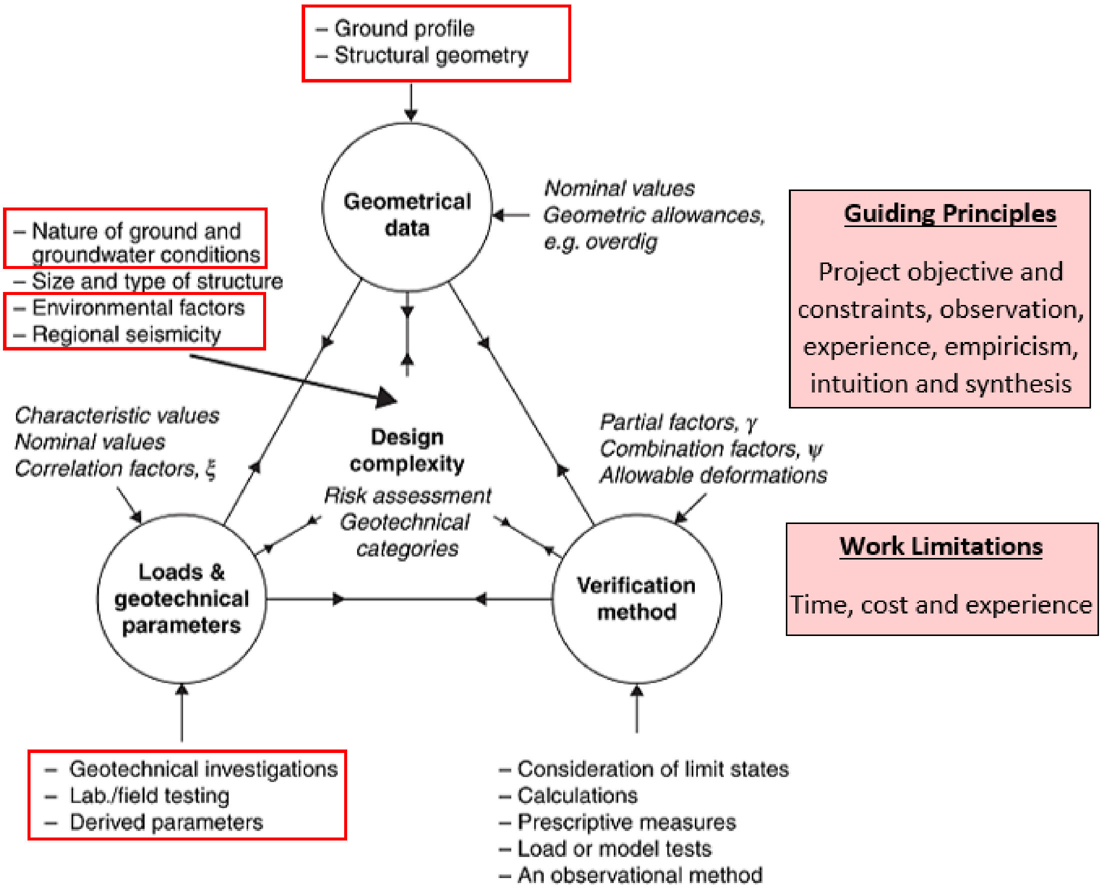
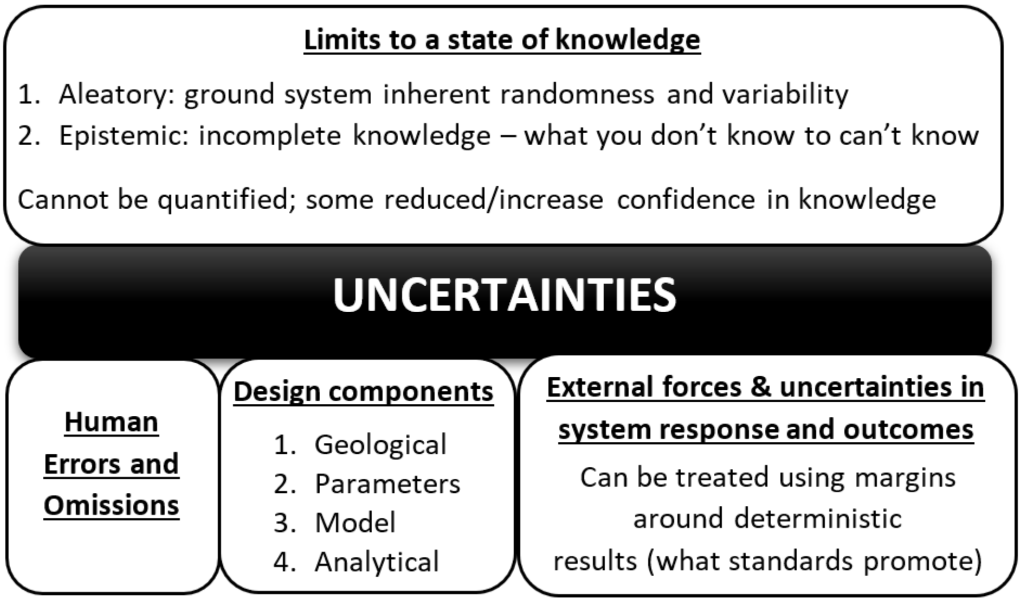


Figure 3-3: Geotechnical design triangle. Contributions from EnGeol are in red outlined boxes and their guiding principles and work limits in the rightmost red boxes. Adapted from Burland (1987), Knill (2003) and Trevor (2012).

3.1.3 Uncertainties

Uncertainties are dealt with by ignoring them, being conservative, managing them as they appear or by quantifying them. Figure 3-4 and Table 3-1 explain some of the manifestations of uncertainties associated with the Technical risks from Figure 3-2.



Limits to a state of knowledge

1. Aleatory: ground system inherent randomness and variability
2. Epistemic: incomplete knowledge – what you don't know to can't know

Cannot be quantified; some reduced/increase confidence in knowledge

UNCERTAINTIES

Human Errors and Omissions

Design components

1. Geological
2. Parameters
3. Model
4. Analytical

External forces & uncertainties in system response and outcomes

Can be treated using margins around deterministic results (what standards promote)

Figure 3-4: Manifestations of uncertainties. Sources: Bowden (2004); Griffiths (2014)*.*

Table 3-1: Compilation of some geotechnical uncertainties, examples and potential management. Adapted from Nadim (2007); Eberhardt (2017); Griffin (2018).

State of Knowledge Uncertainties	**Design Uncertainties**	**Description of some examples**	**Main cause**	**Management** (cannot be eliminated)
Aleatory and Epistemic	Geological	Identification, characterisation and interpretation of the site geology, geologic complexity, tectonic details, geomorphology, hydrogeology, hazards, hazardous ground conditions and all their spatial and temporal variabilities in the ground.	Geology/ Natural limits and human	Increased investigations but many cannot be reduced
Epistemic	Parameter	Spatial variation of parameters; Selection of parameters and statistical generation of parameters (over/underestimated or omitted); Lack of data; Small sample size; Simplification of parameters (anisotropy and heterogeneity)	Human	More sampling; Increased testing; use of probabilistic analyses
Epistemic and Human errors/ omissions	Model	Gaps in the scientific theory needed to make predictions based on inference; Lack of data/missing data; Use of wrong data; Inappropriate model selected; Identified the wrong failure mechanism; Limitations in software/ calculations/ model drawn	Human; computer	Improved through research; Better understanding of limitations of software; Improve accuracy in drawing
Epistemic and Human errors/ omissions	Human/ Analytical	Professional experience; Quality of data collection and sampling; Subjectivity in interpretation; Differing professional opinions; Measurement errors; Reporting errors and/or omissions.	Human; equipment	Improve experience and collaboration

Uncertainties in Table 3-1 are further compounded by the complexity of how natural geological materials react among themselves, their environment and/with the overlying structure. Current design philosophies of limit state design (LSD - Europe) or Load Resistance Factor Design (LRFD – U.S.) separate ground interactions into loads, actions and resistances (L-A-R). Ground uncertainties are initially treated by assigning geotechnical categories and applying partial factors (Figure 3-2). Subsequent treatments are explained in Table 3-5. The age of structures also contributes to uncertainties.

A revision of Eurocode 7 and general FWHA and USACE guidelines show that they cater to new, rehabilitative and reconstructive designs. Typically, new designs have the least ground information while rehabilitative and reconstructive designs have historical records. Nonetheless, additional uncertainties exist for rehabilitative and reconstructive designs, such as:

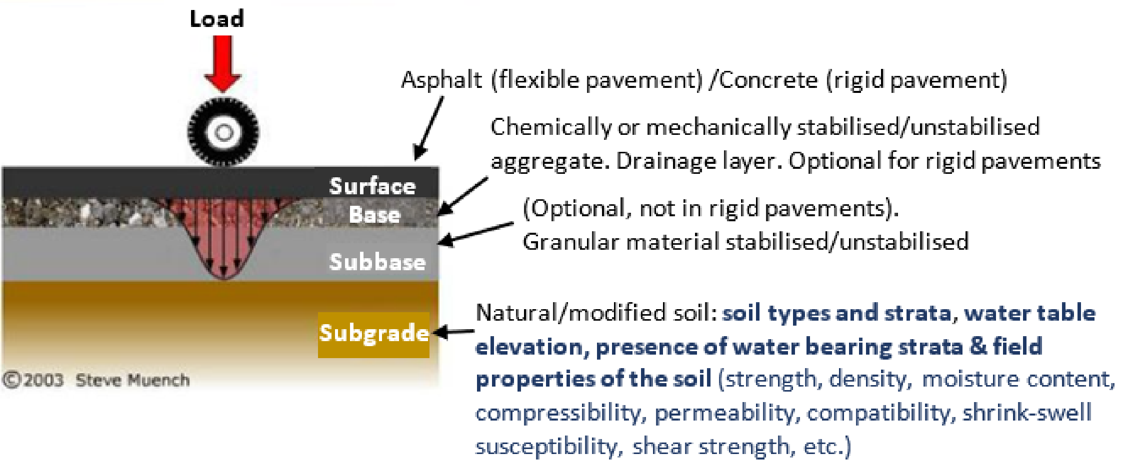
i. Change in material properties from those initially observed and investigated;
ii. If reinvestigation occurs it can positively or negatively impact Table 3-1 uncertainties;
iii. Overconfidence in historical records can lead to introducing investigations late in the design process or during construction (FHWA, 2017).

Nonetheless, all depends on the type of structure being designed which are presented below.

3.2 G.A. Designs

3.2.1 Pavements – Airport runways and taxiways

Airport pavements are designed to support a low volume of dispersed, high load, high tire pressure traffic from aeroplanes (Airport Engineering Division, 2019). It is more susceptible to moisture and environmental distress than load distress as found on roads. Using U.S. standards *FHWA NHI-05-037* (2006), *AC 150-5320-6F* (2016) and circular *AC 150/5100-13C* (2019), EnGeol are primarily concerned with the subgrade design and the provision of raw material for the other strata. Figure 3-5 shows the general design layout and failure modes. Areas of focus include the physical ground and soil properties, soil strength and stiffness, thermo-hydraulic properties and performance-related properties.



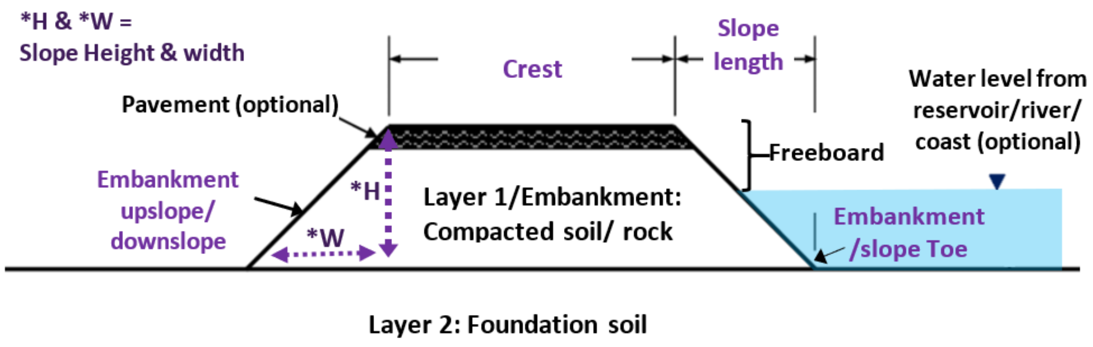
Strata	Failure Modes
Surface	Cracking (various types), formation of potholes and depressions, rutting, shoving, upheavals and ravelling
Base/subbase	Deformations
Subgrade (moisture sensitive)	Differential settlement, heave and bearing capacity failure

Figure 3-5: General pavement layout and failure modes. The parameters of engineering geology are in blue text. Adapted from Muench et al. (2003).

The general design period is around 20 years; however, the subgrade is not likely to change.

3.2.2 Embankments – protection and support of all C.I.

Embankments are raised earth structures and have varying designs but will be used for both the raising of pavements and for flood protection for C.I. Historically, when they were designed, it was for one purpose only – either for pavements or flood protection (FHWA, 2008). They have two main strata with unique failure modes (Figure 3-6).



Strata	Failure Modes
Layer 1	slope stability failure (circular/non-circular), overtopping (if water is being retained), foundation failure, lateral spreading, settlement failure, hydraulic failure (e.g. piping, internal erosion) and surface erosion
Layer 2	liquefaction, leakage, settlement, bearing capacity and hydraulic failure

Figure 3-6: General embankment layout and failure modes.
Source: Eurocode 7.

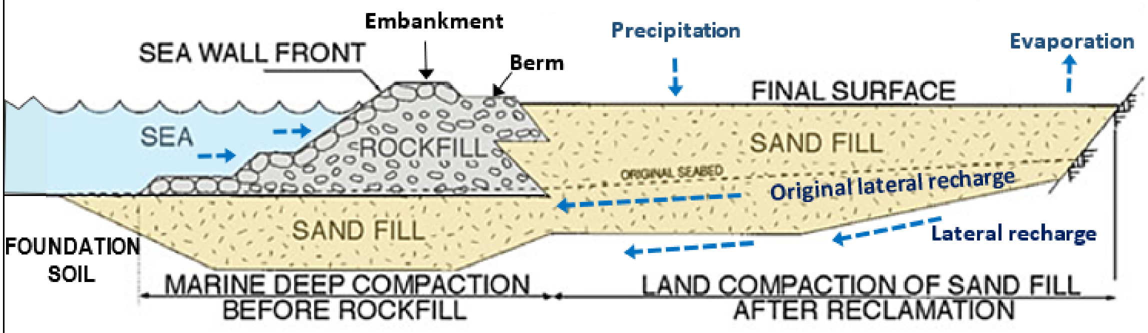
Within Eurocode 7 the parameters required using Figure 3-5 include:

i. Density of fill for embankment construction (see section 3.2.3),
ii. Slope properties (purple text),
iii. Erosion protection methods for exposed slope (e.g. revetments),
iv. Drainage (if berms present),
v. Water levels, groundwater information and permeability of both layers,
vi. Free board (prevent overtopping) and core wall if present in Layer 1.
vii. Layer 2 properties (density, geology, compressibility) and bearing capacity

The design life varies from 30 years to permanent based on the purpose. The built-in safety factor for critical structures is around 1.5 (Javadinejad et al., 2018).

3.2.3 Fill, Ground Improvement and Reinforcement (F-G-R) - potential ground for all C.I.

Land reclamation and Made Ground uses some or all of F-G-R. Coastal reclamation for C.I. normally involves all three and dredging at times. Figure 3-7 shows the use and failure modes of F-G-R in coastal reclamation. Similar components apply if fill were used for Made Ground.



Strata	Failure Modes
Fill (engineered and non-engineered)	Settlement of granular soil (from self-weight or collapse compression); Differential settlement (from heterogeneity of the fill composition and thickness, chemical reactions, biodegradation, groundwater level, pore pressure or moisture changes); Heave/lateral movement if volume change in the fill; Bearing capacity failure (if there is a structure on top); Liquefaction.
Fill and Retaining/ reinforcement structure	Slope stability failure = toe failure and unravelling; Crest failure/overtopping and scour; Armour layer damage; Interior fill exposed; Excess groundwater pressure and piping failure through the armour layer; Rotational sliding; Overturning of armour components; Flanking at end sections
Foundation soil	Consolidation settlement if on soft clay due to the weight of the fill; Bearing capacity; Stability of the ground vertically and horizontally.

Figure 3-7: General layout and failure modes using F-G-R for coastal reclamation. Adapted from Betterground (Hong Kong) Ltd. (1995). Sources: Eurocode 7; U.S. Army Corps of Engineers (2006); Skinner (2012); Encyclopedia.com (2020).

Using Eurocode 7, the parameters required are summarised in Table 3-2. The main concerns for design are the foundation soil's bearing capacity and settlement of the fill.

Table 3-2: Parameters considered for F-G-R designs.

Component	*Design Parameters investigated*
Both Fill and Non-engineered fill	Age of the fill; Grading; Crushing resistance; Plasticity; Permeability; Compactibility; Solubility; Chemical aggression; Organic content; Susceptibility to volume change; Resistance to weathering; Possibility of cementation occurring after placement; Pollution effects; Strength of the underlying ground and effect of excavation; Transportation and placement
Fill that must be improved if natural soil is not suitable	Adjusting the water content; Mixing with materials or cement or lime; Protecting the material; Crush, sieve and wash grains; Using drainage layers
Engineered fill (compacted; safer and more stable)	Adequate depth, strength, stiffness, durability and permeability required
Ground improvement and reinforcement	Thickness and properties of the ground or fill material; Magnitude of water pressure in the various strata; Nature, size and position of the structure to be supported; Prevention of damage to adjacent structures or services; Temporary or permanent improvement; Relationship between the ground improvement method and construction sequence for deformations; Effects on environment - pollution by toxic substances or changes in ground-water level; Long-term material deterioration;
Retaining/Reinforcing Structure	Heavily dependent on the type used but generally geometry; Type of material and composition; Size, shape and interconnectedness of materials; Chemical aggression
Foundation beneath the fill	Elevation; Thickness; Properties of the soil (physical, hydraulic and mechanical); Depth to bedrock and its properties; Groundwater level

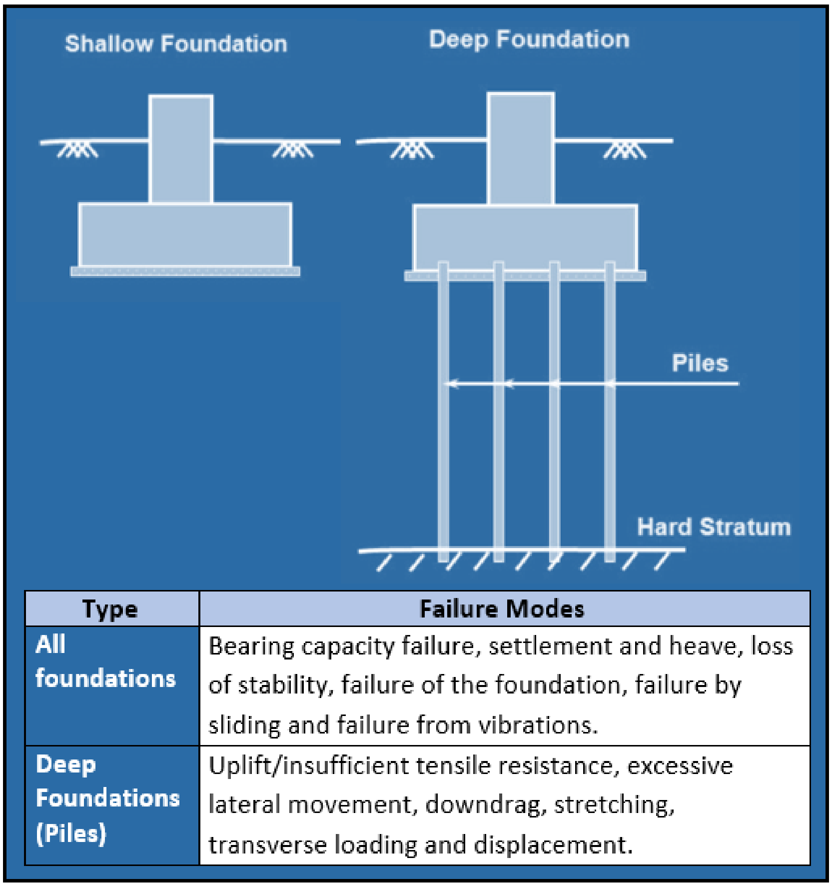
Sources: Eurocode 7; U.S. Army Corps of Engineers, (2006)

3.2.4 Foundations – energy facilities

Foundations are designed to support an overlying structure, resist loads transferred to the ground from the structure, and other forces such as weathering, deterioration, and corrosion (with minimal maintenance) during the design life. Foundations near the coast are also vulnerable to coastal hazards such as scour, erosion, wave action, flooding and debris that would have to be resisted. Figure 3-8 presents the layout and failure modes of foundations.

Whether shallow or deep, using Eurocode 7 the foundations designs are generally concerned with:

i. Reaching an adequate bearing stratum (soil and rock physical properties).
ii. Ground strength and stiffness and the impact of shallow, pile and pile group foundations on it.
iii. Location and depth of expansive soils.
iv. Groundwater and moisture changes (permeability).
v. Effects of works on nearby foundations and structures (adjacent loads).
vi. Any possible ground movement (e.g. consolidation, swelling, earthquakes and ground improvement).
vii. Anything that can reduce the strength in the bearing stratus (by water, general current climate and construction).
viii. High/low temperatures from the structure.
ix. Potential of scour.
x. Presence of soluble material (e.g. limestone).
xi. Effects of long-term water variation (e.g. drought) in arid climates.



Type	Failure Modes
All foundations	Bearing capacity failure, settlement and heave, loss of stability, failure of the foundation, failure by sliding and failure from vibrations.
Deep Foundations (Piles)	Uplift/insufficient tensile resistance, excessive lateral movement, downdrag, stretching, transverse loading and displacement.

Figure 3-8: General layout of foundations and their failure modes.

Design life for concrete-based foundations is 100-120 years, but this has not been proven and is more of an expectation, also studies have shown that reinforced concrete can begin to deteriorate 10 years after completion (Moriconi, 2007).

3.3 Review of Conventional Design

The four G.A. designs are comprehensive and important for ensuring compliance with safety standards. This reduces public risk and clarifies the allocation of risk and liability in cases of failure, encouraging infrastructure investment. It acknowledges and has mechanisms for treating uncertainties and risks (Table 3-1) that have improved with advances in technology, the Internet, Geographic Information Systems, geophysical methods and Business Information Modelling (BIM). Still, some things can be improved. Table 3-3 presents the advantages and disadvantages of conventional design compiled from Sections 3.1, 3.2 and additional studies.

Table 3-3: Advantages and disadvantages of conventional design.

Category	Advantages	Disadvantages
Standardisation or Codification	• Improves communication across engineering fields (Orr, 2012). • Reduces epistemic uncertainties in parameters needed; they are listed. • Guides the design process. • Gives confidence to external parties – Insurance companies and society that structures designed are safe, durable & serviceable (Gibbs, 2012). • Confidence of external parties encourages infrastructure investment (Gibbs, 2012)	• Standards take some time to be updated based on the verification of experiences. • Somewhat vague in the explanation of what is required leaving room for confusion among professionals. • Confidence given is based on a limited period (past, pre-construction and during construction).
Determination of Parameters	• Gives a checklist on the parameters needed. • Empirical, deterministic results derived from testing. • The application of partial factors limits.	• Many assumptions about the professionalism and experience of the persons conducting investigations (human error and omissions uncertainties). • Uses partial factors to treat uncertainties and risk (overconservative design). • Does not clearly indicate how to derive parameters with the complexities of the ground.

Category	Advantages	Disadvantages
Variation in properties with time	• Treats this through monitoring and maintenance and the use of partial factors.	• Maintenance left to the owner/client; not normally managed by the designer, hence some possible disconnect in the design and maintenance. • No indication of how to treat material property variations over time. • Limits structures by assigning a 'design life' which may not be proven.
Treatment of Risk	• Identify hazards to the project. • In Eurocode 7 ground complexity is assigned a geotechnical category. • Recommends site avoidance if geotechnical risk is too high. • Recommends increased testing to reduce risk or use the observational method - design altered based on information from monitoring and during construction. • Use partial factors to treat uncertainties and risk.	• Uses partial factors to treat uncertainties and risk reducing ground complexities to a simple value in an equation (Lin and Zhang, 2009; Kannan, 2017). • The geotechnical categories are vague. • Observational method is not normally used for all types of geotechnical design, especially those deemed less complex e.g. earthworks (Been, 2011).
Timeline of design	• For new builds, repairs and reconstruction	• Could be used for extensions but doesn't address this. • Does not account for the change in the use of a structure.
Response to changes in L-A-R that can cause failure	• Increasing the factor of safety OR, Builds in redundancy using standard and finite key design parameters, e.g. a 1-in-50/100-year event known as the 'worst credible' condition (LSD and LRFD)	• Limited listing of L-A-R. • Doesn't account for any changes outside of the standards (inflexible). • Assumes that the worst credible condition will not change over time/according to a trend with no significant changes in periods.
Impact on innovation		• Can stifle innovation as the design is based on limited concepts of design and limited by preference for the lowest cost (Nicholson and Bruce, 1992; Atkinson, 2013).
Locational Application		• May not be applicable to localities outside of Europe and U.S. due to differing environment, material and societal resources (Omotosho, 1991)
Potential response to climate change		• None – strategy entails protecting the structure, repair, retrofit/adapt if required and rebuild if destroyed. • Considers current climate during investigations and for construction. • Uses building guidelines or empirical and deterministic results to pick a worst-case scenario to design for.

3.3.1 Treatment of Climate Change

Reviewing the G.A. designs from Section 3.2 their main failure modes and uncertainties are:

i. Water effects/hydraulic inputs and outputs on and in the ground (soil-atmospheric interaction and soil-groundwater interaction).
ii. Potential for settlement and consolidation failures from weight and ground heterogeneity.
iii. Change in material properties after placement and construction.
iv. Movement in the ground.

Climate change, which has been found to change weather patterns and their variables along with attributes of extreme events would impact bullet point (i) above. However, C.C. and its effects are not included in the L-A-R or parameters of these designs. Their potential responses to C.C., in Table 3-3, only consider the present, limited guidelines and projections dependent on present and past data. Therefore, neither current nor past designs for new and existing G.A. included C.C. Atkinson (2013) and Griffiths (2014) agree with this deduction and indicated that EnGeol operating within conventional design:

i. Do not incorporate C.C. or their new risks
ii. Promotes the monitoring and designing for mitigating impacts of past industrialization, and
iii. Simplifies or avoids risk through using partial factors; thus, encouraging overconservative designs, stifling innovation and missing potential benefits to future designs (Figure 3-9).

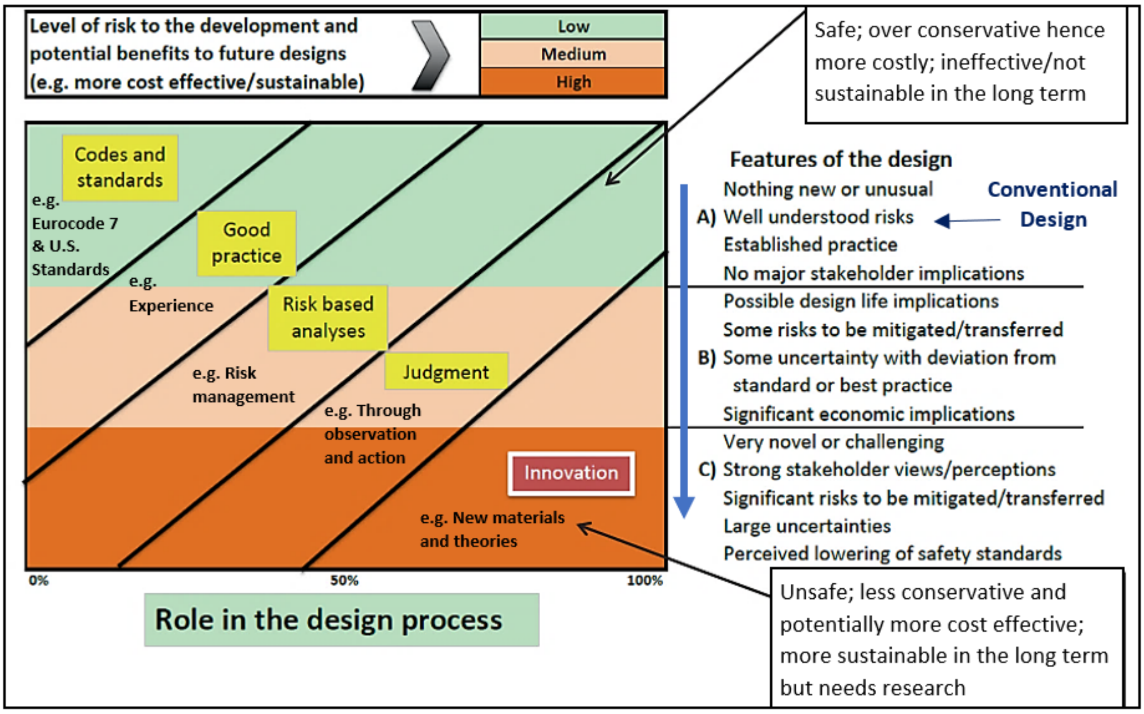


Figure 3-9: Evaluation of risk versus innovation in the design process. From this diagram conventional design is not only codes and standards, but also a way of thinking. Adapted from Griffiths (2014).

The non-incorporation of C.C. into conventional design can be attributed to the uncertainties within climate science (see Chapter 4) and the limited understanding of the impacts and quantification of its effects. However, what is known is that C.C. could affect hydraulic inputs and outputs, soil properties and loads, potentially altering the L-A-R and triggering failures (Chang et al., 2019; Vardon, 2019). Using the principle of design and Figure 3-9, five things would be needed to address C.C.:

i. The standards must be changed, albeit after sufficient information and experience is available;
ii. A deviation from the standards may be necessary;
iii. Use another type of design.

3.4 Risk-based Approaches

This approach is an evolving concept with multiple definitions. In Corporate Compliance it means identifying, classifying and managing risks from highest to lowest (Kelly, 2019). This corresponds with the ISO 31000 risk management process where the management and response are dependent upon the type, importance, weighting and tolerability of the risk in Figure 3-10.

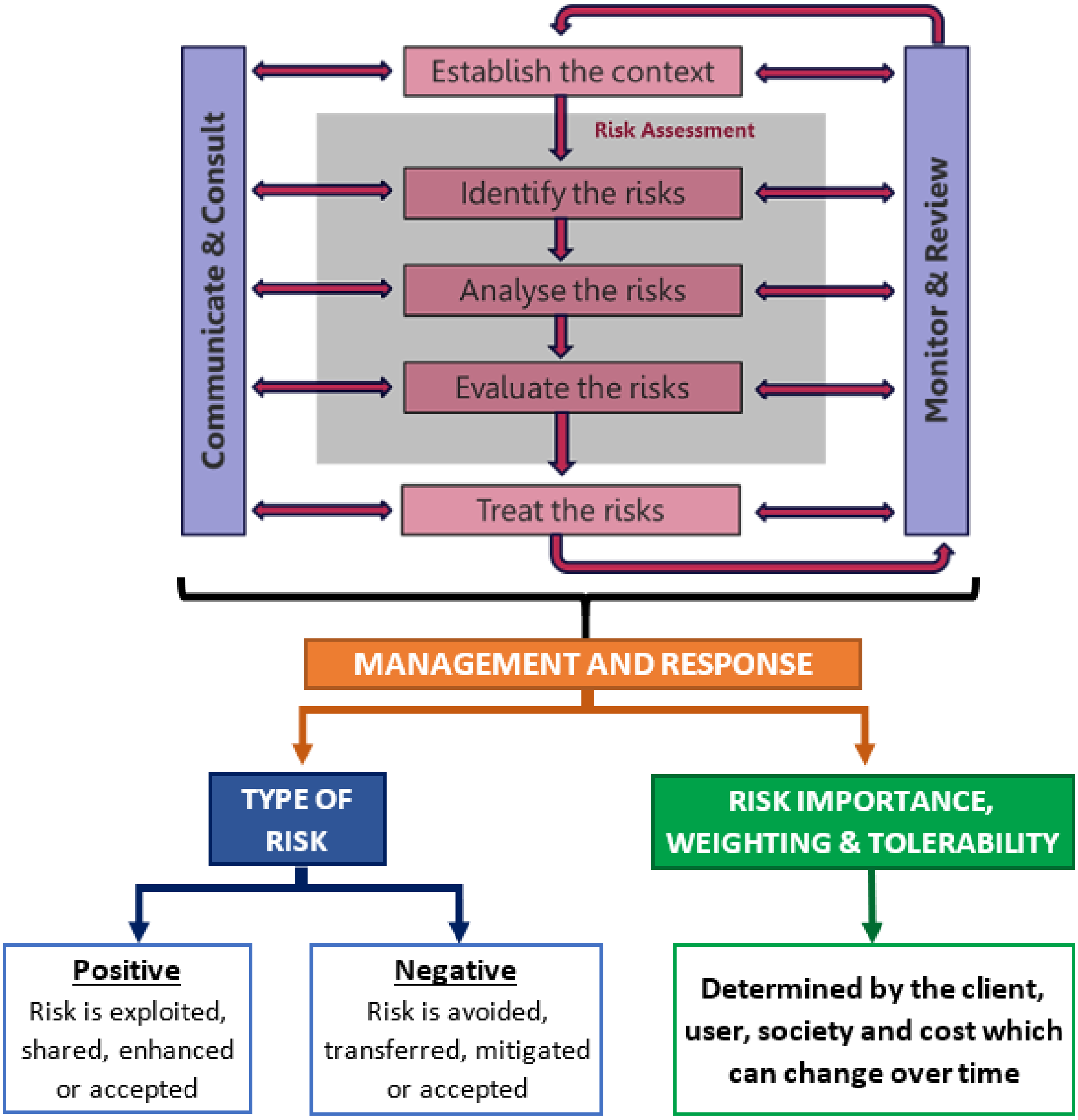


Figure 3-10: The ISO 31000:2009 Risk Management Process including the controls for the management and response. Source: Cybrary.IT (2020).

The principle of this approach recognizes that:

i. Some future uncertainties and risks cannot be eliminated or reduced but must be tolerated by stakeholders who determine what losses are acceptable.
ii. It is impracticable to design a structure to be completely resistant to threats or hazards as they may change over time, come from many places – natural, human-induced and accidental/technical, and act as single or multiple events.
iii. Ignoring or failing to anticipate potential risks and uncertainties could lead to avoidable situations, litigation and missed opportunities, leading to unsustainable solutions.

This approach attempts to incorporate threats from C.C. proactively by including risk management in all stages of construction. It can be used on both new and existing C.I. For example, in G.A.M. it is used to manage existing structures beyond their original design life, assess future potential threats and inform rehabilitation and reconstruction. In Chapter 4, the risk assessment component (Figure 3-7) will be applied to C.I. and G.A. in the Caribbean to assess the applicability and suitability of current designs.

Risk, as commonly discussed in engineering geology and disaster risk management, refers to the negative risk explained in Figure 3-11.

Hazard event ***X*** ***Exposed vulnerable system*** ***= RISK***
(likelihood & magnitude) *(assets and potential impact)*

Figure 3-11: Risk equation (Rüdiger et al., 2018).

Risk quantification using probabilistic methods and hazard and risk assessments have been applied to higher risk geotechnical designs such as offshore, hydroelectric power and seismic structures, mining, nuclear facilities and environmental geotechnics. They overtly consider risk in both design and decision-making (Christian, 2004; Nadim, 2017). Yet, neither the methods nor assimilation in planning and design were applied to or completely integrated into the 'traditional geotechnical designs' in Section 3.2. Appendix A discusses the partial incorporation into traditional designs; however, these are supplementary in conventional design.

Three types of risk-based approaches are Sustainable, Resilient and Adaptive Designs. In the literature there is some confusion about these three types, but they represent a paradigm shift in the thinking and treatment of design and the construction process. Confusion occurred because their origins were psychological, ecological and developmental, currently being translated and integrated into engineering. They are seen differently by politicians, ecologists, engineers and construction companies. The three types will be distinguished based on their original purposes and treatment of future risk/uncertainties. Three major overlaps found with these designs are the incorporation of risk seen in Figure 3-12, belief that the ground is an asset to be managed and a shift from achieving ideal designs to robust designs. They also encourage the use of innovative materials, monitoring equipment and new technologies.

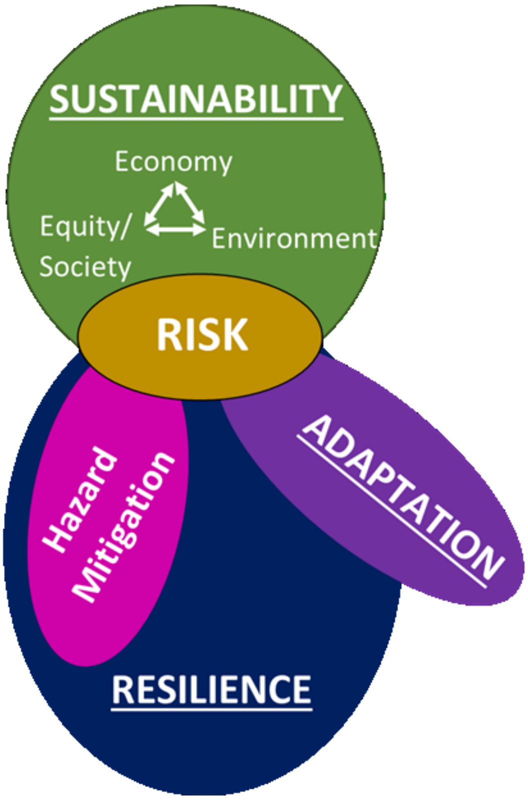


Figure 3-12: Doll diagram explaining the relationship among sustainability, resilience and adaptation.

3.4.1 Sustainable Design

There are two different definitions of sustainability in engineering:

i. Implementing activities with minimal energy and resource depletion and minimal to no harmful environmental impact, while optimizing project costs (Misra and Basu, 2011).

ii. A system's ability to survive and retain its function within a complex relationship among the environment, economy, and society/equity (3 pillars) over a period (Basu et al., 2014).

Definition (i) is largely understood and is used by ground engineers and the construction industry (Gopal, 2020). However, both definitions recognize sustainability within a closed and balanced system with limited resources. Any changes in resources would create an imbalance that needs to be restored. Therefore, considering C.C., the design focus is on mitigation by addressing GHG emissions and other adverse environmental impacts during and after construction. This is shown in Figure 3-13 where geotechnical engineering helps balance the 3 pillars.

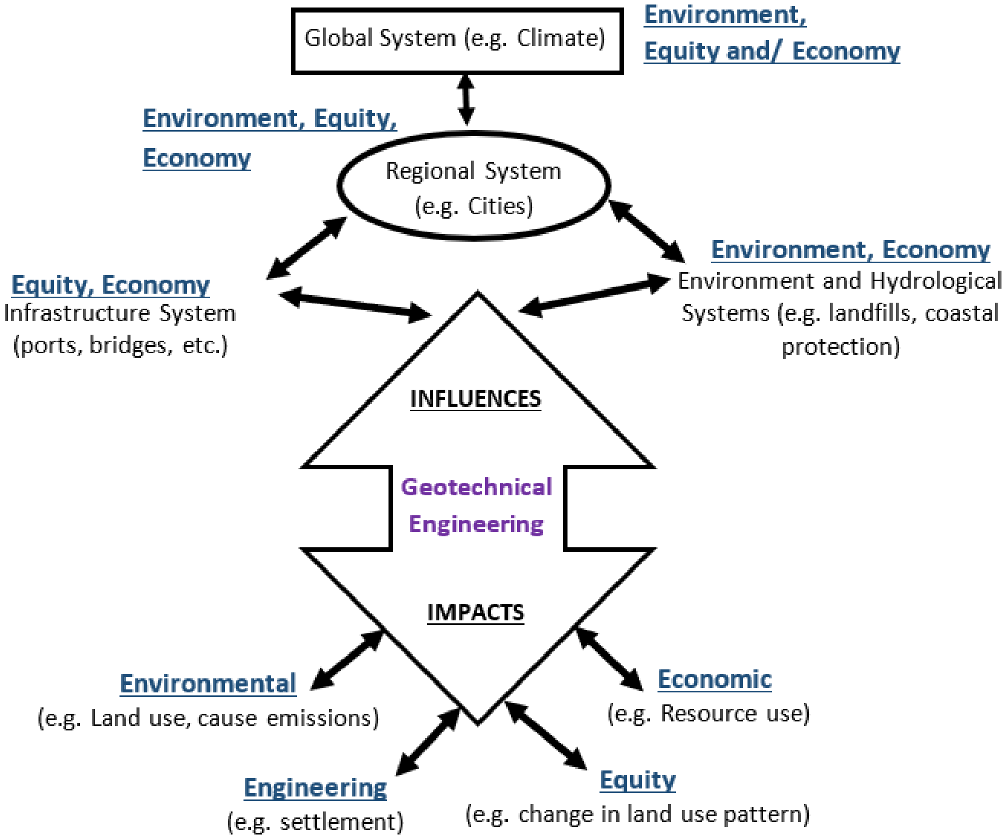
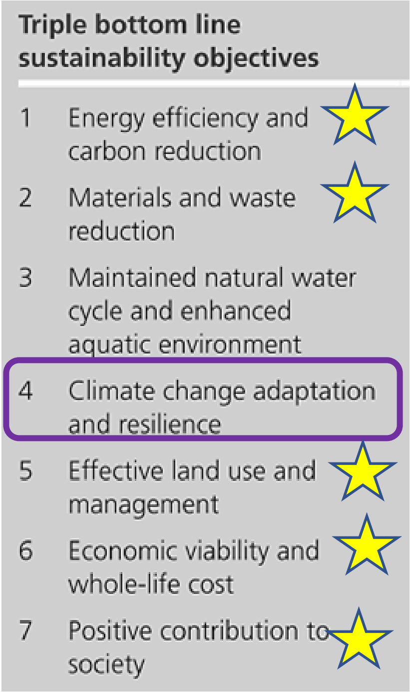


Figure 3-13: Impact and influence of geotechnical engineering in sustainability (Adapted from Basu et al., 2014).

In sustainable geotechnics, a branch of ground engineering, there are seven design objectives (Figure 3-14). Examples of the application of sustainable design in engineering geology for industry and future infrastructure are indicated in Figure 3-14.



Triple bottom line sustainability objectives

1. Energy efficiency and carbon reduction ☆
2. Materials and waste reduction ☆
3. Maintained natural water cycle and enhanced aquatic environment
4. Climate change adaptation and resilience
5. Effective land use and management ☆
6. Economic viability and whole-life cost ☆
7. Positive contribution to society ☆

Figure 3-14: Sustainable geotechnics design objectives (Adapted from Pantelidou et al., 2012). Objective #4 relates directly to C.C. Examples found in the literature of application by EngGeol are indicated with yellow stars (Hearn and Shilston, 2017; Dino et al., 2017; ARUP, 2020).

Challenges arising from this design include:

i. **Balancing the 3 pillars in definition (ii)** - there will be competing interests which can result in delays and imbalances.

ii. **The cycle of restoring an unbalanced system** - There is never an 'end state' and society changes over time, hence the equilibrium will continually need adjusting (Taneja and Vellinga, 2018).

iii. **Sustainable systems vs. true sustainability** - Initially, sustainability was integrated into engineering by retrofitting and redesigning existing structures with energy efficient or new and low carbon materials. However, engineers were not always included in the political and technical discussions on the mitigation of C.C. but, were expected to integrate it into the design through policy changes and project contract specifications (Russel, 2019). Only time would tell whether the initial methods were truly sustainable, especially as additional resources were needed to retrofit and redesign structures.

3.4.2 Resilient Design

Resilience is *"the ability to survive a crisis and thrive in a world of uncertainty,"* (Resilient Organisations Ltd., 2020)" For infrastructure and engineering it can be defined as:

> *Infrastructure or the system's capacity to reduce the magnitude and/or duration of disruptive events. Its effectiveness depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event, while regaining, or even exceeding its original level of performance* (National Infrastructure Advisory Council, 2009; Taneja and Vellinga, 2018).

Spink (2020) best explains the components of resilience using G.A.M. They are resistance, reliability, redundancy, response and recovery and may be explained within risk (Figure 3-15) or as a system (Figure 3-16).

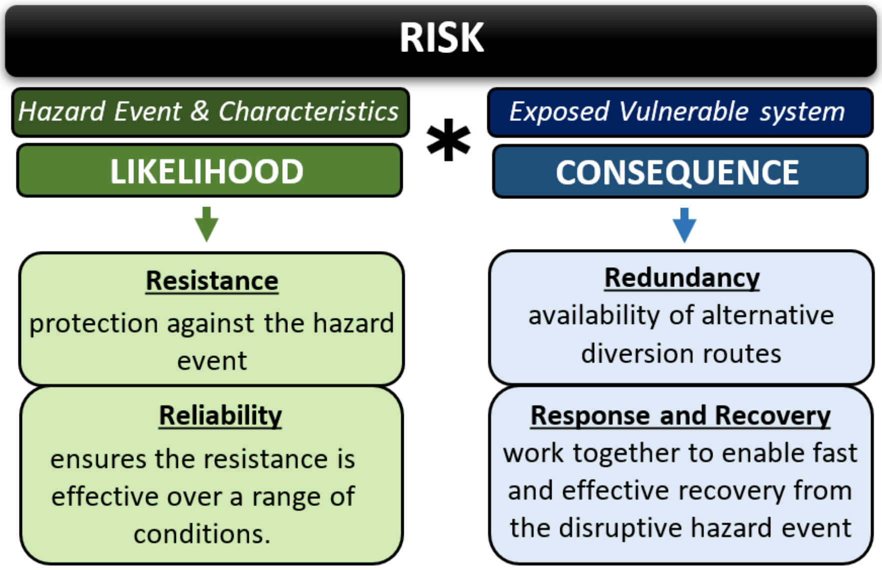


Figure 3-15: Components of resilience explained within risk.

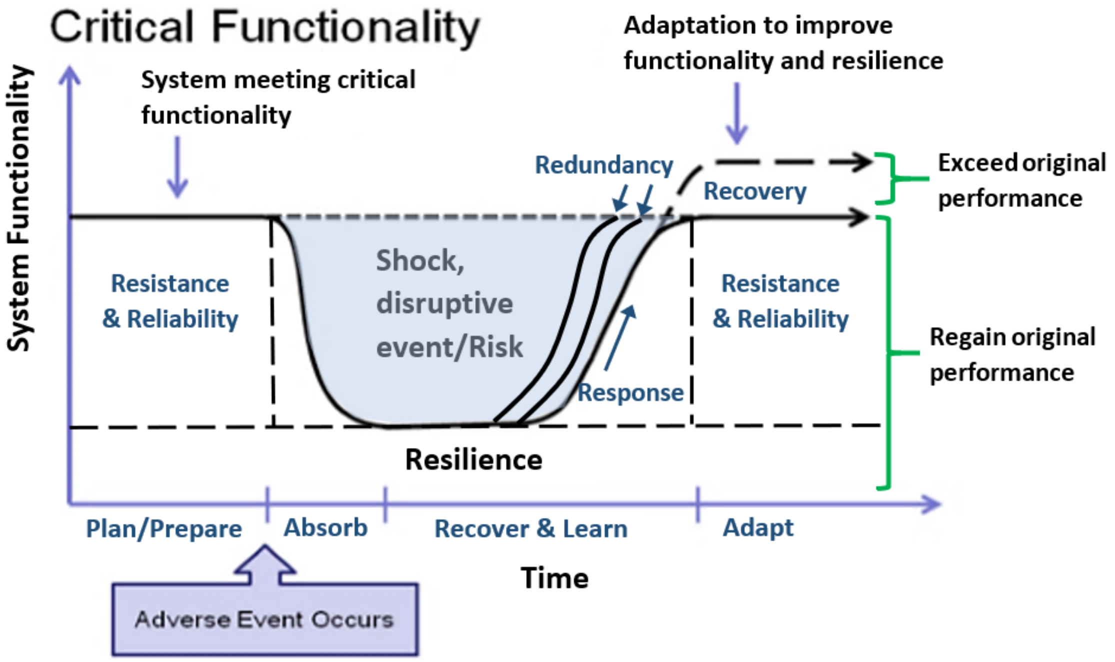


Figure 3-16: Graph explaining resilience for infrastructure and its components (the system). Adapted from Ganin et al., 2015; Linkov and Kott, 2018.

Resilience is not a new concept, some of its components are already part of conventional design. Using partial factors and worst-case scenarios are resistance and reliability. However, response, redundancy (sometimes) and recovery are not incorporated, with design revisited once there is failure. Many old structures in the world that withstood the effects of war, natural disasters and decay could be said to have 'designed' redundancy. They may have been built with additional material, redundant parts (e.g. basement car parks for earthquakes and flooding) and/or used over conservatism in design or for a potential hazard event (The Rockefeller Foundation, 2013). This non-inclusion of these consequence components may arise from roles and responsibilities in a project, budget and transfer to users. Design staff may contribute to but do not build, use or maintain the structure at completion.

The focus in this design is a greater emphasis on the lifelong monitoring and re-assessment of G.A. after minor events and during and after extreme events in combination with an emergency plan to be activated when required (Nikolaou et al., 2017). The U.S. Geological Survey's (USGS) response before, during and after Hurricane Sandy in 2012 is an example of this. They frequently updated Government agencies with information on the potential risks to coastal areas and real-time data-collected for storm surge, water levels and topographic changes. The information was used to inform the response and recovery and improve predictions of storm behaviour and their potential future impacts (Buxton et al., 2013). Engineering geologists would not only be involved in the design, but the planning, monitoring, response and recovery, and will work with many other disciplines to achieve this goal.

3.4.3 Adaptive Design

Adaptation could be defined as "an adjustment in natural or human systems in response to a new or changing environment, for moderating harm or exploiting beneficial opportunities," (McCarthy et al., 2001 in Linham and Nicholls, 2012). As a system, it is described as "flexible and can be altered or employed differently, with relative ease, so that it can be functional under new, different, or changing requirements in a cost-effective manner," (Taneja and Vellinga, 2018). In C.I., this translates to having flexibility as a criterion, planned phased expansions and adaptations and using future-proofing critical parameters for e.g. hydraulic inputs. Hence, this method can incorporate resilient design and extend beyond it (Figures 3-12 and 3-16). It is anticipatory through using projections, early warning systems and relocating structures. It is reactive through changes made after observing the initial impacts of a disturbance, for e.g. repairing protective structures and changes in practices (Knittel, 2016).

Three examples of current adaptation measures are:

i. **Existing infrastructure** – usually their designs are adapted, meaning ensuring old structures are compliant as much as possible with new standards or for a new purpose. If a failure occurs, structures are adapted when the designers may take either a different, more innovative approach or increase the robustness of the structure in to fix the failure. An example is Kansai Airport in Japan where a jack-up system was installed on pillars underneath the passenger terminal building, to mitigate differential settlement (Kansai Airports, 2020).

ii. **Early warning systems** – using monitoring equipment with warning signals or categories signalling potential failure for e.g. inclinometers for slope movement.

iii. **Coastal risk management** – used as a coastal defence strategy. These include do nothing, managed realignment or physical intervention (hold the line, move seaward or limited intervention).

This approach is currently guided by the manual, *Climate-Resilient Infrastructure: Adaptive Design and Risk Management* (Ayyub, 2018). It recommends using probabilistic methods for risk assessment, greater use of the observation method in design, lowering structures' design lives and low-regret adaptation. The two most important components for this design, which also present challenges, are a clear and practical mechanism for monitoring and evaluating results, and funding for monitoring, maintenance and constructing changes.

3.4.4 Comparing Designs

Table 3-4 summarises the analysis of risk-based approaches using all the references mentioned above.

Table 3-4: Comparison of the three types of risk-based approaches.

FEATURE	SUSTAINABLE DESIGN	RESILIENT DESIGN	ADAPTIVE DESIGN
System type	Closed system	Open system	Open system
Features	Economy, Environment and Equity	Resistance, Robustness, Redundancy, Response, Recovery	Flexible, Phased, Responsive and Anticipatory
Main Philosophy	Protect the environment from human activities	Protect human activities from the environment	Adjust to the environment
Purpose in relation to climate change	Mitigate climate change	Resist effects of climate change as much as possible but recover 'quickly' after an event	Acknowledge climate change and build/adjust according to it
Sphere of Influence	Locally and globally based	Locally based	Globally based
System's capacity	Capacity to preserve the system in the long run	Capacity over time to face disturbances, but maintain the same or exceed the original performance	Capacity to be flexible and adjust to current and expected disturbances
Orientation in Time	Past-present oriented (how do we sustain what we have now)	Future-present oriented (how do we adapt for the future)	
Safety Concept	Prevent failure	Safe-fail-adapt-safe	Observe-adapt-safe-repeat
Engineering Geology Contribution	Greater emphasis on limiting resource usage and environmental preservation	Greater emphasis on what a structure can withstand; monitoring and recovery	Greater emphasis on monitoring and decision-making for changes
Administrative Limitations	Cost; Competing priorities from stakeholders and other disciplines; Public and private sector buy-in; Political buy-in and willpower; Uncertainty of the future and climate change; Technical capacity/professional personnel		
Technical and Physical Limitations	Efficiency in usage of materials, may make the structure more vulnerable to natural hazards; No guarantee this method will work	Structure may not be resilient if one component fails e.g. the structure survives but the sewage system fails and needs to be re-designed it is not resilient; Resilience may not be possible	Restricted by information. Uncertainties around how much information do you need to adapt and when to adapt
Challenges for Implementation	Increased collaboration among stakeholders and across disciplines = practical and theoretical challenges; The difficulty in measuring these types; Understanding the exposure and combined impact of multiple hazards on G.A. and C.I.; A limited understanding of the interdependence between G.A. and C.I. systems and networks.		

3.5 Conventional Design vs Risk-based approaches

Table 3-5 is a comparison of conventional design vs. risk-based approaches based on all the information presented and additional information from Stevens and Winter (2012), Orr, (2012) and Gallego-Lopez et al. (2016).

Table 3-5: Comparative analysis of conventional design to risk-based approaches.

FEATURE	CURRENT STANDARDS	RISK-BASED APPROACHES
Incorporation of risk	Plans are made first, risk is introduced and mitigated later in the process	Places risk first and sets the context for/informs planning and decision-making
Treatment of Risk	Reactive; Limited use of data/models; Represented in the EIA, SIA or project management; Reduced to partial factors	Risks identified and assessed early before decisions are made; May include risks not in the standards; Additional risks are the environment, economy and equity; Survival of infrastructure and systems; Future changes
Product/ Output	Focus on delivering infrastructure within a cost, effort and time	Focus on delivering infrastructure in the wider context of society and systems that interact with the infrastructure; Concerns are quality of life, components of resilience, monitoring and flexibility
Responsibilities	Fragmented – planners and designers separate from constructors and maintainers	Could be fragmented but requires greater input and collaboration of all stakeholders
Timeline considerations	Relatively short-term within a fixed concept of time, but updated	Long-term within an understanding that the future will change
Treatment by society	Widely accepted by society, decision makers, insurance and legal system	Not widely accepted as it is a relatively new concept, but changes are being made.
Resource usage	Less time, money and effort in the short term	More time, money and effort in the short term
Stakeholder Engagement	Less engagement	More engagement
Design Principles and Requirements	Safety, serviceability, durability,	Safety, serviceability, durability, risk management and whole-life cycle management
Methodology	Uses what is tried, tested and proven	Encourages alternatives and innovation
Influence on thinking	Meet minimum regulations/requirements	Challenges current thinking even if not proven

3.6 Key Findings

- EnGeol work within conventional design (codes of practice/standards and guidelines) to reduce ground uncertainties and risks which can occur anywhere in a project and result from many variables.
- Each G.A. for the selected C.I. has unique design parameters and failure modes.
- Conventional and past designs do not incorporate C.C. because of uncertainties in climate science and information.
- Risk-based approaches acknowledge that everything cannot be planned for or designed. It uses risk management to identify risks and determine what will be tolerated.
- Sustainable, Resilient and Adaptive Designs are similar in that are new concepts being developed and incorporate risk but view the management of risk from different perspectives.
- The main difference between conventional design and the risk-based approaches is that the former is limited and only considers a structure's design. The latter is open, looking at other factors beyond the structure and design.

4 FUTURE OF THE CARIBBEAN

This Chapter addresses Aim #2: To determine the potential risks of C.C. to select Caribbean C.I. and their ground conditions by 2100.

4.1 The Caribbean

The Caribbean Region can be defined as 31 island territories and archipelagos located between latitude 10°-27° North and longitude 60°-90° West, and three mainland territories of Belize, Guyana and Suriname, see Figure 4-1 (Caribbean Examinations Council, 2009). The islands, the focus of this study, have different characteristics from their mainland counterparts.

4.1.1 General Climate, Topography, Geology and Hazards of Islands

According to the Köppen-Geiger climate classification system, the climate is mostly tropical, ranging from tropical equatorial to tropical savannah, excepting some areas of arid climate (Beck et al., 2018). All islands usually experience one wet and dry season. The wet season is May/June to November/December, coinciding with the Atlantic hurricane season. The dry season is December/January to April/May. Varying elevations on islands, and the northeast trade winds govern weather conditions. Climate varies with phenomena such as the migrations of the Hadley Cell, Inter-tropical Convergence Zone (ITCZ) and El Niño Southern Oscillation (ENSO) (Caribbean Regional Climate Centre, n.d.). Average regional temperatures are 21°-30°C. Annual precipitation is generally 1200-2500mm with humidity being generally high and varies during the wet and dry season (Bleasdell et al., 2008).

Island topography and size varies across the region and is governed by location, tectonic, geologic, hydro-geological and atmospheric conditions and geohazards. Most islands lie within the Caribbean Plate and were formed and currently affected by relative movements at the tectonic boundaries (convergent, divergent and transform) see Figure 4-1. Numerous islands are mountainous or have mountainous interiors (e.g. Jamaica and St. Lucia) while others are flat and gently sloping (e.g. The Bahamas and Barbados). The tectonic setting has also affected the islands' diverse geology, resulting in limestones (Greater Antilles, Lucayan Archipelago, Barbados and some of the Lesser Antilles), igneous and metamorphic rocks (Greater Antilles and Lesser Antilles), sands and tropical soils (Mitchell, 2013). Resulting landforms include raised limestone terraces, karst topography, steep slopes and conical hills.

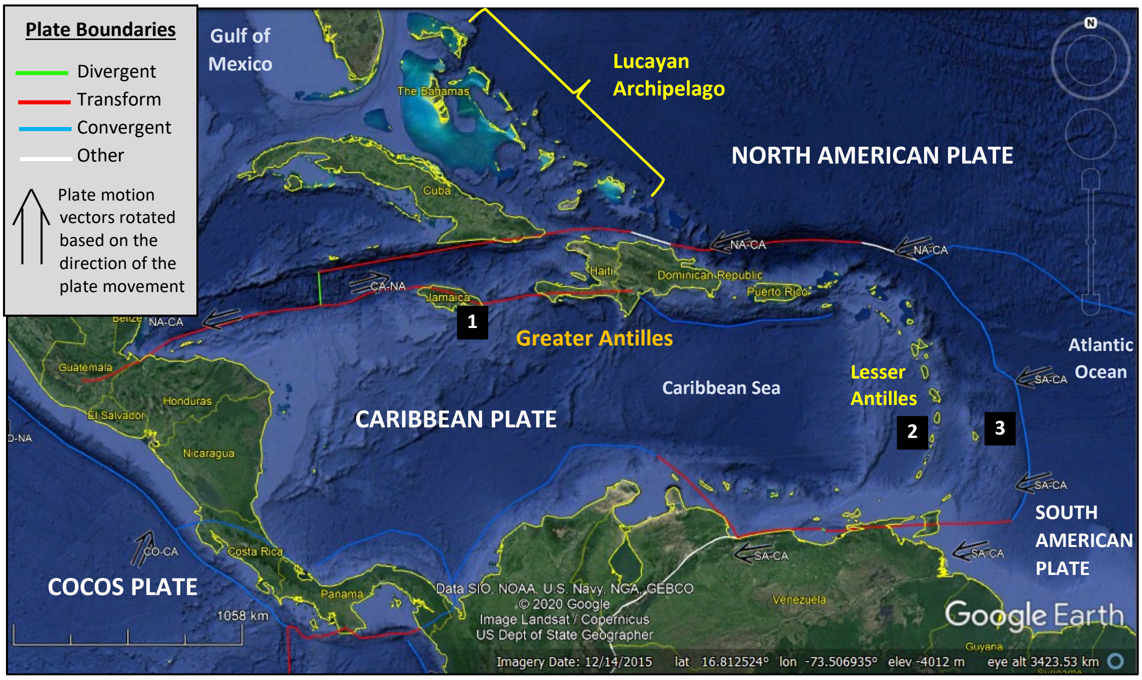


Figure 4-1: The Caribbean and its plate boundaries (Source: Google Earth Pro & USGS, 2020a). The countries selected for analyses are numbered black boxes – (1) Jamaica, (2) St. Lucia and (3) Barbados.

Mountainous islands near convergent plate boundaries or affected by convergence in their geological past (e.g. Greater Antilles islands) are vulnerable to seismic hazards such as earthquakes, tsunamis and slope failures. Islands formed in the Lesser Antilles through subduction are also vulnerable to volcanic hazards, which could lead to disasters, e.g. 1995 volcanic eruption in Montserrat that rendered the south of the island uninhabitable.

The tropical climate, tectonics, exposure to climate phenomena and coastal surroundings expose the islands to multiple and diverse natural hazards such as volcanism, earthquakes, tropical storms, torrential rainfall, slope instability/mass movement, flooding, coastal hazards (tsunamis, erosion, storm surge), accelerated weathering, drought, wildfires and arid tropic processes (Ahmad, 2018). Adding C.C.'s threats makes the Caribbean one of the most hazard exposed regions globally (Climate Risk & Early Warning Systems (CREWS), 2020).

4.1.2 Demographics and Infrastructure

With a population of approximately 43 million, the islands are classified as SIDS having small economies with limited resources, high economic volatility, high debt and low growth (UN, n.d.). Settlements and developments are mainly driven by topography and economic benefits. For islands with mountain interiors and steep slopes, most developments and settlements are along the coast. Most islands benefit economically from their natural environment, with 70% of economic activities including shipping, fishing and tourism, within 3.2 km of coastlines (CREWS, 2020).

Some coastal C.I. consist of infrastructure for transport (airports, seaports, etc.), energy, water and sanitation (desalinisation and sewage treatment plants etc.), tourism (cruise ship ports, hotels, etc.) and social (healthcare, education etc.). Funding to build and maintain C.I. is limited due to the small economies, limited land and small populations. Thus, aging infrastructure, many beyond their design life, are vulnerable but vital to these small economies. Their upkeep and replacement depend on government policies, foreign investment and since the 1990s, disaster risk management (Harris, 2020).

4.1.3 Engineering geology

Based on regional characteristics, potential hazards and infrastructure, EnGeol must consider the unique environment, geology, and geohazards such as:

i. Tropical environment - higher weathering rates,
ii. Volcanic, karst or both environments and their uniqueness (sinkholes, slope instability, topography, geochemistry, etc.),
iii. Tectonics and seismicity,
iv. Coastal and marine environments and
v. Environments with difficult terrain logistically for personnel and equipment.

Rock types include marine deposits (limestone) and volcanic rocks with potentially more discontinuities and weaker joint planes due to the tectonic and tropical environment. Soil types include mature and immature tropical residual soils. According to Toll (2012), tropical soils are unique in engineering geology as they are generally difficult for classification, ground investigations, sampling and testing due to:

i. Potential for highly variable particle sizes from weathering
ii. Their mostly unsaturated state of existence
iii. Presence of iron and aluminium oxides, secondary cementation and weathered clays (potentially expansive)
iv. Limited coverage in classification and definitions under current standards, e.g. Eurocode 7 (Hencher, 2008)

4.1.4 Threat of Climate Change

Climate change may manifest in many ways regionally (Figure 4-2). Most will occur in the long-term, except for extreme events such as droughts, intense rainfall, storms and storm surge. These manifestations also have secondary effects on society, affecting health (heat stress and vector-borne diseases), agriculture (food availability), land availability, coastal cities, water availability (from saltwater intrusion, contamination and increased extraction), nature and ecosystems and overall economies (Taylor, 2015). Regional evidence of this threat correlate with significant changes observed comparing climate periods 1960-1989 and 1990-2019 in global temperature trends (Figure 4-3), and the characteristics and cost of disasters (Figure 4-4 & 4-5).

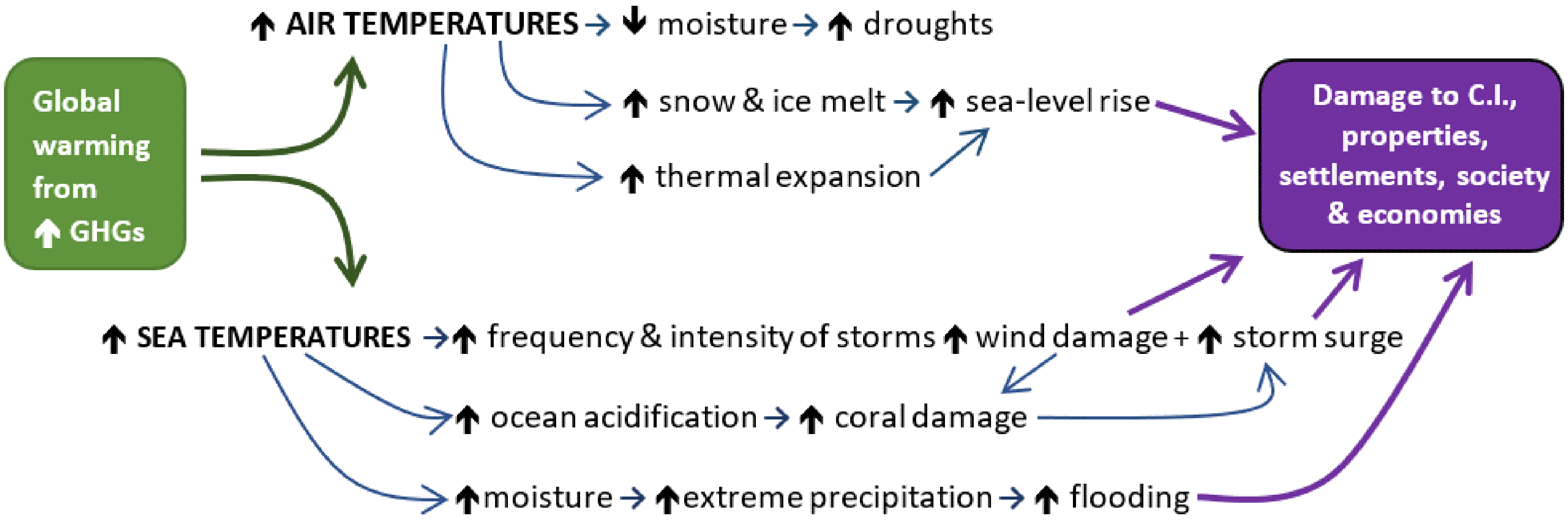


Figure 4-2: Manifestations of C.C. and potential hazards in the Caribbean.

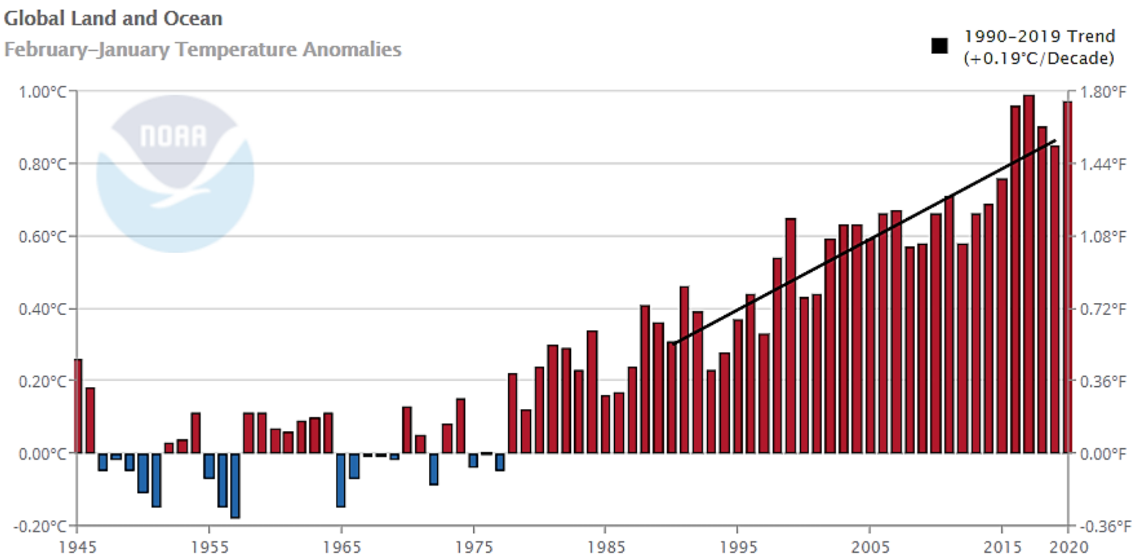
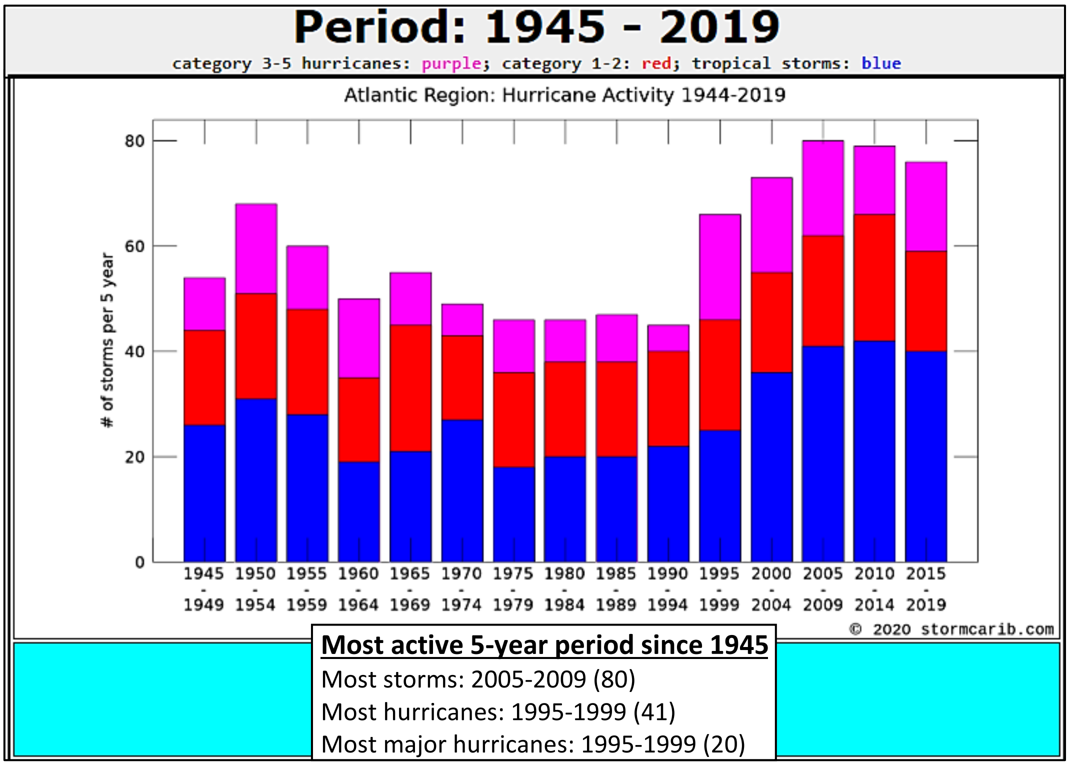


Figure 4-3: Global land and ocean temperatures from 1945-2019 showing the most recent trend 1990-2019. This change in the trend, from ~1978 correlates with observations in Figures 4-4 and 4-5.

Source: NOAA National Centers for Environmental information (2020).



Most active 5-year period since 1945

Most storms: 2005-2009 (80)

Most hurricanes: 1995-1999 (41)

Most major hurricanes: 1995-1999 (20)

Figure 4-4: Storms in the Caribbean since 1945. This period was selected as 1944 is observed as the beginning of "reliable" hurricane observations.
Source: Caribbean Hurricane Network (2020).

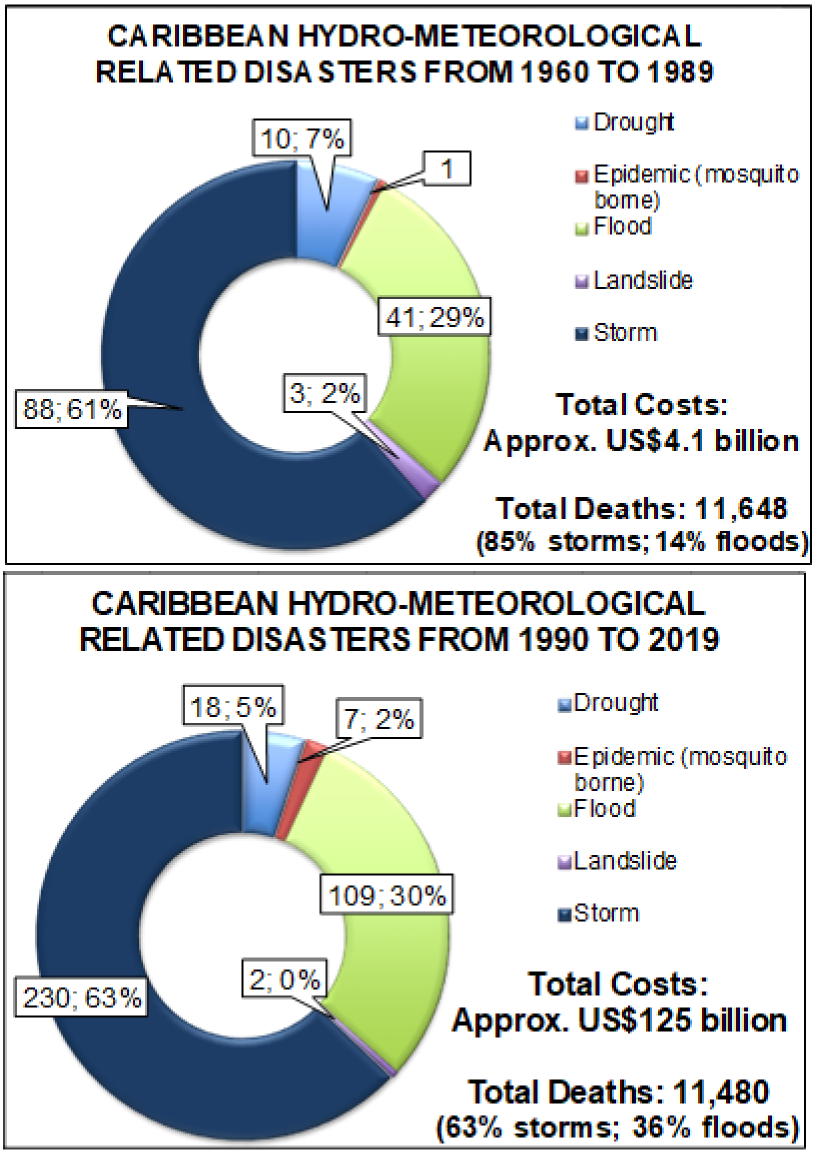


Figure 4-5: Comparison of 1960-1989 and 1990-2019 Caribbean hydro-meteorological-related disasters. Increased storm disasters corelate with Figure 4-4. Generated using data from Guha-Sapir et al. (2020).

Annually, disaster losses are around US$3-4 billion with over 90% caused from storms and flooding from intense rainfall (not from storms) (Figure 4-5). These disasters and rising temperatures potentially contributed to the increase in mosquito-borne diseases (Figure 4-5) and increased coral bleaching (Taylor, 2015). Storms and flooding could trigger increased geohazards (e.g. landslides) and contribute further to C.C. from energy transformation and releasing CO_2 stored in soil, further threatening the region.

Two examples of the damage to C.I. and G.A. by increased storm frequency and intensity and intense rainfall are presented. In 1979, 10 years after completion, the reclamation at Dominica's Port and concrete bridges supporting it were damaged by storm waves (Wason, 1998). The reclamation was originally designed for a Category 3 hurricane and lower waves as historical records showed hurricane wave damage was rare. However, when Category 4 Hurricane David struck, storm waves dislodged revetment boulders protecting the reclamation, triggering slope failure. Design options were to make the revetment more wave-resistant using dolos, raise the reclamation or both, but as with many construction projects, maintaining the lowest possible cost (using dolos) was selected.

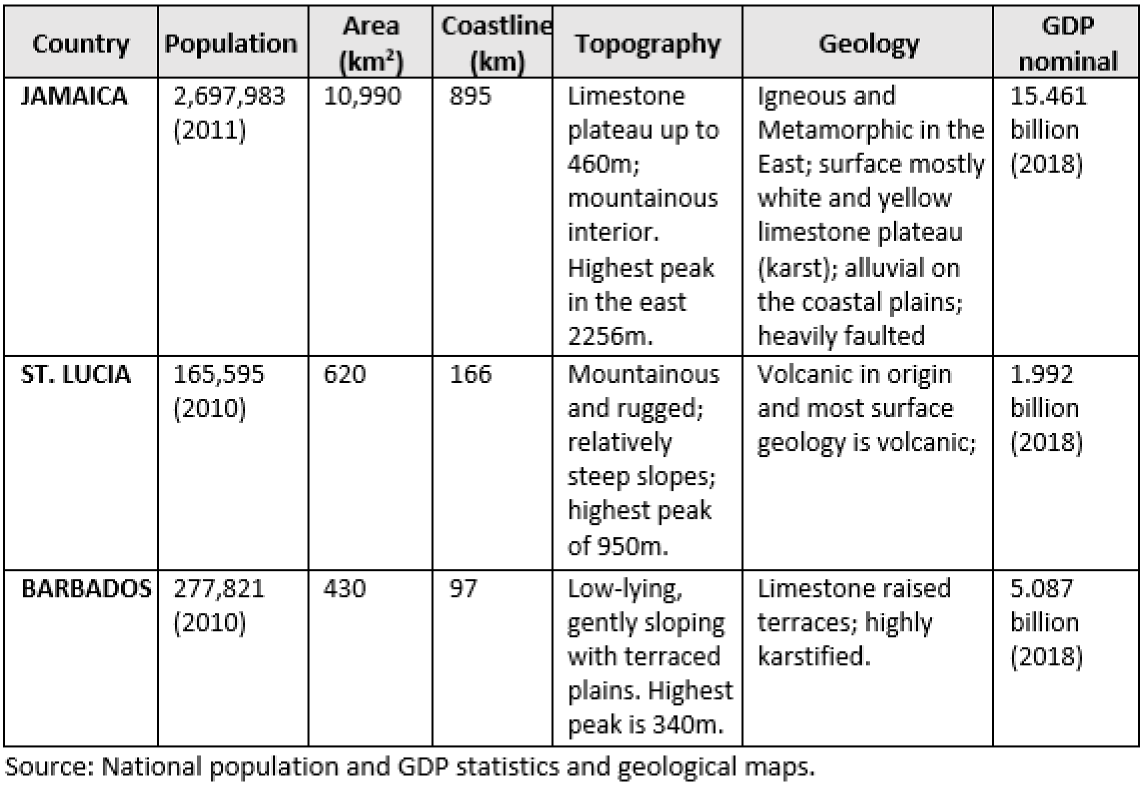
In 2017, Hurricanes Irma and Maria, two weeks apart, flooded and damaged infrastructure and equipment such as airports, seaports and energy facilities. In countries such as Dominica, Sint-Maarten, Barbuda and Puerto Rico, triggered landslides prevented access to these C.I. Airports and seaports were operating in short order (a few days). However, electricity took the longest time to restore (Anon, 2017; Cassady and Achenbach, 2017).

4.2 Coastal C.I. – Airports, Seaports and Energy Facilities

There are around 129 airports (active, public and airstrips), 173 seaports (container, cruise, piers, jetties and wharves) and 134 energy facilities (power plants and stations, oil and gas terminals and a research nuclear power station) in the Caribbean (Becker and Bove, 2017; New Energy Events, 2018; Smith, 2019). Historically, as the Caribbean was under the plantation economic system, many cities were developed around ports and coastal areas to export raw materials to Europe. This led to dispersed settlements concentrated on the coast and on flatter land for farming, excluding steeper and rougher terrains. Power plants and oil and gas terminals were near the coast for unloading petroleum and surrounding settlements. Most airports were built during World War II as bases were set up to defend the Western Hemisphere. They followed typical requirements of being located near cities (for supplies) but away from properties and buildings, with favourable wind and large land area. (Agravante, 2019). Additionally, the limited land space and the Caribbean's tourism business model of the 3S' – sun, sea and sand, encouraged the growth of airports, seaports and energy facilities in coastal areas.

Islands under investigation are Jamaica, St. Lucia and Barbados and the G.A. are those of Section 3.2. Table 4-1 describes the islands. All countries were former British colonies and have C.I. that were recently expanded/upgraded or are currently being designed.

Table 4-1: General description of islands under investigation.

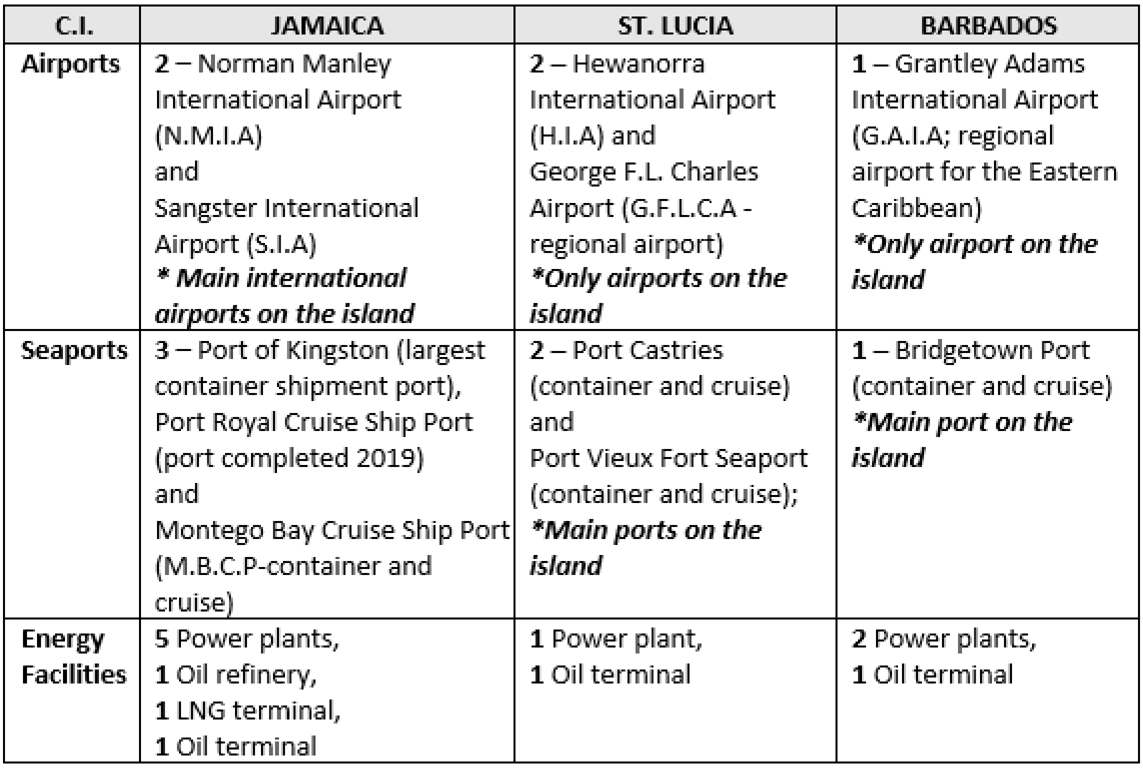


Country	Population	Area (km^2)	Coastline (km)	Topography	Geology	GDP nominal
JAMAICA	2,697,983 (2011)	10,990	895	Limestone plateau up to 460m; mountainous interior. Highest peak in the east 2256m.	Igneous and Metamorphic in the East; surface mostly white and yellow limestone plateau (karst); alluvial on the coastal plains; heavily faulted	15.461 billion (2018)
ST. LUCIA	165,595 (2010)	620	166	Mountainous and rugged; relatively steep slopes; highest peak of 950m.	Volcanic in origin and most surface geology is volcanic;	1.992 billion (2018)
BARBADOS	277,821 (2010)	430	97	Low-lying, gently sloping with terraced plains. Highest peak is 340m.	Limestone raised terraces; highly karstified.	5.087 billion (2018)

Source: National population and GDP statistics and geological maps.

The 24 selected C.I. are listed in Table 4-2 and presented graphically in Figures 4-6, and Figure 4-7 where they are separated into zones. All C.I. are the major ones on each island and all energy facilities use fossil fuels. Table 4-4 identifies the G.A. found at each C.I. Table 4-3 summarises the comprehensive description of ground, hazard and special characteristics of each C.I. compiled in Appendix B.

Table 4-2: List of coastal C.I. selected.



C.I.	JAMAICA	ST. LUCIA	BARBADOS
Airports	**2** – Norman Manley International Airport (N.M.I.A) and Sangster International Airport (S.I.A) **** Main international airports on the island***	**2** – Hewanorra International Airport (H.I.A) and George F.L. Charles Airport (G.F.L.C.A - regional airport) ****Only airports on the island***	**1** – Grantley Adams International Airport (G.A.I.A; regional airport for the Eastern Caribbean) ****Only airport on the island***
Seaports	**3** – Port of Kingston (largest container shipment port), Port Royal Cruise Ship Port (port completed 2019) and Montego Bay Cruise Ship Port (M.B.C.P-container and cruise)	**2** – Port Castries (container and cruise) and Port Vieux Fort Seaport (container and cruise); ****Main ports on the island***	**1** – Bridgetown Port (container and cruise) ****Main port on the island***
Energy Facilities	**5** Power plants, **1** Oil refinery, **1** LNG terminal, **1** Oil terminal	**1** Power plant, **1** Oil terminal	**2** Power plants, **1** Oil terminal

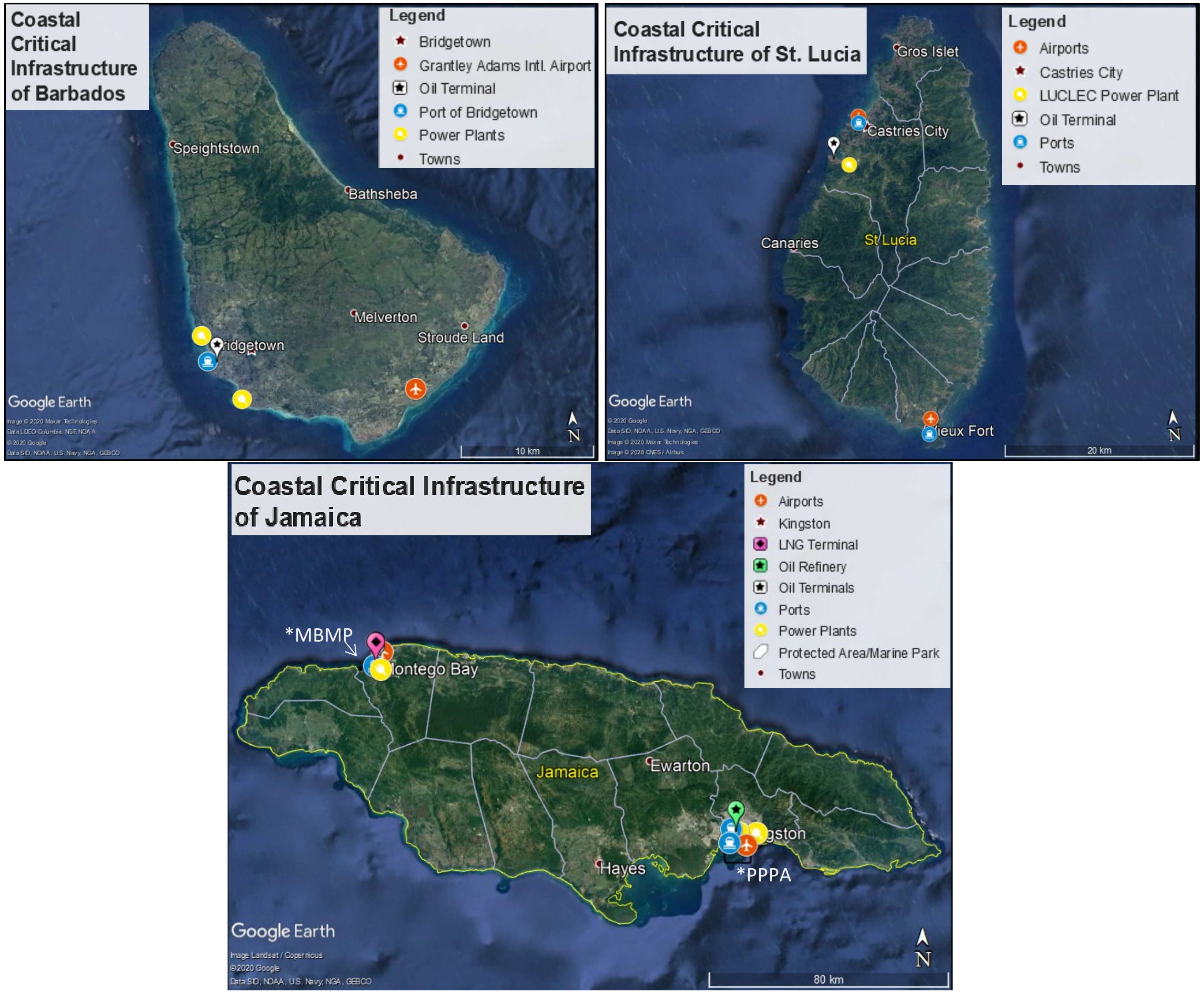


Figure 4-6: Select countries and their C.I. (Google Earth Pro, 2020b). Acronyms: MBMP – Montego Bay Marine Park; PPPA – Port Royal-Palisados Protected Area.

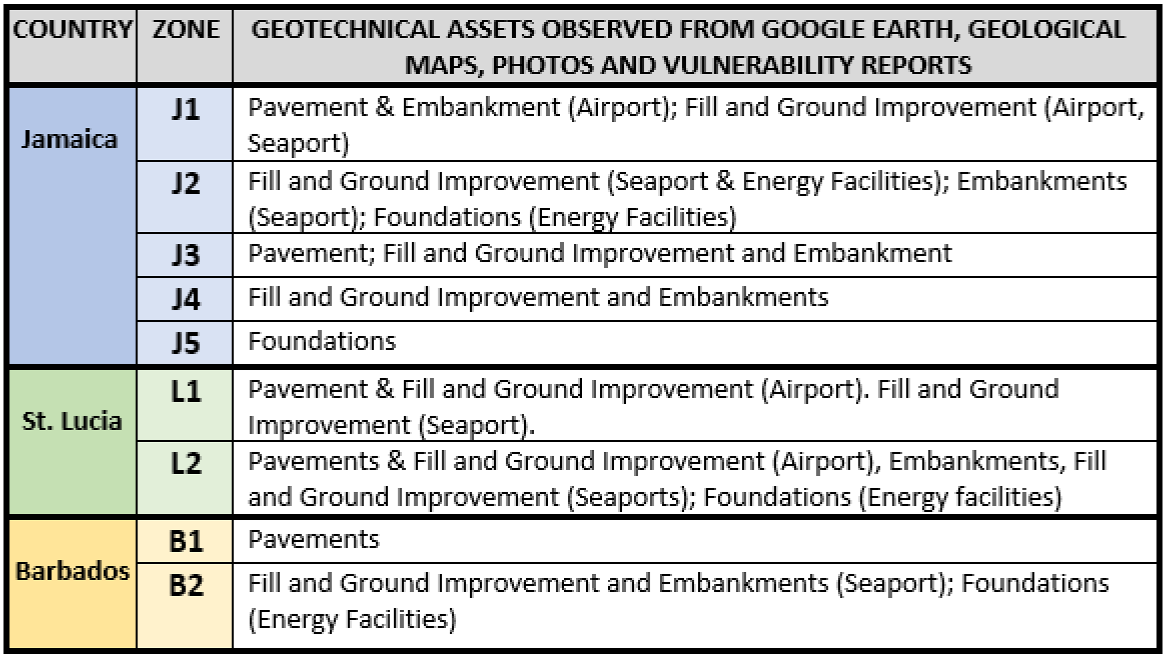
Figure 4-7: The C.I. separated by zones (Google Earth Pro, 2020b).

Table 4-3: Summary on the C.I.s' ground and hazards by zones. Comprehensive version in Appendix B.

COUNTRY	ZONE	GEOLOGICAL CONSIDERATIONS	HAZARD FOUND IN THE LITERATURE	OTHER CONSIDERATIONS
Jamaica	**J1**	Alluvium and Engineered fill (hydraulic). Alluvium is compacted in upper 1m and is peat clays, fine sand, silt and gravel and marl. Fill was fine-medium grained GRAVEL with a trace of shell fragments. Compaction and surcharge were used for ground improvement. Organic silt and varying proportions of decayed vegetative material beneath the engineered fill.	Liquefaction, fissuring, subsidence and differential settlement from earthquake damage prior to fill. Storm surge, hurricane wind damage, potential scouring of embankments and earthworks. Potential deformation from organic material.	Located in a marine protected area. Naturally protected by coastal vegetation and features.
	J2	Engineered and non-engineered fill overlying alluvium soil. Upper unconfined and lower confined aquifers. Groundwater 2m bgl.	Urban flooding, subsidence from groundwater extraction, hurricanes, tsunamis/seiche.	Naturally protected by the Palisados spit complex, shallow cays and shallow areas in the harbour.
	J3	Engineered platform of compacted marl on a lagoon overlying consolidated marine calcareous sands and silty sand on top of a coastal reef platform. Groundwater 0.914m/3ft bgl.	Hurricanes, storm surges, scour, earthquakes, coastal flooding, urban flooding, liquefaction, sinkholes.	Located in a marine protected area.
	J4	Dredged and reclaimed land (coralline rock and sand) overlying marshland deposits with low bearing capacity. High water table.	Subsidence, erosion and scour, hurricanes and storm surge, earthquakes, liquefaction and tsunamis.	Located in a marine protected area.
	J5	Alluvium (interbedded with loose unconsolidated gravels, sand, clays and organic matter). Bearing capacity varies from moderate (0.3MPa) to a low of (0.08MPa).	Possibly hurricanes, flooding, earthquakes and subsidence.	Protected from the coast with a sewage treatment plant and mangroves.

COUNTRY	ZONE	GEOLOGICAL CONSIDERATIONS	HAZARD FOUND IN THE LITERATURE	OTHER CONSIDERATIONS
St. Lucia	**L1**	Airport on Made Ground overlying coarse sand and clay. Port is on Made Ground overlying basalt and andesite agglomerated tuff. Nearby groundwater 1.7m bgl.	Flooding from storms and intense/prolonged rainfall events. Coastal flooding.	
	L2	Alluvium; Basalt agglomerate, clay, silty clay soils on agglomerate tuffs and altered andesite ash.		
Barbados	**B1**	Thin friable dark brown sandy CLAY. Overlying coral limestone; soil rich in lime and phosphates.	Located near to mapped sinkholes.	Rarely affected by hurricanes. One of the few islands with a lowest risk of hurricane damage. Limestone geology at a high risk of coastal erosion.
	B2	Many areas of Made Ground but composition and treatment unknown. Black-dark grey sandy CLAY. The clay is smectoid (swelling) formed from weathered coral and ash fall overlying coral limestone. Contains 4% organic content and low in soluble phosphates.	At risk of flash flooding.	

Table 4-4: G.A. identified at selected C.I.



COUNTRY	ZONE	GEOTECHNICAL ASSETS OBSERVED FROM GOOGLE EARTH, GEOLOGICAL MAPS, PHOTOS AND VULNERABILITY REPORTS
Jamaica	**J1**	Pavement & Embankment (Airport); Fill and Ground Improvement (Airport, Seaport)
	J2	Fill and Ground Improvement (Seaport & Energy Facilities); Embankments (Seaport); Foundations (Energy Facilities)
	J3	Pavement; Fill and Ground Improvement and Embankment
	J4	Fill and Ground Improvement and Embankments
	J5	Foundations
St. Lucia	**L1**	Pavement & Fill and Ground Improvement (Airport). Fill and Ground Improvement (Seaport).
	L2	Pavements & Fill and Ground Improvement (Airport), Embankments, Fill and Ground Improvement (Seaports); Foundations (Energy facilities)
Barbados	**B1**	Pavements
	B2	Fill and Ground Improvement and Embankments (Seaport); Foundations (Energy Facilities)

4.3 Climate Projections

Projections from the Intergovernmental Panel on Climate Change (IPCC) and Regional Organisations can be represented using either emission (via Representative Concentration Pathways – RCPs) or global temperature increase scenarios. See Appendix C for the relationship between RCPs and temperature. Many comprehensive studies on the Caribbean are based on the Paris Agreement adopted in 2015, to limit global temperatures to less than 2.0^{o}C above pre-industrial levels. This was based on the region's extreme vulnerability to C.C. and the belief that 1.5^{o}C is the limit the region can tolerate (Anon, 2018). Table 4-5 presents climate projections for 1.5^{o}C and 2.0^{o}C scenarios and Table 4-6 for the islands. Some researchers do not think this target can be met, with a recent study forecasting temperature may exceed 1.5^{o}C between 2020-2024 (World Meteorological Organisation, 2020). However, there is still hope to reverse this trend as the study only considered a short period of time (5 years) compared to the long-term effects of climate and this forecast is of a 20% chance. Additionally, the IPCC's latest report suggested that attaining 1.5^{o}C by 2100 may still be possible if global net human CO_2 emissions reach zero by 2050 (IPCC, 2018).

Table 4-5: Summary of Caribbean climate projections by 2100 using two scenarios.

THREAT	1.5°C BY 2100	2.0°C BY 2100
Global Sea Level rise (melting ice, thermal expansion and land storage) [Baseline year 2000]	**+0.48m (+28-82)**	**+0.56m (+28-96)**
Global Marine heatwave [Baseline pre-industrial levels]	**x 16**	**x 23**
Global Ocean acidity by 2100 [Baseline 1986-2005]	**+9%**	**+24%**
Caribbean near surface temperature change [Baseline pre-industrial levels]	**+1.2°C** **(+1.0°-1.4°C)**	**+1.6** **(+1.4°-1.9°C)**
Caribbean annual precipitation [Baseline 1971-2000]	**+4%**	**0%**
Caribbean Annual days rainfall >10mm (heavy) [Baseline 1971-2000]	**-1 to +2**	**-4 to +1**
Caribbean Time in mod-severe drought [Baseline 1976-2005]	**17% (~3 months)**	**26% (~5 months)**

Sources: *Taylor et al., 2018; Carbon Brief, 2020.*

Table 4-6: Climate projections by 2100 for selected countries.

Climate Feature	St. Lucia	Jamaica	Barbados
Temperature	Warmer (baseline 1970-1999); Mean +1.8 °C by the 2050s and 3°C by the 2080s	Mean +0.75 to +1.04°C (2030s), +0.87 to +1.74°C (2050s) and +2.0 to 3.0°C/1.5 to 2.3°C (2100)	Approx. Mean +1°C to 2°C by 2067. Using statistical modelling 2.3°C/0.7°C by 2100.
	Land warming faster than ocean areas; more hot days and less cold days; sea surface temperatures at slightly lower magnitude than air surface temperatures above.		
Precipitation	Drier by 2100; projected median annual decreases in rainfall are 22% and 32 %.	10% drier by 2050's, 21% drier for the most severe scenario by 2100. Potential spatial variation. Annually +5% wetter at 1.5°C but -2% drier at 2°C.	Drier average decrease of 7% to 18% by 2090s. Rainfall intensity may increase up to 45% for extreme events. Annual precipitation +2% at a 1.5°C but -7% at 2°C
Sea level	Mean rise of 0.31 - 0.35m by 2060 and 0.56 - 0.76 m by 2100 depending on the scenario.	Mean rise of 0.43 to 0.67m by 2100 & a max of 1.05m	Mean rise of 0.2-0.4m by 2067. Compared to 1980-1999 baseline ranges from 0.13-0.56m by 2100.
Storms	Small/moderate increases in storm surge levels; mostly decreases in the wave power of extreme storms. Hurricane intensity to increase, but not necessarily the frequency.	No statistically significant increase in the frequency, but 80% increase in Category 4 and 5 hurricanes to 2100; Wind increase +2% to +11%; Rainfall rates +20% to +30% for the hurricane's core	Possible increase in hurricane intensity of 2% to 11% by 2067.

Sources: Chen et al., 2006; Mcsweeney et al., 2012; UNCTAD, 2017c; UNCTAD, 2017b; Barbados Climate Change, 2017.

4.3.1 Commentary on Projections

Observations from Tables 4-5 and 4-6 indicate that baselines and methodologies vary in the projections. Initial attempts to correlate these data with other temperature projections (Appendix C and D) compound this observation. These contribute to the aleatory risks, e.g. natural variation in temperature and precipitation. Some epistemic risks identified during research included:

i. Relatively young age of climate science (formally accepted in 1988),
ii. Existence of 39 climate models that have differing parameters and complexity,
iii. A limited understanding on climate systems and the interaction between and among each weather variable,
iv. Variation in results from instruments (ground vs. satellite and weather balloons),
v. Difficulties in predicting and projecting weather and forecasting precipitation and storms,
vi. Limits to computing power, and
vii. The limited historical, regional and global data as C.C. will have varying effects on regions and not all regions are equal in data collection, monitoring and equipment (Legates, 2002; Henderson and Hooper, 2017; National Center for Atmospheric Research, 2020).

4.3.2 Potential Impact on C.I. and G.A.

All manifestations of C.C. threaten C.I. with the only difference being the timeline with slow and progressive changes and more rapid changes. The most immediate threats to coastal C.I. are storms, storm surges and SLR. All manifestations will affect the operations, function, maintenance and survival of C.I. Using above projections and additional information, Table 4-7 summarizes C.C.'s potential impacts on C.I.

Table 4-7: Potential impacts of C.C. related hazards on the C.I. investigated.

Hazard	Impact: Airports	Impact: Seaports	Impact: Energy Facilities
Increased Temperatures	Need for runway extensions from impact on aircraft performance; Change to heating and cooling requirements - adds stress on water and energy; Heat damage to runways and taxiways; Change in demand patterns; Operational challenges	Damage to infrastructure, equipment and cargo; Asset lifetime reduction; Thermal impact on paved surfaces and load bearing equipment; Heat related illnesses; Increased energy usage and costs.	Increased energy demand; Lower generation efficiency; Change in heating and cooling requirements and stress on water.
Change in precipitation (drought; intense rainfall events)	Damage to infrastructure and support facilities; Flooding; Increased maintenance; Operational challenges.	Flooding and inundation of onshore components; Operational challenges (including problems with cranes); Damage to cargo & equipment; Changes in demand	Flooding and damage to underground structure; Damage to infrastructure and equipment; Increased stress on water resources
Increase in storms	Operational challenges (cancellations, rerouting of flights thus increase in fuel usage); Storm surge; Flooding Damage to infrastructure and erosion; Damage to ground access to facility	Scour, erosion & damage to infrastructure and coastal defences from debris and strong winds; Flooding; Operational challenges; Increased maintenance costs; Increase in siltation and maintenance dredging	Service disruptions; Damage to infrastructure & equipment from physical damage or erosion.
SLR (also increase in storm surge)	Loss of capacity (inundated); Damage and deterioration of infrastructure, foundations, pavements and other facilities through scour, erosion and corrosion; Increased maintenance and repairs and cost; Stresses the emergency management function of the facility (acting as a shelter and hub for relief)	Inundation; Damage to infrastructure and cargo; Deterioration of coastal protection and increased erosion of infrastructure; Changes in sedimentation and navigation channels; Higher construction & maintenance costs; Operational, logistical and health challenges.	Inundation of facilities; Pollution and contamination of groundwater and the environment.

N.B. Operational challenges include delays, downtime, damage to equipment

Sources: Emmanuel (2013); UNCTAD (2017a); Burillo (2019).

These hazards also impact the ground and G.A. For the Caribbean these include changes in hydraulic inputs and outputs, weathering, material properties and geochemical composition. Other impacts are increased loads and actions from SLR, winds, debris, precipitation and the force of water from flooding and increased wave action. Table 4-8 summarizes the potential impact of C.C. on the ground and G.A. tailored for projections in Table 4-6 and 4-7. It was compiled using information on:

i. The potential impact of C.C. on the ground
ii. G.A.M. for transport C.I. in Europe and the U.S.
iii. Failure modes for G.A. in Section 3.2
iv. Ground and hazard conditions in Table 4-3
v. Observations made from reconnaissance reports from the *Geotechnical Extreme Events Reconnaissance* (GEER) *Association* on storm damage within the Caribbean and U.S. between 2008-2017.

Table 4-8: Potential impact and failure modes on the ground and potentially most affected G.A. from the threat of C.C. (Adapted from Vardon, 2015; Vahedifard et al., 2018; Argyroudis et al., 2019).

Climate Hazard	Potential Impact	G.A. most affected	Failure Modes
Increased temperature and extreme hot weather	• Soil drying from higher evaporation rates ➔ increased suction, desiccation cracking. • Soil organic carbon oxidation ➔ shrinkage, subsidence. • Changes in vegetation amount ➔ varied effect.	**Pv** **Em** **Fdn**	Uplift; differential settlement; thermal fatigue.
Decreased precipitation and longer droughts, especially induced by ENSO	• Soil drying ➔ desiccation cracking, clay shrinkage and increased suction. • Reduced vegetation ➔ increased surface erosion. • Reduction in water table, especially if also used for domestic extraction ➔ Settlement; Increased susceptibility to intense precipitation from desiccation cracking and shrinkage.	**Pv** **Em** **Fdn** **Potentially F&G**	Piping; internal erosion; slope instability; differential settlement.
Intense precipitation from ENSO/storms	• Rapid soil wetting ➔ dynamic pore pressure changes. • Increased ground saturation, swelling of clay materials if prolonged • Increased surface runoff – flash flooding/overland flow ➔ substantial soil erosion. • Trigger shallow/reactivate landslides and debris flows ➔ increased friction on soil, loss of suction, increased soil weight and decreased resistance.	**Pv, Em, ShFdn,** **Potentially DpFdn & F&G**	Piping; slope erosion and instability (along discontinuities, toppling, falls, sliding, slumping and translational failure); soil erosion; seepage; scour; settlement; uplift. Em and Fdn: instability failure of foundation or material strength/material failure.
Stronger winds from storms	• Increased action from wind, blown debris and wave action ➔ physical damage, increased ground scour and erosion, need more durable revetments for coastal protection.	**Em, ShFdn, F&G**	Scour; wave erosion; undercutting and slope instability; overtopping with waves

*Acronyms: Pavements (Pv); Embankments (Em); Foundations (Fdn) – Shallow (ShFdn), Deep (DpFdn); Fill and Ground Improvement (F&G)

Climate Hazard	Potential Impact	G.A. most affected	Failure Modes
Sea Level Rise and storm surge	• Coastal flooding and wave action ➔ lowered suction due to wetting, increased risk of multiple failure mechanisms, increased erosion from the seas and debris, movement of boulders used in revetments. • Inundating structures ➔ pore pressure increase; reduction in strength; change in density/material properties. • Increase the intensity of storms (see impacts related to storms). • Saltwater intrusion and changing the interface between freshwater and seawater ➔ potential corrosion of concrete foundations and reduction in strength especially for if not designed for saltwater conditions. • Groundwater levels could rise (groundwater flooding) as saltwater is denser than freshwater ➔ large pore pressure increases and reduction in strength, soil wetting and softening, heave or possibly affect erosion rates in karst.	**Pv** **Fdn** **Em** **F&G**	Inundation, piping, internal erosion, seepage, overtopping, scour, wave erosion, washout, corrosion to foundations, costal erosion and landslides, slope instability, uplift
More acidic oceans	• Potential corrosion of steel and dissolution of concrete ➔ reduction in strength of foundations; oceans absorbing CO_2 will lead to $H_2CO_3 + Ca(OH)_2 <=> CaCO_3 + 2H_2O$. • Enhanced coral bleaching can potentially reduce the natural buffer from storms and strong waves ➔ increased coastal erosion. • Changes in vegetation (e.g. mangroves) ➔ varies but can also reduce coastal protection.	**Fdn**	Corrosion; increased coastal erosion and scour

*Acronyms: Pavements (Pv); Embankments (Em); Foundations (Fdn) – Shallow (ShFdn), Deep (DpFdn); Fill and Ground Improvement (F&G)

Direct Sources: Masuda (2002); Collins et al. (2015); New Hampshire Coastal Risk and Hazards Commission (2016); Ingham et al. (2016); Jamal (2017); Cementaid (UK) Limited (2020).

4.4 Testing SLR Scenarios

4.4.1 The Risk to C.I.

Based on the information from Section 4.3, global temperatures of 1.5^{o}C and 2^{o}C, and an upper limit of 3^{o}C by 2100 were used for SLR scenarios. The *Surging Seas Mapping Choices* KML file was superimposed on *Google Earth Pro maps (*Section 2.3*)*. Figures 4-8 to 4-10 display the changes in SLR across the range of temperatures in each zone. Two things that could not be included in these scenarios were isostacy from:

i. Activity at the Caribbean Plate boundaries and
ii. Localized responses - differential uplift of 0-0.6mm/yr in Barbados and both differential uplift and subsidence in Jamaica of -0.2mm/yr to +0.14mm/yr (United Nations Environment Programme et al., 1993; Speed et al., 2012).

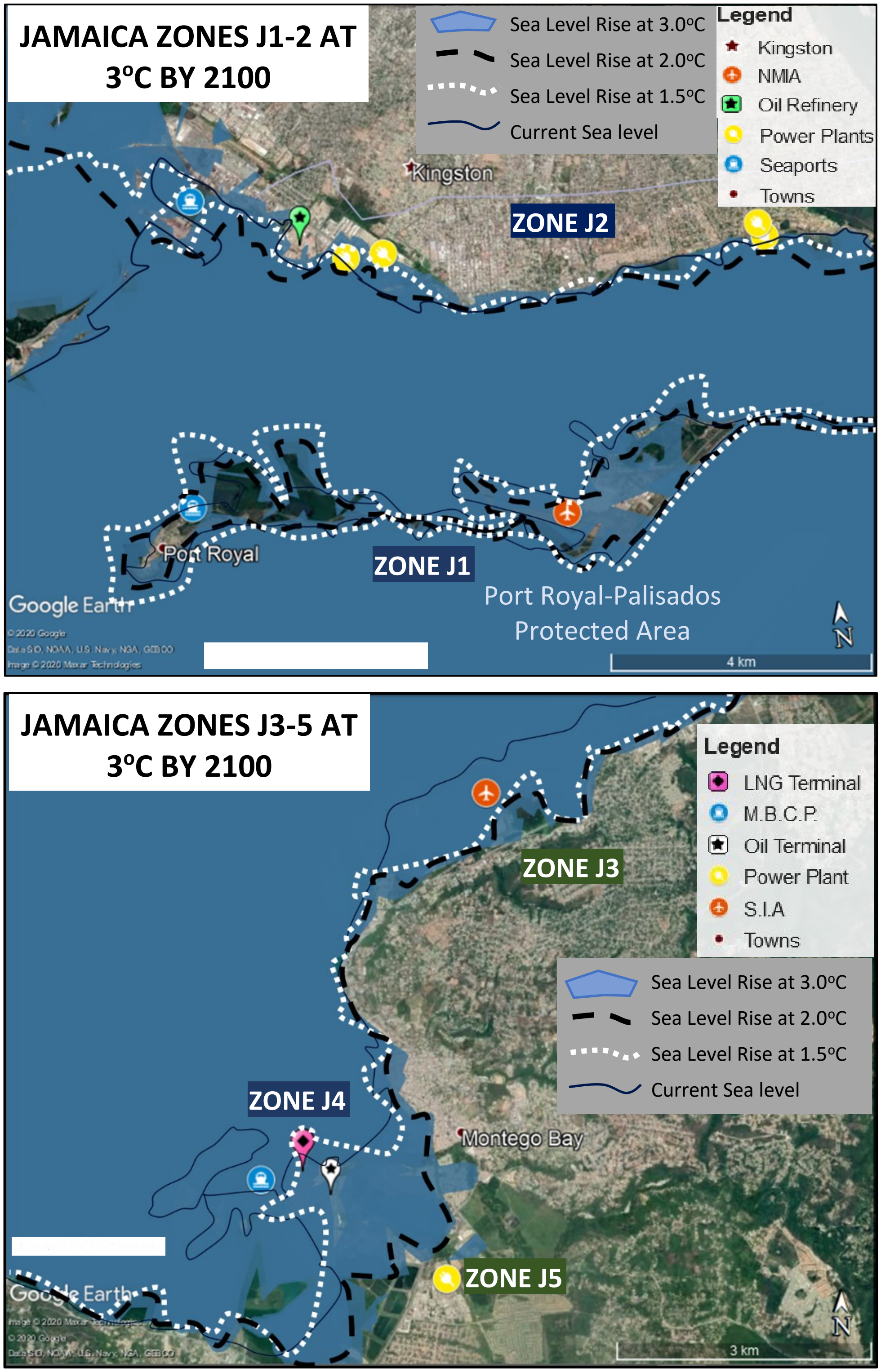


Figure 4-8: Zones J1-5 by 2100 at different SLR scenarios.
Sources: Climate Central, 2020; Google Earth Pro, 2020b.

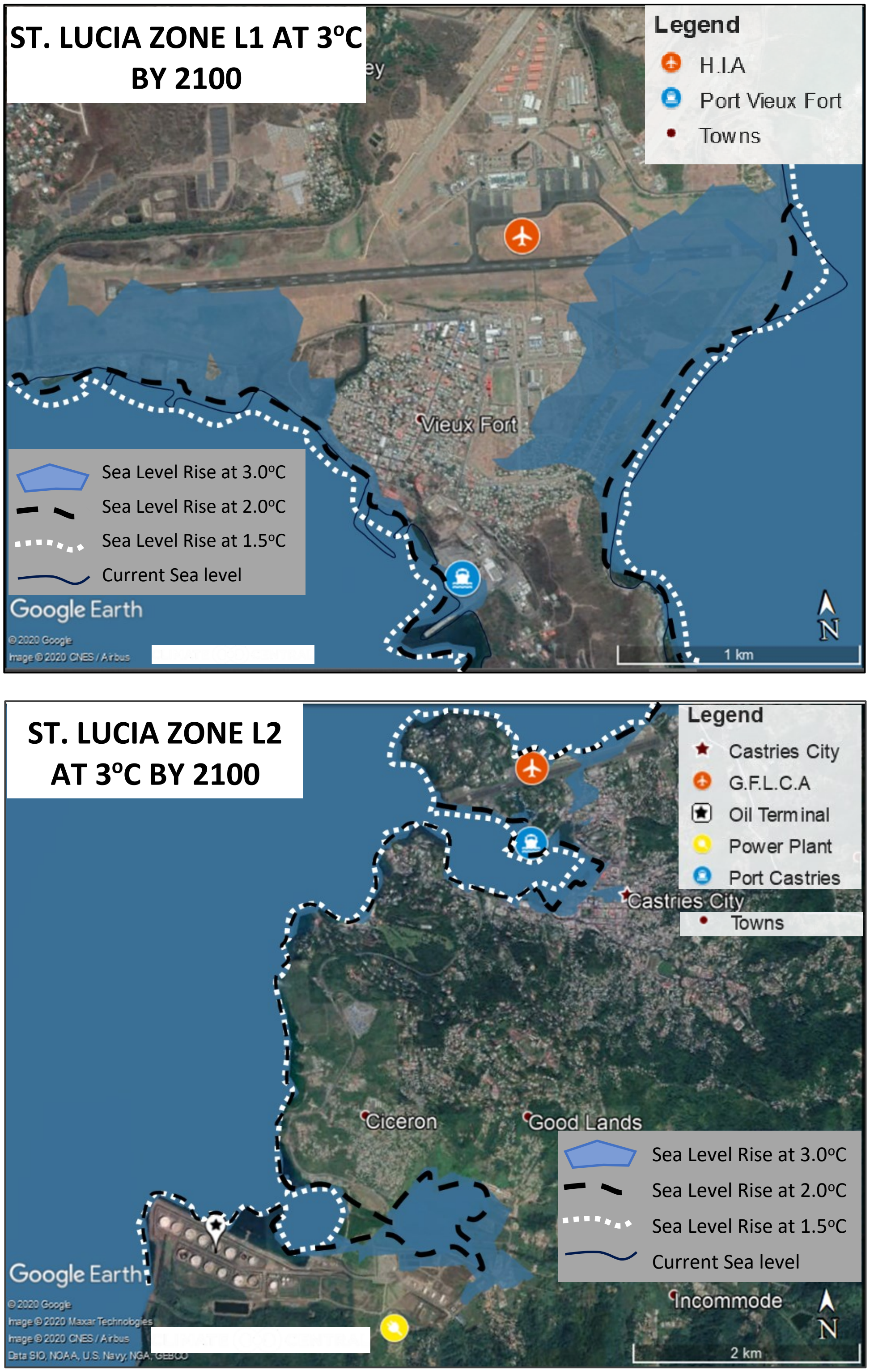


Figure 4-9: Zones L1 and L2 by 2100 at different SLR scenarios. Sources: Climate Central, 2020; Google Earth Pro, 2020b.

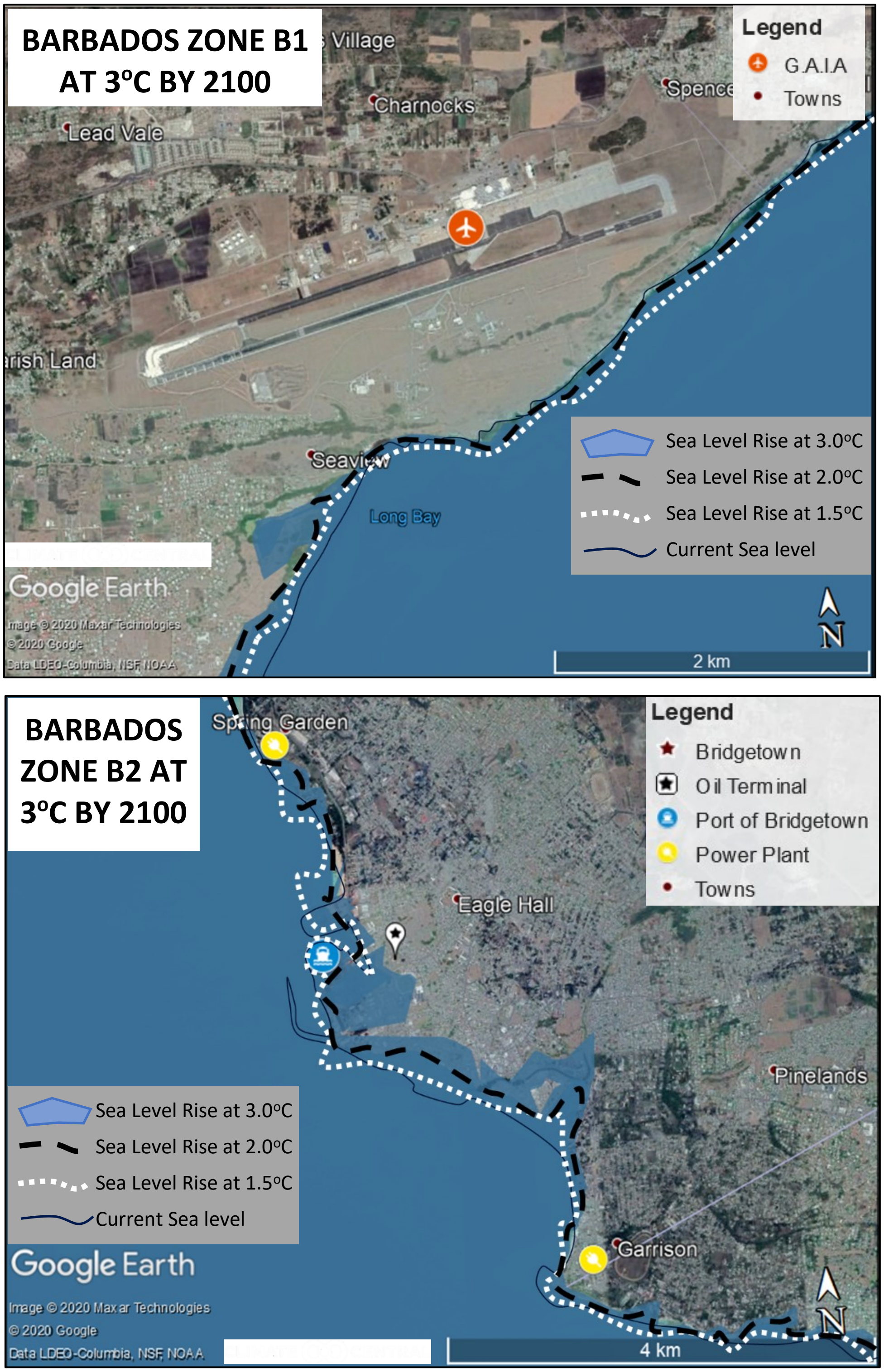
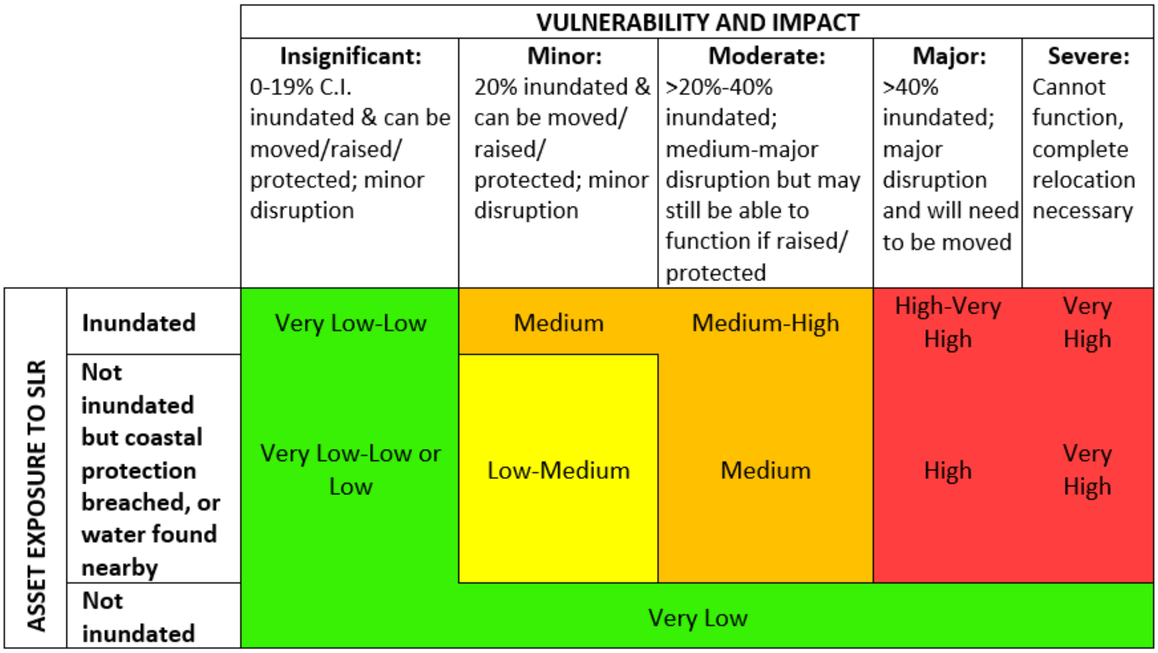


Figure 4-10: Zones B1 and B2 by 2100 at different SLR scenarios. Sources: Climate Central, 2020; Google Earth Pro, 2020b.

Figures 4-8 to 4-10 show that C.I. in Barbados are the least vulnerable to inundation, followed by St. Lucia and Jamaica. Most of the C.I. in Jamaica and St. Lucia are inundated at a global temperature of 3°C. All C.I. in Barbados and St. Lucia, excepting ports, would not be inundated at 1.5°C and 2°C. For Jamaica, S.I.A. in Zone J3 will be completely inundated at 1.5°C followed by zones J4 then J2 and J1.

Observations made when zoomed-in at each zone were used to generate a risk matrix for the impact on C.I. (Figure 4-13). Using information from Table 4-7, measuring the length of inundation in and near C.I. from the scenario maps and making an estimation whether the assets could be protected for e.g. using a physical barrier or moved in land (based on reports for Jamaica and St. Lucia from UNCTAD, 2017) a risk matrix was developed (Figure 4-11). The interdependence of the C.I., surrounding settlements and roads to and from the C.I. were not considered in the risk matrix.

(a)



		VULNERABILITY AND IMPACT				
		Insignificant: 0-19% C.I. inundated & can be moved/raised/ protected; minor disruption	**Minor:** 20% inundated & can be moved/ raised/ protected; minor disruption	**Moderate:** >20%-40% inundated; medium-major disruption but may still be able to function if raised/ protected	**Major:** >40% inundated; major disruption and will need to be moved	**Severe:** Cannot function, complete relocation necessary
ASSET EXPOSURE TO SLR	**Inundated**	Very Low-Low	Medium	Medium-High	High-Very High	Very High
	Not inundated but coastal protection breached, or water found nearby	Very Low-Low or Low	Low-Medium	Medium	High	Very High
	Not inundated	Very Low				

Figure 4-11: (a) Risk matrix legend and (b) risk matrix for the potential impact of SLR at 1.5°C, 2°C and 3°C on selected C.I.

Figure 4-11 contd.

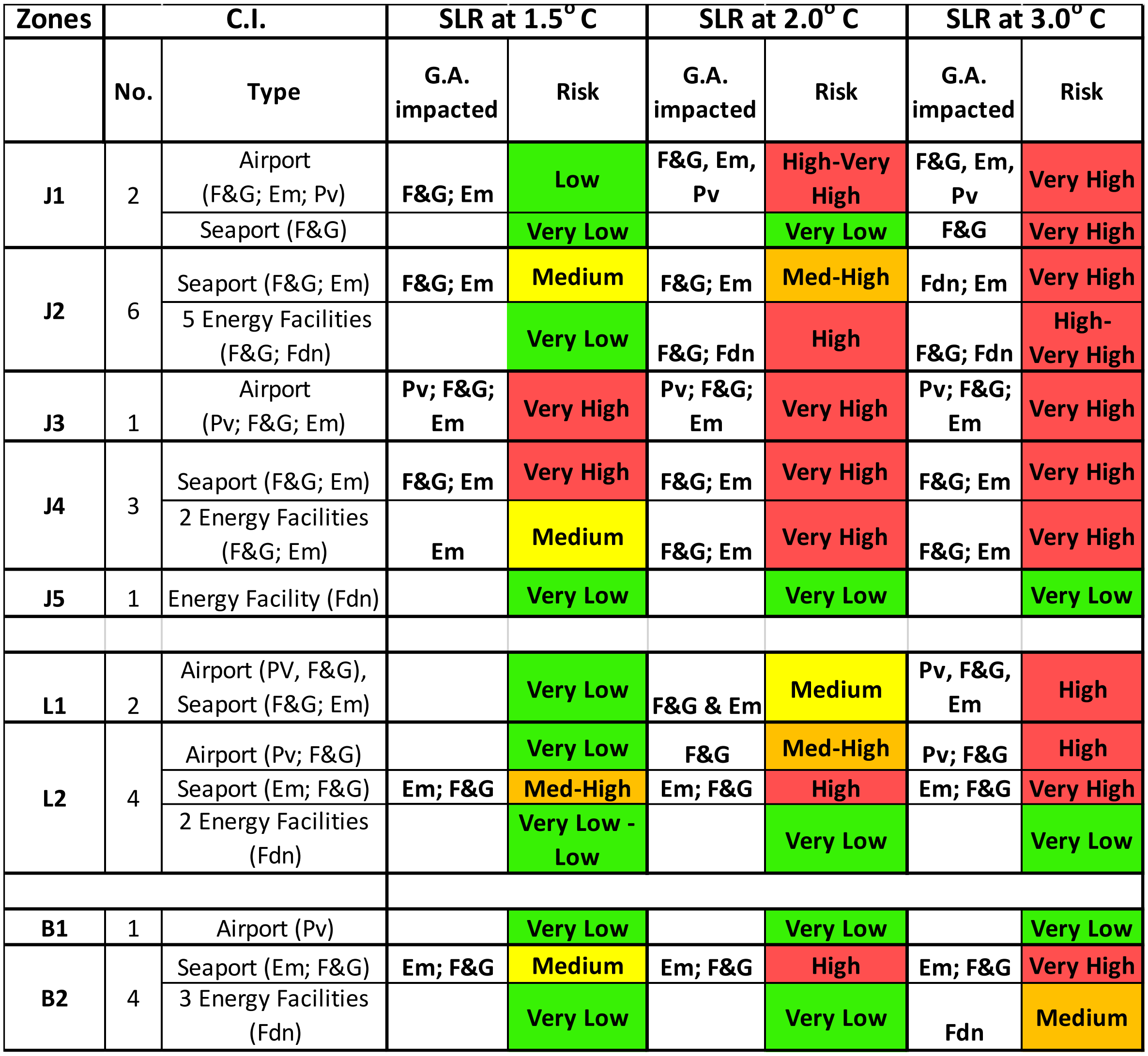
(b)

Zones	C.I.		SLR at 1.5° C			SLR at 2.0° C			SLR at 3.0° C		
	No.	Type	No. Impacted	Description	Risk	No. Impacted	Description	Risk	No. of C.I. Impacted	Description	Risk
J1	2	Airport,	1	Sea defense breached but runway not affected	Low	1	Approx. 50% of the airfield and some of the other facilities are	High-Very High	1	Completely inundated	Very High
		Seaport	0		Very Low	0		Very Low	1	Completely inundated	Very High
J2	6	Seaport	1	Parts of the port are inundated but not >15%	Medium	1	Approx. 30% of the port is inundated	Medium-High	1	Completely inundated	Very High
		5 Energy Facilities	0		Very Low	3	Part of the refinery breached and one part inundated; 2 power plants inundated	High	3	Approx. 50 % of the refinery inundated; 2 power plants completely inundated; 2 power plants safe	High to Very High
TOTAL IMPACTED			2/8			5/8			6/8		
J3	1	Airport	1	Airport fully inundated	Very High	1	Completely inundated	Very High	1	Completely inundated	Very High
J4	3	Seaport		Mostly inundated	Very High	1	Completely inundated	Very High	1	Completely inundated	Very High
		2 Energy Facilities	0	Not inundated but adjacent port is	Medium	2	Completely inundated	Very High	2	Completely inundated	Very High
J5	1	Energy Facility	0		Very Low	0		Very Low	0		Low
TOTAL IMPACTED			1/5			4/5			4/5		
L1	2	Airport, Seaport	0		Very Low	1	Sea defense breached but runway not affected	Low	2	Approx. 20% of the runway is flooded; Approx. over 50% of the cargo holding area is inundated	High
L2	4	Airport	0		Very Low	1	Sea defences breached and a small part of the southwest field is inundated but not near the runway.	Low	1	Approx. 50% of the runway is inundated	High
		Seaport	0	Water breaches a small part (~5%) of the cruise and container terminals.	Low	1	Over 50% of the container terminal is inundated but about 10% of the cruise terminal is inundated.	Medium-High	1	All port facilities inundated	Very High
		2 Energy Facilities	0		Very Low	0		Very Low	0		Very Low
TOTAL IMPACTED			0/6			3/6			4/6		
B1	1	Airport	0		Very Low	0		Very Low	0		Very Low
B2	4	Seaport	1	Approx. 10% of seaport terminal inundated	Low	1	Approx. 20% of seaport terminal and pier inundated	Medium	1	Completely Inundated	Very High
		3 Energy Facilities	0		Very Low	0		Very Low	1	Water nearby but most C.I. not touched; 1 power plant inundated	Medium & Medium-
TOTAL IMPACTED			1/5			1/5			2/5		

Figure 4-11b showed Jamaica has the most at-risk C.I. at the lowest scenario of 1.5°C, namely in Zones J3 and J4 in the city of Montego Bay. The C.I. in St. Lucia and Barbados appear to be safe at 1.5°C and are more at risk progressively from 2°C to 3°C with seaport terminals impacted first, followed by other C.I. Even at 2.0°C, the C.I. in Jamaica would be the most at risk, which would be problematic as the airports investigated are the country's main airports. The facilities with the lowest risk for all scenarios are the Airport at B1, and Energy Facilities within Zones L2 and J5. These are the safest based on either the elevation of the C.I., their location away from the coast or if they have some form of protective barrier/buffer for e.g. Zone J5's energy facility is protected by wetlands and a sewage treatment plant (see Figure 4-8).

4.4.2 The Risk to G.A.

Figure 4-12 summarises the risk matrix on the potential impact of SLR scenarios on the G.A. found in Appendix E. It was compiled using tables 4-3 and 4-4, SLR and storm surge in Table 4-8, and visual observations on the proximity of SLR to the G.A. A different legend was used for this matrix, comprising the probability of SLR reaching the G.A. and consequence it could have. Assumptions were based on potential impacts on these structures; no information was found on current ground conditions or deterioration rates to improve the risk matrix. Moreover, out of all the G.A., foundations were the hardest to assign a risk rating as they are underground.



Zones	C.I.		SLR at 1.5° C		SLR at 2.0° C		SLR at 3.0° C	
	No.	Type	G.A. impacted	Risk	G.A. impacted	Risk	G.A. impacted	Risk
J1	2	Airport (F&G; Em; Pv)	**F&G; Em**	**Low**	**F&G, Em, Pv**	**High-Very High**	**F&G, Em, Pv**	**Very High**
		Seaport (F&G)		**Very Low**		**Very Low**	**F&G**	**Very High**
J2	6	Seaport (F&G; Em)	**F&G; Em**	**Medium**	**F&G; Em**	**Med-High**	**Fdn; Em**	**Very High**
		5 Energy Facilities (F&G; Fdn)		**Very Low**	**F&G; Fdn**	**High**	**F&G; Fdn**	**High-Very High**
J3	1	Airport (Pv; F&G; Em)	**Pv; F&G; Em**	**Very High**	**Pv; F&G; Em**	**Very High**	**Pv; F&G; Em**	**Very High**
J4	3	Seaport (F&G; Em)	**F&G; Em**	**Very High**	**F&G; Em**	**Very High**	**F&G; Em**	**Very High**
		2 Energy Facilities (F&G; Em)	**Em**	**Medium**	**F&G; Em**	**Very High**	**F&G; Em**	**Very High**
J5	1	Energy Facility (Fdn)		**Very Low**		**Very Low**		**Very Low**
L1	2	Airport (PV, F&G), Seaport (F&G; Em)		**Very Low**	**F&G & Em**	**Medium**	**Pv, F&G, Em**	**High**
L2	4	Airport (Pv; F&G)		**Very Low**	**F&G**	**Med-High**	**Pv; F&G**	**High**
		Seaport (Em; F&G)	**Em; F&G**	**Med-High**	**Em; F&G**	**High**	**Em; F&G**	**Very High**
		2 Energy Facilities (Fdn)		**Very Low - Low**		**Very Low**		**Very Low**
B1	1	Airport (Pv)		**Very Low**		**Very Low**		**Very Low**
B2	4	Seaport (Em; F&G)	**Em; F&G**	**Medium**	**Em; F&G**	**High**	**Em; F&G**	**Very High**
		3 Energy Facilities (Fdn)		**Very Low**		**Very Low**	**Fdn**	**Medium**

*Acronyms: Pavements (Pv); Embankments (Em); Foundations (Fdn) – Shallow (ShFdn), Deep (DpFdn);
Fill and Ground Improvement (F&G)

Figure 4-12: Summary risk matrix for G.A. at different SLR scenarios by 2100. Comprehensive version in Appendix E.

Figure 4-12 shows that the G.A. in Jamaica will potentially be the most at risk to SLR if global temperatures were to reach 2° or 3°C. Both C.I. and G.A. in Montego Bay, Jamaica (Zones J3 and J4) would be the most at-risk for the lowest scenario of 1.5°C.

4.5 Additional regional design consideration

To plan for and mitigate the risks identified, other considerations need to be mentioned that could affect or be affected by geotechnical design. As identified in Banton et al., (2017) these are:

i. Limited natural resources for construction – e.g. sand, rock and aggregate and poor rock quality for coastal protection, e.g. Barbados.
ii. Construction logistics – how to get material through and to the islands.
iii. The limited land for relocating C.I., compounded by social or infrastructural constraints.
iv. Environmental concerns – coral reefs, mangroves and other natural systems that act as a buffer to SLR and wave action must be encouraged and not harmed.
v. The application and suitability of new technology - the Caribbean's location may make some solutions prohibitive (limits to adaptation).
vi. Social benefits or inclusion of locals in projects.
vii. Designs should be stable under current forecasts but adaptable to future projections.
viii. Designs must be technically and economically feasible for small economies with limited funding for maintenance.

4.6 Key Findings

- The Caribbean is diverse and extremely vulnerable to C.C. based on its location, hazard-prone nature, island characteristics, natural environment and other socio-economic factors.
- Ground characteristics of the selected sites include engineered and non-engineered ground, weathered volcanic and carbonate soils and karstified ground.
- The most at-risk C.I. and G.A. to the impact of SLR are found in Jamaica especially within Zones J3 and J4 for all scenarios.

- Seaport terminals on Made Ground will be the first C.I. affected by SLR. Some can be moved but not all.
- Elevation, distance inland and buffer zones protected some facilities in the scenarios tested.
- Additional studies must be done to refine the risk matrices generated for future scenarios.
- Additional regional considerations, such as limited construction resources and funding, environmental protection and preservation will need to be included in existing and new geotechnical designs.

5 APPLICATION OF DESIGNS

Using the risk-assessment portion of the risk management process has been useful in identifying potential C.I. and G.A. at risk to SLR scenarios in the Caribbean. Now, the potential impact and application of these designs to the future scenarios in fulfilment of Aim #3 will be discussed.

5.1 Conventional designs

Under existing C.I. and G.A., Section 4.4 shows that six of the 24 C.I. would be safe under all SLR scenarios (Figure 4-11). This corresponds to the G.A. in Zones J5, B1 and L2, and most energy facilities in Zone B2 (Figure 4-12 and Appendix E) which may survive all SLR scenarios tested. Therefore, current conventional designs may apply to these G.A. by 2100. All other C.I. and their G.A. may be at risk and may need to use risk-based approaches. However, it could be said that:

i. The survival of the C.I. and G.A. examined were mostly based on their location rather than their design.
ii. Risk rating allocations were based on visual observations and limited information assumptions.
iii. Projections were based on assumptions of a future that may not come to fruition.

Nevertheless, new risks identified for Caribbean C.I. and G.A. need to be addressed. Hence, there are two options on how to treat the existing and new C.I., either continue using conventional design or use the risk-based approaches.

Conventional design solutions now being implemented to mitigate the impact of SLR on C.I. include, using climate projections to construct higher land, increasing worst-case scenario events designed, building protective sea walls, introducing better and higher capacity drainage systems and constructing physical barriers (Agravante, 2019). All solutions would utilize and/or impact existing and new G.A. designs and could address at-risk C.I. and G.A.

Table 5-1 presents the potential application of these solutions with additional information and case studies in Appendix F. Even though these solutions use climate projections, they are still based upon the principles and features of conventional design; which are inflexible, reactive, 'avoids risk' and has the potential for missing potential future benefits or threats to designs indicated in Section 3.3.

Table 5-1: Potential application of conventional solutions for the C.I. and G.A. investigated.

Conventional design solutions to mitigate SLR	Where possibly NOT NEEDED	Where it possibly COULD WORK	Where it possibly COULD NOT WORK
Construct Higher Land e.g. raising embankments and revetments	**At 1.5°C** Nearly all zones except J3, J4 and the Seaports at J2, L2 and B2. **At 2.0°C** Zone J5. Most C.I. in Zones L2, B1 and B2 except seaports at J1. **At 3.0°C** C.I. in Zones J5, L2 and B1	Potentially at all seaport terminals with medium or higher risk and at airports in zones L1 and L2.	• Potentially at J2, J3, J4, B2. J2 and J4's engineered fill overly organic material with some indication of subsidence recorded at J4. As J3 was reclaimed wetland there is the potential of organic material the foundation soil. • All underground structures e.g. drainage, foundations, etc. would have to be redesigned. • J2 and B3 is located within capital cities and any changes may have to be implemented for the entire city.
Increasing Worst-Case Scenarios in the design e.g. from the usual 1 in 50/100-year events to 1 in 10,000-year events		For the expansion/upgrading of all C.I. and their G.A. This will be dictated by policy, cost, technical feasibility and information available to determine what event can be designed.	
Building Protective Sea Walls e.g. raising or building new walls for mitigating storm surge and SLR		For all facilities with Medium-High risk in Table. However, as all islands are surrounded by the sea, the feasibility of this may not be practical in the long-term and may have a negative impact on the natural environment.	
Introducing Better and Higher Capacity Drainage Systems e.g. assessing and upgrading drainage		For all medium or higher risk facilities though cost and practicality will determine feasibility. Information is needed on the current and expected capacity to and maintenance of the drains are important for its functioning.	
Constructing Physical Barriers e.g. Levees, tidal gates, holding ponds and pumping stations to act as barriers/buffering		For all medium or higher risk facilities though cost and practicality will determine feasibility. The physical barrier may also have an impact on the surrounding coastline and ecosystem and may be problematic for Zones J1-4 which are in Marine Protected Areas.	

5.2 Risk-based approaches

The sustainable, resilient and adaptive designs, all could be used to varying degrees for at-risk G.A. identified in Figure 4-12. As there are limited physical, natural, societal and economic resources in the Caribbean, sustainable designs would be relevant. However, the impact they will have on reducing SLR in the region are unknown and may not be useful without a greater global involvement in tackling C.C. Resilient and adaptive designs may be more feasible as the Caribbean islands have additional hazards outside of SLR that could weaken structures. According to Mr. Harris, Jamaica's concern is more aligned with resilient design, however if SLR scenarios tested were to come to fruition, especially for the Airport at Zone J3 (Figure 4-8), then an adaptable design would be more suitable. Table 5-2 presents the possible application and suitability of these designs to the SLR scenarios using information from Sections 3.4 and 4.2-4.5.

Table 5-2: Potential application of risk-based approaches for C.I. and G.A. investigated.

Type of Risk-based approach	Potential measures to design for SLR	Where possibly NOT NEEDED	Where it possibly COULD WORK	Where it possibly COULD NOT WORK
Sustainable	Greater efficiency with energy and resources, or introduce new materials and technology to reduce GHG and ground resources	Inundated C.I. and G.A.	For expanding and new C.I. and G.A. but cannot be determine for those tested with SLR scenario. There is no guarantee this will slow down SLR regionally.	
Sustainable	Promote environmental solutions	?	All sites, especially those in Marine Protected Areas of J1-J4. These solutions may be a more cost-effective and can act as a buffer for stronger waves and flooding however, it will require monitoring and maintenance and the impact is unknown.	
Resilient	Add redundancy measures	C.I. and G.A. with very low risk	Dependent on the type that will be used competence of the geology for support, cost, space and technical limitations.	
Resilient	Plan for response and recovery	C.I. and G.A. with low risk	Potentially for all C.I. and G.A. with low to medium risk. Any higher and another design needs to be used. Heavily dependent on cooperation of other stakeholders.	
Adaptive	Relocation	C.I. and G.A. with very low risk	Needed for all inundated facilities especially S.I.A. in Zone J3 at all scenarios, but will be determined by the cost, technical and practical feasibility and policy.	
Adaptive	Using new technology/ materials (e.g. floating structures or hydraulic jacks to raise structures)	C.I. and G.A. with very low risk	Dependent upon the cost, technical capacity and funding for use and maintenance, current and future ground conditions and buy-in from stakeholders	
Adaptive	Flexible and planned phased designs	Inundated C.I. and G.A.	For port terminals at risk. Potentially for oil and gas terminals.	Limited for airports and power plants and the oil refinery at risk.

5.3 Uncertainties and issues that need to be addressed in the designs

If conventional designs are to be used, whether for existing or new designs some things need to be addressed:

i. The non-inclusion of C.C. in their standards, L-A-R or parameters.
ii. The linear process of conventional design which encourage a reactive and inflexible response to C.C.
iii. If empirical and deterministic data will be used for designs, there must a reference point to measure and justify changes over time that will be used for decision-making.
iv. If all the geotechnical uncertainties and risks mentioned in Section 3.1 were never acknowledged, addressed and potentially reduced, their risks could be compounded and introduce additional risks even with designing for future projections of C.C.

If risk-based designs are to be used, whether for existing or new designs, the understanding of each of the three will require a consensus among all stakeholders and additional research and information will be needed. As indicated in bullet (iii) above a reference point will be needed for all to measure the success of each. However, concrete determinations on the applicability and suitability of both designs cannot be made. Tables 5-1 and 5-2 reveal that there are many interconnected factors and uncertainties both in and outside of design that must be addressed. They are:

1. **The current condition of the G.A.**

   Regardless of which type of design is implemented, the current ground conditions of the G.A. need to be determined. This is especially important for the islands studied as diverse geologies and other features will feed into design. Also, as promoted with resilient and adaptive designs, monitoring changes over time as well as improving knowledge on the potential impact the solutions or its surroundings have on one another and on current G.A. would be necessary to determine the applicability.

2. **Cost, Policy and buy-in from stakeholders**

   These factors are very important for the applicability and choice of design used. Questions arising in discussions concern the feasibility and long-term efficiency of implementation, when to implement solutions, government and private sector concerns and how new solutions will affect surrounding cities. Discussions with Mr. Harris and Ms. Nurse from the region indicated that the Caribbean's primary concern is disaster risk reduction for storms and earthquakes (Jamaica) and sinkholes (Barbados). Less attention is paid to long-term effects of C.C. such as SLR, which is valid because they are more frequent short-term hazards (Harris, 2020; Nurse, 2020). Additionally, continuous storm impacts may weaken structures at a faster rate.

   Political willpower could also be another factor. Caribbean governments generally have political terms of five years. If SLR is a long-term manifestation of C.C. with impact expectations by 2100 (next 80 years), there is no guarantee action will occur in the near term. However, it should be adequately timed, based on the findings of Chapter 4, to make plans for their C.I. and cities in advance.

   Additionally, uncertainties with climate data and science mentioned in Section 4.2.1.1, may not be acceptable to investors in the construction and maintenance of C.I. and may delay or curtail any of the conventional solutions used. However, that will be determined by the client and available funding which is most times aligned with maintaining the lowest possible cost. Even introducing new technology and materials in construction is novel and not normal which relates to the acceptance of risk-based solutions which are not widely accepted currently (Table 3-5 in Section 3.5). These factors pose one of the greatest threats to the applicability of both design types.

3. **Data and information used in designs**

   The quality, time frame and credibility of information available in designs are very important for determining solutions. In compiling the Caribbean information, it was found that much of the geologic, environmental and hydrometeorological data and hazard maps, were collected from internationally financed projects and were dated (e.g. geological maps from the early 1900s). It could be assumed, from limits to technical capacity, data and funding, that the data are not monitored vigorously as in the U.K. or U.S. where G.A.M. is being implemented. If the quality of information used in design is not reviewed, the designs may not apply. Additionally, if uncertainties in climate data and science (Section 4.2.1.1) are untreated, there is no guarantee that designed used will survive under new conditions.

4. **Technical and environmental limitations – is it practical?**

   The practicability and sustainability of implementing solutions will depend upon the unique characteristics of each country and additional regional considerations listed in Section 4.5. Both types of designs will have to be considered, but the best solutions for reducing public risk will take priority. The prioritisation will ultimately affect the sustainable designs. Locating and constructing new C.I. may not be financially and technically feasible in the short-term. Resilience may not be possible for fully inundated C.I. identified and limits to adapting by relocating or using novel technologies may apply from the limits on land, layout of cities and funding constraints.

5. **New Uncertainties**

   Within C.C., new climate phenomena and uncertainties are emerging. As recently as August 22, 2020 the first double-hurricane to exist within the Caribbean manifested. Stormquakes, rainbombs, multiple and new hazard events are being discovered and studied (Anon, 2019). Outside of C.C., projected changes in policy and funding, demographics and urbanisation, alternative energy, high-tech construction/advanced materials, rapid digital transformation and new technology, smart cities and new transport modes will have to be considered in designs (Global Infrastructure Hub et al., 2020).

A synergy between the conventional and risk-based approaches may be best. However, new uncertainties that will appear in the future make a stronger case for the application of the risk-based approach.

5.4 Potential role of the EnGeol for future designs

First to make a more meaningful contribution, their role on the design team should be elevated so that risks identified are not left to the geotechnical engineer for interpretation, but to project management for meaningful decision-making. Their role should no longer be limited to design but to one encompassing the life of the structure. EnGeol for the future would have to play a greater role in planning, site selection, monitoring, communicating, decision making and researching the effects of C.C. to make a meaningful contribution. As with the risk-based approaches, monitoring will be a key area for the EngGeol involvement.

The new climate phenomena outside of the challenges of investigating tropical geology (Section 4.1.3), will bring new challenges in the ground investigation. Conversations with Ms. Nurse indicated that in Barbados, the interface of seawater and freshwater, resulting from C.C. is already proving a challenge for the identification of sinkholes using geophysical equipment (Nurse, 2020). EnGeol will have to be at the forefront of working with multiple disciplines such as climate science and geophysics to develop new technologies and methods to manage future uncertainties. A more involved role in communication and decision making as mentioned in the example of the USGS activity during Hurricane Sandy (2012) may be necessary. Other areas where developments could be made are in the site investigation and research. Site investigations in the future may need to include the potential threats to the site over time or to categorise the uncertainties so that they can be better quantified through time. The relationship of other structures to the C.I. and how C.I. could impact them and thus in turn affect the C.I. under investigation will also be necessary.

6 CONCLUSION AND RECOMMENDATIONS

Testing the C.C. scenarios of SLR using components of a risk-based approach were helpful in identifying at-risk C.I. and G.A. on three Caribbean Islands. The scenarios tested showed SLR affected each country differently. Jamaica had the most vulnerable C.I. and most of the C.I. and G.A. investigated would be at risk from the median scenario of 2°C. Both conventional design and the risk-based approaches – sustainable, resilient and adaptive, could be useful for implementation in the Caribbean at various sites for all scenarios. To be truly applicable for the future, the structure of conventional design needs to change, current uncertainties must be addressed and the role of the EnGeol will need to diversify to better manage the uncertainties of the future.

Conventional designs do not incorporate C.C. and will not be able to effectively manage future risks in a timely manner, especially if they occur before predicted in the design life. For the risk-based approaches, the proactive identification of potential risks could be used to assist with decision making for all stakeholders, including EnGeol who need to be involved from as early as the planning stages to make the best decisions. However, uncertainties in the definition of the concepts, geotechnical components, climate science, variation in the geology of the Caribbean, current ground conditions, political and financial conditions of the Caribbean and other future uncertainties may reduce the effectiveness of designs and must be addressed.

The risk-based approach provides a framework to manage these uncertainties as they arise as it acknowledges that the most important component is not the identification of uncertainties and risks but how they will be tolerated and managed by society. The role of the EnGeol must be changed to include a more wholistic approach with the lifetime of a structure from the concept to demolition. They should play a greater role in not on the design of structures, but their protection and decision-making required, especially in the Caribbean, one of the most hazard-prone regions of the world. Some of their contributions outside of the design will involve the planning, monitoring and maintenance, decision making, research and communication.

As we plan for an uncertain future with many twists and turns an Engineering Geologist should be at the forefront to thrive both on the ground and a in world of uncertainty.

6.1 Recommendations for further research

Further research could be conducted to refine or build upon this study. Some are:

i. Investigating the relationship between isostacy and SLR in the Caribbean.
ii. Refining the risk assessments using financial information and updates on the quality of the G.A.
iii. Examining the role of EnGeol in these countries and the relationship between the designers and those tasked with the maintenance of the G.A.
iv. Assessing local design practices for both C.I. and the surrounding infrastructure to better understand the relationship among assets.
v. Applying other manifestations of C.C. such as extreme rainfall, storms of a certain magnitude etc. to the C.I. and G.A. of these countries.
vi. Assessing the effects of multiple hazards at weakening structures over time.

REFERENCES

Agence France-Presse 2019. Climate impacts ‘to cost world $7.9 trillion’ by 2050. *France 24*. [Online]. [Accessed 14 August 2020]. Available from: https://www.france24.com/en/20191120-climate-impacts-to-cost-world-7-9-trillion-by-2050.

Agravante, M. 2019. Climate change forces airports to future-proof against rising sea levels and floods. *INHABITAT*. [Online]. [Accessed 4 September 2020]. Available from: https://inhabitat.com/climate-change-is-forcing-major-airports-to-future-proof-against-rising-sea-levels-and-floods/.

Airport Engineering Division 2019. *Advisory Circular 150/5100-13C, Development of State Aviation Standards for Airport Pavement Construction, 12/6/2019* [Online]. [Accessed 18 August 2020]. Available from: https://www.faa.gov/airports/resources/publications/orders/.

Airport Engineering Division, F. 2016. *AC 150/5320-6F, Airport Pavement Design and Evaluations*.

Airports Council International 2018. *Airports’ Resilience And Adaptation To A Changing Climate Questions For Airports* [Online]. [Accessed 10 July 2020]. Available from: www.aci.aero.

Anon 2018. Caribbean has long pushed for 1.5°C — UWI scientists. *Jamaica Observer*. [Online]. [Accessed 31 August 2020]. Available from: http://www.jamaicaobserver.com/environment-watch/caribbean-has-long-pushed-for-1-5-c-uwi-scientists_147103?profile=1606.

Anon 2020. Coastal floods: Netherlands . *Climatechangepost.com*. [Online]. [Accessed 4 September 2020]. Available from: https://www.climatechangepost.com/netherlands/coastal-floods/.

Anon 2017. Hurricane Irma causes devastation in the Caribbean - BBC News. *BBC News*. [Online]. [Accessed 16 August 2020]. Available from: https://www.bbc.co.uk/news/world-latin-america-41182991.

Anon 2019. ‘Stormquakes’: Hurricanes and earthquakes can create hybrid natural disaster, study finds. *Associated Press*. [Online]. [Accessed 9 September 2020]. Available from: https://www.nbcnews.com/mach/science/stormquakes-hurricanes-earthquakes-can-create-hybrid-natural-disaster-study-finds-ncna1067756.

Argyroudis, S.A., Mitoulis, S., Winter, M.G. and Kaynia, A.M. 2019. Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience. *Reliability Engineering and System Safety*. **191**, p.106567.

ARUP 2010. *Highways Agency: A Risk-based based framework for geotechnical asset management Phase 2 Report*.

ARUP 2020. Services: Sustainable Buildings Design & Construction. [Accessed 4 September 2020]. Available from: https://www.arup.com/expertise/services/buildings/sustainable-buildings-design.

ASCE 2019. *Future World Vision: Infrastructure Reimagined*.

Atkinson, J. 2013. Where is the Zeitgeist of geotechnical engineering? Discussion in LinkedIn on behalf of Géotechnique Letters, groups-nore- ply@linkedin.com, 11:14.

Ayyub, B.M. (ed.). 2018. *Climate-Resilient Infrastructure : Adaptive Design and Risk Management* [Online]. Reston, VA: American Society of Civil Engineers. Available from: https://ascelibrary.org/doi/abs/10.1061/9780784415191.

Banton, J., Warner, P., Smith, D. and Morin, V. 2017. Selection of Appropriate Coastal Protection Strategies for Caribbean Coastlines *In*: *Coastal Structures and Solutions to Coastal Disasters 2015* [Online]. Reston, VA: American Society of Civil Engineers, pp.570–581. [Accessed 23 June 2020]. Available from: http://ascelibrary.org/doi/10.1061/9780784480304.061.

Barbados Climate Change 2017. Climate Change. [Accessed 7 September 2020]. Available from: https://climatechangebarbados.com/climate-change/.

Basu, D., Misra, A. and Puppala, A.J. 2014. Sustainability and geotechnical engineering: Perspectives and review. *Canadian Geotechnical Journal*. **52**(1), pp.96–113.

Baynes, F.J. 2010. Sources of geotechnical risk. *Quarterly Journal of Engineering Geology and Hydrogeology*. **43**(3), pp.321–331.

Beck, H.E., Zimmermann, N.E., McVicar, T.R., Vergopolan, N., Berg, A. and Wood, E.F. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Scientific Data*. **5**(1), p.180214.

Becker, A. and Bove, G. 2017. GIS Inventory and Risk Assessment for Critical Coastal Infrastructure Land Use in Caribbean SIDS *In*: *UNCTAD Regional Workshop 'Climate Change Impacts and Adaptation for Coastal Transport Infrastructure in the Caribbean', 5 – 7 December 2017, Bridgetown, Barbados* [Online]., pp.1–19. [Accessed 5 June 2020]. Available from: www.uschamberfoundation.org/blog/post/hurricane-.

Been, K. 2011. TC37 Interactive Geotechnical Design. *International Society For Soil Mechanics And Geotechnical Engineering*., pp.3791–3794.

Betterground (Hong Kong) Ltd. 1995. North Lantau Expressway, Tai Ho Section, Hong Kong. [Accessed 17 August 2020]. Available from: https://www.betterground.com/projects/north-lantau-expressway-tai-ho-section/.

Bleasdell, S.G., Cheong, E. and Tan, K.-S. 2008. *CSEC new integrated Geography*. [San Fernando Trinidad] ;San Fernando Trinidad: Caribbean Educational Publishers.

Bowden, R.A. 2004. Building confidence in geological models. *Geological Prior Information: Informing Science and Engineering. Geological Society, London, Special Publications*. (239), pp.157–173.

British Standards Institution 2013. *BS EN 199701:2004+A1:2013. Eurocode 7: Geotechnical design - Part 1: General Rules*.

British Standards Institution (BSI) 2007. Eurocode 7-Geotechnical design Part 2: Ground investigation and testing. BS EN 1997-2:2007.

Burillo, D. 2019. Effects of Climate Change in Electric Power Infrastructures *In*: *Power System Stability* [Online]. IntechOpen. [Accessed 7 September 2020]. Available from: www.intechopen.com.

Buxton, H., Andersen, M., Focazio, M., Haines, J., Hainly, R., Hippe, D. and Sugarbaker, L. 2013. *Meeting the Science Needs of the Nation in the Wake of Hurricane Sandy— A U.S. Geological Survey Science Plan for Support of Restoration and Recovery* [Online]. Available from: http://pubs.usgs.gov/circ/1390/.

Carbon Brief 2020. Interactive: The impacts of climate change at 1.5C, 2C and beyond. [Accessed 31 August 2020]. Available from: https://interactive.carbonbrief.org/impacts-climate-change-one-point-five-degrees-two-degrees/.

Caribbean Development Bank 2018. *Financing the Blue Economy: A Caribbean Development Opportunity | Caribbean Development Bank* [Online]. [Accessed 14 August 2020]. Available from: https://www.caribank.org/publications-and-resources/resource-library/thematic-papers/financing-blue-economy-caribbean-development-opportunity.

Caribbean Examinations Council 2009. Caribbean Secondary Education Certificate CSEC ® GEOGRAPHY SYLLABUS.

Caribbean Hurricane Network 2020. Atlantic Region - 5 year activity - Climatology of Caribbean Hurricanes - 1945-2019. [Accessed 31 August 2020]. Available from: https://stormcarib.com/climatology/ATLN_5year.htm.

Caribbean Regional Climate Centre n.d. Caribbean Climatology. *Caribbean Regional Climate Centre*. [Online]. [Accessed 17 June 2020]. Available from: https://rcc.cimh.edu.bb/caribbean-climatology/.

Cassady, D. and Achenbach, J. 2017. 'Why can't we get out of here?' Airports in Puerto Rico, other islands, damaged and slow to recover. *The Washington Post*. [Online]. [Accessed 16 August 2020]. Available from: https://www.washingtonpost.com/national/why-cant-we-get-out-of-here-airports-in-puerto-rico-other-islands-damaged-and-slow-to-recover/2017/09/27/44d83cb4-

a2e8-11e7-8cfe-d5b912fabc99_story.html.

Cementaid (UK) Limited 2020. Salt water and corrosion of reinforced concrete. [Accessed 7 September 2020]. Available from: http://cementaid.co.uk/salt-water-and-corrosion-resistant-concrete/.

Chang, I., Lee, M. and Cho, G.C. 2019. Global CO2 emission-related geotechnical engineering hazards and the mission for sustainable geotechnical engineering. *Energies*. **12**(13), p.2567.

Chen, A.A., Chadee, D.D. and Rawlins, S. (eds.). 2006. *Climate Change Impact on Dengue: The Caribbean Experience. Mona, Jamaica: University of the West Indies, Climate Studies Group, Mona.*

Christian, J.T. 2004. Geotechnical engineering reliability: How well do we know what we are doing? *Journal of Geotechnical and Geoenvironmental Engineering*. **130**(10), pp.985–1003.

Christian, J.T. and Asce, H.M. 2004. Geotechnical Engineering Reliability: How Well Do We Know What We Are Doing? 1.

CL Environmental Co. Ltd. 2014. *Environmental Impact Assessment: Phase 2 of the Palisadoes Rehabilitation and Shoreline Protection Project , Kingston*.

Climate Central 2020. Surging Seas: Mapping Choices. [Accessed 14 August 2020]. Available from: https://choices.climatecentral.org/#legal.

Climate Risk & Early Warning Systems (CREWS) 2020. CREWS Impact Feature, Earth Day 2020: Bridging the Gender Divide in Early Warning Access Across the Caribbean. [Accessed 14 August 2020]. Available from: https://eird.org/americas/news/earth-day-2020/.

Collins, T.J., Dhir, R.K., McCarthy, M.J. and Caliskan, S. 2015. Inspection Of Structures In The Marine Environment. *Concrete for Transportation Infrastructure.* ., pp.377–384.

Cybrary.IT 2020. Negative and Positive Risks . [Accessed 4 September 2020]. Available from: https://www.cybrary.it/study-guides/pmp-exam-study-guide/negative-and-positive-risks/.

DiChristopher, T. 2019. Climate disasters cost $650 billion over 3 years: Morgan Stanley. *CNBC News*. [Online]. [Accessed 14 August 2020]. Available from: https://www.cnbc.com/2019/02/14/climate-disasters-cost-650-billion-over-3-years-morgan-stanley.html.

Dino, G.A., Danielsen, S.W., Chiappino, C. and Engelsen, C.J. 2017. Recycling of rock materials as part of sustainable aggregate production in Norway and Italy. *Quarterly Journal of Engineering Geology and Hydrogeology*. **50**(4), pp.412–416.

Eberhardt, E. 2017. Lecture 1 : Introduction - Uncertainty and Design. EOSC433/536 Geological Engineering. University of British Colombia.

Eggers, M.J. 2016. Diversity in the science and practice of engineering geology. *Geological Society Engineering Geology Special Publication*. **27**(1), pp.1–18.

Eitner, V., Katzenbach, R. and Stolben, F. 2002. Geotechnical Investigation and testing - an outlook on European and International Standardisation *In*: Y. Honjo, O. Kusakabe, K. Matsui, M. Koda and G. Pokharel, eds. *Foundation Design Codes and Soil Investigation in View of International Harmonization and Performance Based Design: Proceedings of the IWS Kamakura 2002 Conference, Japan, 10-12 April 2002* [Online]. CRC Press, pp.211–215. Available from: https://books.google.co.uk/books?id=5hjGxxzhWjgC&pg=PA211&lpg=PA211&dq=international+geotechnical+standards&source=bl&ots=dA7nTr1Usf&sig=ACfU3U2Xcnz776VbUd9LUSmHujdtLSOEBA&hl=en&sa=X&ved=2ahUKEwih9oDy_efpAhUyTRUIHSWiB4oQ6AEwCHoECAsQAQ#v=onepage&q=internat.

Emmanuel, K. 2013. Build Better Jamaica Presentation at Caribbean Sch…. [Accessed 7 September 2020]. Available from: https://www.slideshare.net/BuildBetterJamaica/dr-kwame-emmanuel-build-better-jamaica-presentation-at-caribbean-school-of-architecture-april-25-2013.

Encyclopedia.com 2020. Chapter 13: Application of Geotechnical Instruments in Reclamation and Soil Improvement Projects. *Encyclopedia.com*. [Online]. [Accessed 17 August 2020]. Available from: https://www.encyclopedia.com/construction/trade-magazines/application-geotechnical-instruments-reclamation-and-soil-improvement-projects#A.

Federal Highway Administration (FHWA) 2008. Highway Embankments versus Levees and other Flood Control Structures . [Accessed 18 August 2020]. Available from: https://www.fhwa.dot.gov/engineering/hydraulics/policymemo/20080910.cfm.

Franco, E.G. 2020. *The Global Risks Report 2020 Insight Report 15th Edition*.

Gallego-Lopez, C., Essex, J. and (with input from DFID) 2016. *Designing for infrastructure resilience* [Online]. [Accessed 25 June 2020]. Available from: http://dx.doi.org/10.12774/eod_tg.july2016.gallegolopezessex2.

Ganin, A.A., Massaro, E., Gutfraind, A., Steen, N., Keisler, J.M., Kott, A., Mangoubi, R. and Linkov, I. 2015. Operational resilience: concepts, design and analysis OPEN. *Nature Publishing Group*.

Gibbs, M.T. 2012. Time to re-think engineering design standards in a changing climate: The role of risk-based approaches. *Journal of Risk Research*. **15**(7), pp.711–716.

Global Infrastructure Hub, World Economic Forum and Boston Consulting Group 2020. *Infrastructure Future Scenarios - Draft*.

Global Infrastructure Initiative 2018. *Voices on Infrastructure: Future-proofing infrastructure in a fast changing world*.

Google Earth Pro. 2020a. Satellite Map of the Caribbean. [Accessed June 5, 2020]

Google Earth Pro. 2020b. Satellite Map of Jamaica, St. Lucia and Barbados. [Accessed July 18]

Gopal, M. 2020. Sustainability in Construction & Civil Engineering. *TheConstructor.org*. [Online]. [Accessed 4 September 2020]. Available from: https://theconstructor.org/construction/sustainability-construction-civil-engineering/9492/.

Griffin, M. 2018. Types of Geotechnical Uncertainty. *LinkedIn*. [Online]. [Accessed 5 September 2020]. Available from: https://www.linkedin.com/pulse/types-geotechnical-uncertainty-martin-griffin-ceng-cgeol-rogep-/.

Griffiths, J.S. 2014. Feet on the ground: Engineering geology past, present and future. *Quarterly Journal of Engineering Geology and Hydrogeology*. **47**(2), pp.116–143.

Guha-Sapir, D., Below, R. and Hoyois, P. 2020. EM-DAT: The CRED/OFDA International Disaster Database. *EM-DAT: The Emergency Events Database - Université Catholique de Louvain, Brussels, Belgium*. [Online]. [Accessed 4 September 2020]. Available from: https://www.emdat.be/.

Harris, N. 2020. Conversation with Norman Harris. 18 August.

Hearn, G.J. and Shilston, D.T. 2017. Terrain geohazards and sustainable engineering in Ladakh, India. *Quarterly Journal of Engineering Geology and Hydrogeology*. **50**(3), pp.231–238.

Hencher, S. 2008. The ‘new’ British and European standard guidance on rock description. *Ground Engineering*. **41**, pp.17–21.

Henderson, D.R.. and Hooper, C.L. 2017. Flawed Climate Models . *Hoover Institution*. [Online]. [Accessed 31 August 2020]. Available from: https://www.hoover.org/research/flawed-climate-models.

Ingham, J., McKibbins, L. and Barnes, R. 2016. Chemical analysis for asset management of concrete infrastructure. *Infrastructure Asset Management*. **3**(3), pp.106–119.

IPCC 2018. *2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate c*.

Jamal, H. 2017. Acid Attack on Concrete. [Accessed 7 September 2020]. Available from: https://www.aboutcivil.org/acid-attack-on-concrete.html.

Jared, M.., Dupuis, S.T.., Goguen, P.. and Parsons, R.. 2018. Development of a Geotechnical Asset Management Program for the New Brunswick of Transportation and Infrastructure *In*: *2018 Annual Conference of the Transportation Association of Canada*., p.15.

Javadinejad, S., Eslamian, S., Ostad-Ali-Askari, K., Mirramazani, S.M., Zadeh, L.A. and Samimi, M. 2018. Embankments *In*: P. Bobrowsky and B. Marker, eds. *Encyclopedia of Engineering Geology. Encyclopedia of Earth Sciences Series* [Online]. Springer, Cham, pp.1–8. [Accessed 17 August 2020]. Available from: https://doi.org/10.1007/978-3-319-12127-7_105-1.

Kannan, R. 2017. Risk-Based Approach in Geotechnical Design. *Geotechnical Special Publication*. (GSP 283), pp.524–533.

Kansai Airports 2020. [KIX] Measures against unequal settlement. [Accessed 6 September 2020]. Available from: http://www.kansai-airports.co.jp/en/efforts/our-tech/kix/sink/hudou.html.

Keaton, J.R. 2013. Engineering Geology: Fundamental Input or Random Variable? *In*: *Foundation Engineering in the Face of Uncertainty* [Online]. Reston, VA: American Society of Civil Engineers, pp.232–253. [Accessed 23 June 2020]. Available from: http://ascelibrary.org/doi/10.1061/9780784412763.020.

Kelly, M. 2019. Unraveling What a Risk-Based Approach Means. *GAN Integrity*. [Online]. [Accessed 1 July 2020]. Available from: https://www.ganintegrity.com/blog/what-a-risk-based-approach-means/.

Kelsey, C. 2020. Implementation of Geotechnical Asset Management . *Geosynthetica.com*. [Online]. [Accessed 19 August 2020]. Available from: https://www.geosynthetica.com/geotechnical-asset-management-gap2019/.

Knittel, N. 2016. Climate Change Adaptation: Needs, Barriers and Limits. *Climate Policy Info Hub*. [Online]. [Accessed 5 September 2020]. Available from: https://climatepolicyinfohub.eu/climate-change-adaptation-needs-barriers-and-limits.

Legates, D.R. 2002. Limitations of Climate Models as Predictors of Climate Change. *National Center for Policy Analysis*. [Online]. [Accessed 31 August 2020]. Available from: http://www.ncpathinktank.org/pub/ba396.

Lin, W.-K. and Zhang, L. 2009. Limit state design example - Cut slope design *In*: Y. Honjo, M. Suzuki, T. Hara and F. Zhang, eds. *Geotechnical Risk and Safety: Proceedings of the 2nd International Symposium on Geotechnical Safety and Risk, Gifu, Japan, 11-12 June 2009* [Online]. London: Taylor & Francis Group, pp.159–164. [Accessed 30 June 2020]. Available from: https://books.google.co.uk/books?id=kzhOjdzLUzQC&pg=PA161&lpg=PA161&dq=define:+conventional+design+in+geotechnical&source=bl&ots=eXtyqpr1vl&sig=ACfU3U1eREvmTms7hmnl-xXi8deYPLUnHA&hl=en&sa=X&ved=2ahUKEwj62_iSi6rqAhUySEEAHZN4AF0Q6AEwCXoECAkQAQ#v=onepage&q=d.

Linham, M.M. and Nicholls, R.J. 2012. Adaptation technologies for coastal erosion and flooding: a review. *Proceedings of the Institution of Civil Engineers - Maritime Engineering*. **165**(3), pp.95–112.

Linkov, I. and Kott, A. 2018. Fundamental Concepts of Cyber Resilience: Introduction and Overview *In*: *Cyber Resilience of Systems and Networks*., p.8.

Masuda, M.Y. 2002. Condition Survey Of Salt Damage To Reinforced Concrete Buildings In Japan *In*: *Challenges of Concrete Construction: Volume 6, Concrete for Extreme Conditions* [Online]. Thomas Telford Publishing, pp.823–836. [Accessed 7 September 2020]. Available from: https://www.icevirtuallibrary.com/doi/abs/10.1680/cfec.31784.0080.

Mcclarthy, C. 2019. *Approaches to Disaster Risk Reduction & Climate Resilience at the Norman Manley International Airport (NMIA)*.

Mcsweeney, C., New, M. and Lizcano, G. 2012. *UNDP Climate Change Country Profiles: Barbados*.

Misra, A. and Basu, D. 2011. Sustainability In Geotechnical Engineering Internal Geotechnical Report 2011-2. *Technical Reports*.

Mitchell, S. 2013. Caribbean Geology Lecture Notes.

Monioudi, I., Asariotis, R., Becker, A., Bhat, C., Dowding-Gooden, D., Esteban, M., Feyen, L., Mentaschi, L., Nikolaou, A., Nurse, L., Phillips, W., Smith, D., Satoh, M., Trotz, U.O., Velegrakis, A.F., Voukouvalas, E., Vousdoukas, M.I. and Witkop, R. 2018. Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. *Regional Environmental Change*. **18**(8), pp.2211–2225.

Morgan, K. 2018. CARICOM moving to create the World’s first Climate Resilient Region in the year ahead – Incoming Chairman. *CARICOM Today*. [Online]. [Accessed 14 August 2020]. Available from: http://today.caricom.org/2017/12/31/caricom-moving-to-create-the-worlds-first-climate-resilient-region-in-the-year-ahead-incoming-chairman/.

Moriconi, G. 2007. Recyclable materials in concrete technology: sustainability and durability *In*: R. N. Kraus, T. R. Naik, P. Claisse and S.- Pouya, eds. *Sustainable construction materials and technologies, 11-13 June 2007 Coventry, Special papers proceedings., Pub. UW Milwaukee CBU* [Online]., pp.1–12. [Accessed 17 August 2020]. Available from: http://www.claisse.info/specialabstracts.htm.

Muench, S.T., Mahoney, J.P. and Pierce, L.M. 2003. The WSDOT Pavement Guide Interactive. *WSDOT, Olympia, WA.* [Online]. Available from: http://guides.ce.washington.edu/uw/wsdot.

Nadim, F. 2017. Reliability-based approach for robust geotechnical design *In*: *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul 2017* [Online]. Seoul, pp.191–211. [Accessed 1 July 2020]. Available from: https://www.iso.org/obp/ui/#iso:std:iso:guide:73:ed-1:v1:en.

Nadim, F. 2007. Tools and strategies for dealing with uncertainty in geotechnics *In*: *CISM International Centre for Mechanical Sciences, Courses and Lectures* [Online]. Springer International Publishing, p.72. [Accessed 5 September 2020]. Available from: https://link.springer.com/chapter/10.1007/978-3-211-73366-0_2.

Nathanail, J. and Banks, V. 2009. Climate change: implications for engineering geology practice. *Geological Society, London, Engineering Geology Special Publications*. **22**(1), pp.65–82.

National Center for Atmospheric Research 2020. Increased warming in latest generation of climate models likely caused by clouds. *Phys.org*. [Online]. [Accessed 31 August 2020]. Available from: https://phys.org/news/2020-06-latest-climate-clouds.html.

National Infrastructure Advisory Council 2009. *Critical Infrastructure Resilience Final Report and Recommendations*.

New Energy Events 2018. Caribbean Renewable Energy: Five Projects We're Watching in 2018 - New Energy Events. *Caribbean, CREF Market News, Industry Analysis*. [Online]. [Accessed 3 July 2020]. Available from: http://newenergyevents.com/caribbean-renewable-energy-five-projects-were-watching-in-2018/.

New Hampshire Coastal Risk and Hazards Commission 2016. *Preparing New Hampshire for Projected Storm Surge, Sea-Level Rise, and Extreme Precipitation* [Online]. Available from: http://www.nhcrhc.org/wp-content/uploads/2016-CRHC-final-report.pd.

Nicholson, P.J. and Bruce, D.A. 1992. Opportunities and constraints for innovative geotechnical contractor *In*: *Excavation and Support for the Urban Infrastructure* [Online]. New York: American Society of Civil Engineers (ASCE). [Accessed 14 August 2020]. Available from: http://www.geosystemsbruce.com/v20/biblio/z074 Opportunities and Constraints for the Innovative Geotech.pdf.

Nikolaou, S., Antonaki, N., Kourkoulis, R., Gelagoti, F., Georgiou, I. and Gazetas, G. 2017. Geotechnical Engineering Challenges in the Path to Resilient Infrastructure. *Geotechnical Special Publication*. (GSP 283), pp.206–215.

NOAA National Centers for Environmental information 2020. Climate at a Glance: Global Time Series. [Accessed 31 August 2020]. Available from: https://www.ncdc.noaa.gov/cag/global/time-series/globe/land_ocean/12/1/1945-2020?trend=true&trend_base=10&begtrendyear=1990&endtrendyear=2019.

Nurse, L.A., McLean, R.F., Agard, J., Briguglio, L.P., Duvat-Magnan, V., Pelesikoti, N., Tompkins, E. and Webb, A. 2014. Small Islands *In*: V. R. Barros, C. Field, D. Dokken, M. D. Mastrandrea, K. Mach, T. . Bilir, M. Chatterjee, K. Ebi, Y. . Estrada, R. . Genova, B. Girma, E. . Kissel, A. . Levy, S. MacCracken, P. . Mastrandrea and L. . White, eds. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Online]. New York, USA: Cambridge University Press, pp.1613–1654. [Accessed 14 August 2020]. Available from: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-Chap29_FINAL.pdf.

Nurse, N. 2020. Conversation with Nesha Nurse. 14 August.

Omotosho, P.O. 1991. Engineering Design in Developing Nations: Are Foreign Standards Adequate? *Journal of Professional Issues in Engineering Education and Practice*. **117**(4), pp.351–357.

Orr, T. 2012. Chapter 10: Codes and standards and their relevance *In*: *ICE manual of geotechnical engineering: Volume I* [Online]., pp.105–124. Available from: https://www.icevirtuallibrary.com/doi/abs/10.1680/moge.57074.0105.

Pantelidou, H., Nicholson, D. and Gaba, A. 2012. Chapter 11: Sustainable geotechnics *In*: *ICE manual of geotechnical engineering: Volume I* [Online]., pp.125–136. Available from: https://www.icevirtuallibrary.com/doi/abs/10.1680/moge.57074.0125.

Resilient Organisations Ltd. 2020. What is organisational resilience? [Accessed 5 September 2020]. Available from: https://www.resorgs.org.nz/about-resorgs/what-is-organisational-resilience/.

Rüdiger, E.-W., Bouali, E.H. and Oommen, T. 2018. Risk Assessments *In*: P. T. Bobrowsky and B. Marker, eds. *Encyclopedia of Engineering Geology*. Springer International Publishing, pp.757–758.

Russel, P.R. 2019. A Call to Action for Engineers on Climate Change. *Engineering News-Record*. [Online]. [Accessed 4 September 2020]. Available from: https://www.enr.com/articles/48389-a-call-to-action-for-engineers-on-climate-change.

Sjöstedt, M. and Povitkina, M. 2017. Vulnerability of Small Island Developing States to Natural Disasters. *The Journal of Environment & Development*. **26**(1), pp.82–105.

Skinner, H.D. 2012. Chapter 58: Building on fills *In*: B. John, C. Tim, B. Michael and S. Hilary, eds. *ICE manual of geotechnical engineering: Volume II*. Thomas Telford Ltd., pp.899–910.

Smith, A. 2019. PM Says Newly Commissioned LNG Terminal Will Reduce Energy Costs - Jamaica Information Service. *Jamaica Information Service*. [Online]. [Accessed 3 July 2020]. Available from: https://jis.gov.jm/pm-says-newly-commissioned-lng-terminal-will-reduce-energy-costs/.

Speed, R.C., Speed, C. and Sedlock, R. 2012. Geology and Geomorphology of Barbados. *The Geological Society of America, Special Paper*. (419), p.63.

Spink, T. 2020. Strategic geotechnical asset management. *Quarterly Journal of Engineering Geology and Hydrogeology*. **53**(2), pp.304–320.

Stevens, L. and Winter, J. 2012. Conventional vs . Sustainable : A Matrix for Decision Making *In*: *APWA National Sustainability Conference, 26 June 2012, Pittsburg, PA*.

Tal, J. 2018. America's Critical Infrastructure: Threats, Vulnerabilities and Solutions | Security Info Watch. *SecurityInfowatch.com*. [Online]. [Accessed 14 August 2020]. Available from: https://www.securityinfowatch.com/access-identity/access-control/article/12427447/americas-critical-infrastructure-threats-vulnerabilities-and-solutions.

Taneja, P. and Vellinga, T. 2018. Towards Sustainable Port Infrastructure Through Planned Adaptation *In*: *PIANC-World Congress Panama City, Panama 2018*., p.13.

Tang, A.M., Hughes, P.N., Dijkstra, T.A., Askarinejad, A., Brenčič, M., Cui, Y.J., Diez, J.J., Firgi, T., Gajewska, B., Gentile, F., Grossi, G., Jommi, C., Kehagia, F., Koda, E., TerMaat, H.W., Lenart, S., Lourenco, S., Oliveira, M., Osinski, P., Springman, S.M., Stirling, R., Toll, D.G. and Van Beek, V. 2018. Atmosphere-vegetation-soil interactions in a climate change context; Impact of changing conditions on engineered transport infrastructure slopes in Europe. *Quarterly Journal of Engineering Geology and Hydrogeology*. **51**(2), pp.156–168.

Taylor, M.A. 2015. *Why Climate Demands Change*. GraceKennedy Foundation.

Taylor, M.A., Clarke, L.A., Centella, A., Bezanilla, A., Stephenson, T.S., Jones, J.J., Campbell, J.D., Vichot, A. and Charlery, J. 2018. Future Caribbean climates in a world of rising temperatures: The 1.5 vs 2.0 Dilemma. *Journal of Climate*. **31**(7), pp.2907–2926.

The Rockefeller Foundation 2013. Resilient Buildings. [Accessed 5 September 2020]. Available from: https://www.rockefellerfoundation.org/blog/resilient-buildings/.

Toll, D.G. 2012. Chapter 30: Tropical soils *In*: J. Burland, T. Chapman, H. Skinner and M. Brown, eds. *ICE manual of geotechnical engineering: Volume I* [Online]. ICE Publishing Ltd, pp.341–361. Available from: https://www.icevirtuallibrary.com/doi/abs/10.1680/moge.57074.0341.

U.S. Army Corp of Engineers 2006. Shore Protection Projects *In*: *Coastal Engineering Manual - Part V*., pp.30–31.

U.S. Department of Transport Federal Highway Administration 2006. *NHI-05-037 - Geotechnical Aspects of Pavements Reference Manual* [Online]. [Accessed 18 August 2020]. Available from: https://www.fhwa.dot.gov/engineering/geotech/pubs/05037/03a.cfm.

UN n.d. Small Island Developing States. *Sustainable Development Knowledge Platform*. [Online]. [Accessed 7 September 2020]. Available from: https://sustainabledevelopment.un.org/topics/sids.

UNCTAD 2017a. *Climate change impacts on coastal transport infrastructure in the Caribbean: enhancing the adaptive capacity of Small Island Developing States (SIDS), Climate Risk and Vulnerability Assessment Framework for Caribbean Coastal Transport Infrastructure. UNDA*.

UNCTAD 2017b. *Climate Change Impacts on Coastal Transport Infrastructure in the Caribbean: Enhancing the Adaptive Capacity of Small Island Developing States (SIDS), JAMAICA : A case study. UNDA project 1415O*.

UNCTAD 2017c. *Climate Change Impacts on Coastal Transport Infrastructure in the Caribbean: Enhancing the Adaptive Capacity of Small Island Developing States (SIDS), SAINT LUCIA: A Case Study. UNDA project 1415O. For*.

United Nations Environment Programme, United Nations Educational, S. and C.O. and Intergovernmental Oceanographic Commission 1993. *Climatic Change in the Intra-Americas Sea: Implications of Future Climate on the Ecosystems and Socio-economic Structure in the Marine and Coastal Regions of the Caribbean Sea, Gulf of Mexico, Bahamas and the Northeast Coast of South America* [Online]. Edward Arnold. [Accessed 4 September 2020]. Available from: https://stg-wedocs-new.unep.org/handle/20.500.11822/29289.

US Agency for International Development (USAID) 2001. Kingston Metropolitan Area Seismic Hazard Assessment. *Caribbean Disaster Mitigation Project*. [Online]. [Accessed 24 June 2020]. Available from: https://www.oas.org/cdmp/document/kma/seismic/kma1.htm.

Vahedifard, F., Williams, J.M. and Aghakouchak, A. 2018. Geotechnical Engineering in the Face of Climate Change: Role of Multi-Physics Processes in Partially Saturated Soils. *Geotechnical Special Publication*. **2018**-**March**(GSP 295), pp.353–364.

Vardon, P.J. 2019. Editorial: Soil–atmosphere interaction. *Environmental Geotechnics*. **6**(6), pp.320–322.

Vessely, M., Robert, W., Richrath, S., Schaefer, V.R., Smadi, O., Loehr, E. and Boeckmann, A. 2019. *Geotechnical Asset Management for Transportation Agencies, Volume 1: Research Overview*. Transportation Research Board.

Wason, A.T. 1998. *Buildings and Infrastructure Project: A Case Study of Caribbean Infrastructure Projects that have Failed Due to the Effects of Natural Hazards* [Online]. [Accessed 16 August 2020]. Available from: https://www.oas.org/cdmp/document/failinfr.htm#Intro.projstudied.

Weeks, J. 2013. Failure Becomes an Option for Infrastructure Engineers Facing Climate Change - Scientific American. *Scientific American*. [Online]. [Accessed 14 August 2020]. Available from: https://www.scientificamerican.com/article/failure-becomes-an-option-for-infrastructure-engineers-facing-climate-change/.

Wilkinson, E., Twigg, J. and Few, R. 2018. *Briefing note Building back better A resilient Caribbean after the 2017 hurricanes*. London.

World Meteorological Organisation 2020. *Global Annual to Decadal Climate Update - Target years: 2020 and 2020-2024* [Online]. Available from: https://hadleyserver.metoffice.gov.uk/wmolc/WMO_GADCU_2019.pdf.

APPENDICES

Appendix A: How Conventional Design incorporates the risk-based Approach

Attempts to incorporate a risk-based approach into conventional design include:

1. Combining probabilistic methods and deterministic approach to generate the "worst-case scenario, best-case scenario and most-likely scenario" used in slope stability.
2. Updating designs with risk assessments but only after knowledge and experience increases and a reliable design parameter can be assigned.
3. Using semi-quantitative or qualitative risk assessments of geological hazards through hazard maps and/or risk registers, but not fully outlined in conventional design. These maps and registers benefit risk communicating but do not consider changes over time. Furthermore, if the EnGeol communicate ground uncertainties and hazards qualitatively, its translation and quantification are left to the geotechnical engineer, introducing a loss of/misinterpretation of information in the process adding another risk to the project.

Appendix B: Comprehensive information on the history, geology and hazards of each C.I. on the selected islands by zone.

Table B-1: Description of each C.I. in Jamaica.

ZONES	C.I.	History and Current State	Geology/Geological History	Historical and Current Hazards	Other Considerations
J1	Airport (NMIA) & Port Royal Cruise Ship Port	Airport completed in 1948. Elevation: 3-7m asl. Runway: asphalt and concrete; Port constructed in 2019 with a floating pier at what used to be an Old Coal Wharf (used from the 1800s). Elevation: 4-5m asl.	Alluvium Soils over possibly Coastal Group Limestone. Alluvium soil from inland rivers that connected offshore islands via a spit complex. Alluvium 10-30m thick and comprised of peat clays, fine sand, silt and gravels. Published densities: 1.7-2.3; 1.7; 1.76-1.92 g/cm^3. Airport built on engineered fill. The fill was 2.4 to 7m thick hydraulic fill of fine to medium-grained sand and gravel with a trace of shell fragments. Ground improvement methods such as conventional compaction and surcharge were used. Underlying the engineered fill, the soil consists of 1.5 to 6 m of organic silt, fine sand and varying proportions of decayed vegetation (soft, compressible soil). Port - upper 1m of soils is compacted sands and gravels (west) and compacted marl to the (east).	Earthquake in 1692. 1907 earthquake (liquefaction, evidence of fissuring, subsidence and differential settlement). Hurricanes, storms and storm surges mainly 1772 hurricane (5m storm surge) and Hurricane Ivan 2004 (2m storm surge with damage to coastal dunes and vegetation). Airport: Potential scour of embankments and earthworks (Mcclarthy, 2019)	Located in the Palisadoes and Port Royal Protected Area (PPRPA). Bordered by the Kingston Harbour, 7th largest natural harbour in the world. Protected by vegetation, dunes and cays in the protected area.

ZONES	CI	History and Current State	Geology/Geological History	Historical and Current Hazards	Other Considerations
J2	Port of Kingston; Oil Refinery; 4 Power plants	Current port design constructed from 1975; Refinery constructed 1964; 2 power plants over 40 years old and 2 constructed in the 1990's. Buildings 2-17m above sea level.	Soils are non-engineered fill (2 power plants), engineered fill (Refinery and ½ Port of Kingston) located on the Liguanea Alluvial Fan (2 power plants and ½ Port of Kingston). Alluvium soil and engineered fill as above with low permeability and transmissivity with an upper unconfined aquifer and a lower confined aquifer. Static groundwater measured in 1996 is average 2m bgl on alluvium.	Earthquakes and threat of liquefaction as above. Fluvial flooding, subsidence from groundwater extraction, hurricanes and tsunamis/seiche. No record of storm surge.	Protected by the Palisados spit complex, shallow cays below the spit complex and shallow areas within the harbour from deep-water waves.
J3	Airport - SIA	Completed 1947. Elevation: 1-7m asl. Runway is asphalt. Important for tourism industry.	Built on an engineered platform made of well-compacted marl on what used to be a large mangrove-lined lagoon. Below are consolidated soils comprising of marine calcareous sands and silty sand upon a thick sequence of coastal reef platform. Ground water typically 3 feet bgl. A near vertical fault runs parallel to the airport and separates the platform from the limestone hills to the south that belong to the Montpellier Formation (White Limestone Group).	Threats: hurricane force winds, storm surge, earthquakes and flooding from storm events. Coastal flooding and wind damage from Hurricanes Allen (1980) and Gilbert (1988). Heavy rainfall normally induces urban flooding (low lying and close to drain lines and wetlands). The 1957 earthquake (magnitude of 6.5) damaged buildings. Reclaimed land susceptible to liquefaction.	Located within the Montego Bay Marine Park. Lowest airport in the Caribbean.

ZONES	CI	History and Current State	Geology/Geological History	Historical and Current Hazards	Other Considerations
J4	LNG terminal, Oil terminal, Montego Bay Cruise Ship Port	On land 2-3m asl. Cruise ship port constructed in the 1970’s. LNG terminal commenced operations in 2016.	Located on dredged and reclaimed land constructed in 1967. Reclaimed land is 3.7 million cubic meters of marine coralline rock and sand dredged and used to fill (and connect) several mangrove islands, marshland and peat. The soil is sandy/coralline in texture with little clay/loam content (very pervious and has a low erosion potential). High water table. Potential underlying swamp and marsh deposits are still relatively loose and compressible and have a low bearing capacity.	Minor subsidence has been observed in the surrounding area. High-water table the sand layers have a high probability of liquefying during a major earthquake event.	
J5	Power Plant	Completed 2003. Upgraded for LNG.	Quaternary Alluvium, typically interbedded loose unconsolidated gravels, sand, clays and organic matter (Plate 3-2). The bearing capacity varies from moderate (0.3MPa) to a low of (0.08MPa) especially where organic material is present.	Susceptible to all hazards but no records found.	Protected from the coast with a sewage treatment plant and mangroves.

Sources: Mcclarthy (2019); Reports from the Airports Authority of Jamaica; Reports from Environment Impact Reports from the National Environment and Planning Agency (NEPA); Reports from the Jamaica Public Service; Reports from the Port Authority of Jamaica; USAID, (2001).

Table B-2: Description of each C.I. in St. Lucia by zone.

ZONES	C.I.	History and Current State	Geology/Geological History	Historical and Current Hazards
L1	Airport (HIA) Port Vieux	Airport completed 1941. Elevation: 5-10m asl. The runaway in HIA took its present shape in the 1950s and the river course around the airport has changed since then.	Made Ground on top of potentially coarse sand (Alluvial Beach Terrace) on top of clay (lagoonal) for HIA. Nearby groundwater measured at 1.7m bgl. Soil map for Port Vieux indicates made ground atop basalt andesite agglomerated tuff.	Control tower inundated during flooding in December 2013. Deposition of silt debris continued more than a week. Flash flood risk map shows airport is susceptible to flooding from a 1:5 (154.0 mm - 3.25 hrs) and 1:20 (247.2 mm in 5.5 hrs) rainfall event. Located in an area with low landslide risk but landslides impacted connecting roads to and from the airport during Hurricane Tomas. No experience of flooding due to storm surge but classified as medium level threat of coastal flooding.
L2	Airport (GFLCA); Castries Port; Power plant; oil terminal	Airport completed 1950. Elevation: 5-13m asl.	Clay, agglomerates and silty clay soils for oil terminal and power plant. Alluvial beach and terrace (GFLCIA) and Basalt agglomerate underlying the Castries Port. Agglomerate tuffs (oil terminal) and andesite ash altered (power plant).	Flooding at GFLCIA due to storm surge by Hurricane Tomas (2010) and Hurricane Dean (2006). Inundation (10-30cm) occurred at part of runaway and control towers. Sometimes small inundation by heavy rainfall due to poor drainage. Approximately 20-25% of the airport is at risk of a 1:5 (154.0 mm - 3.25 hrs) or 1:10 (197.8 mm in 4.42 hrs) rainfall event. Low risk of landslides from Susceptibility Map

Sources: Geological and soil maps of St. Lucia; The Caribbean Handbook for Risk Information Management (CHARIM) Database; UNCTAD, (2017c).

Table B-3: Description of each critical infrastructure in Barbados by zone.

ZONES	C.I.	History and Current State	Geology/Geological History	Historical and Current Hazards
B1	Airport (GAIA)	First paved runway 1956; Runway: asphalt Elevation: 50-57m asl.	Thin friable dark brown sandy CLAY. Overlying coral limestone located below the first high cliff coral rock terrace; soil rich in lime and phosphates. Terrace overlies oceanic rock (sandstone, clays and marls exposed in the north-eastern Scotland District).	Very low risk of landslides, coastal flooding and riverine flooding. Located within proximity to mapped sinkholes as limestone is heavily karstified.
B2	Bridgetown Port, 2 Power plants, 1 oil terminal	Port commissioned 1961; Power plants commissioned 1967 and 1990. Elevation: 1-9m asl.	Black-dark grey sandy CLAY. The clay is smectoid (swelling) and formed from weathered coral and ash fall overlying coral limestone. Contains 4% organic content and low in soluble phosphates. Port constructed on reclaimed land in 1956-60, 1978 and in 2002. All overly oceanic rock as above.	Risk from flash flooding - transfer through steep karst gullies from the second and first high cliff in the Northeast, exacerbated by undersized and blocked drains. Susceptible to a 1:100-year storm events storm surge.

Sources: Geological and soil maps; Hazard maps for sinkholes and flooding; Information from Barbados Light and Power Company; Speed et al. (2012); Nurse (2020).

Appendix C: Relationship between RCPs and Global Temperatures

RCPs are based on radiative force values corresponding with 2.6, 4.5, 6, and 8.5 Wm^{-2} respectively, tied to the concentration of carbon dioxide (CO_2). Table C-1 projections for RCPs with respect to emissions, temperature and SLR.

Table C-1: Explanation and estimated temperatures and sea level rise by 2100 using RCPs with a baseline of 1981-2005. (IPCC, 2013)

RCP Scenarios	Explanation and emissions by 2100	Global warming by 2100 using range 2081-2100	Conversion to other temperature ranges	Global SLR using range 2081-2100
2.6	Strict measures, no emissions by 2100. CO_2-equivalent concentration of 420 ppm	0.3-0.17 ^{0}**C** (Avg. 1.0^{0}**C**)	For reference period of 1850–1900 add 0.61 °C; For reference period 1980–99 add 0.11 °C.	0.26-0.55m (Avg. 0.4m)
4.5	Median greenhouse gas emissions. Co_2-equivalent concentration of 540 ppm	1.1-2.6 ^{0}**C** (Avg. 1.8)		0.32-0.63m (Avg. 0.47m)
6.0	Median greenhouse gas emissions. Co_2-equivalent concentration of 660 ppm	1.4-3.1 ^{0}**C** (Avg. 2.2^{0}**C**)		0.33-0.63m (Avg. 0.48m)
8.5	High greenhouse gas emissions. Co_2-equivalent concentration of 940 ppm	2.6-4.8 ^{0}**C** (Avg. 3.7^{0}**C**)		0.45-0.82m (Avg. 0.63m)

Appendix D: Two temperature change projections developed using the full CMIP5 ensemble for Caribbean climate change projections

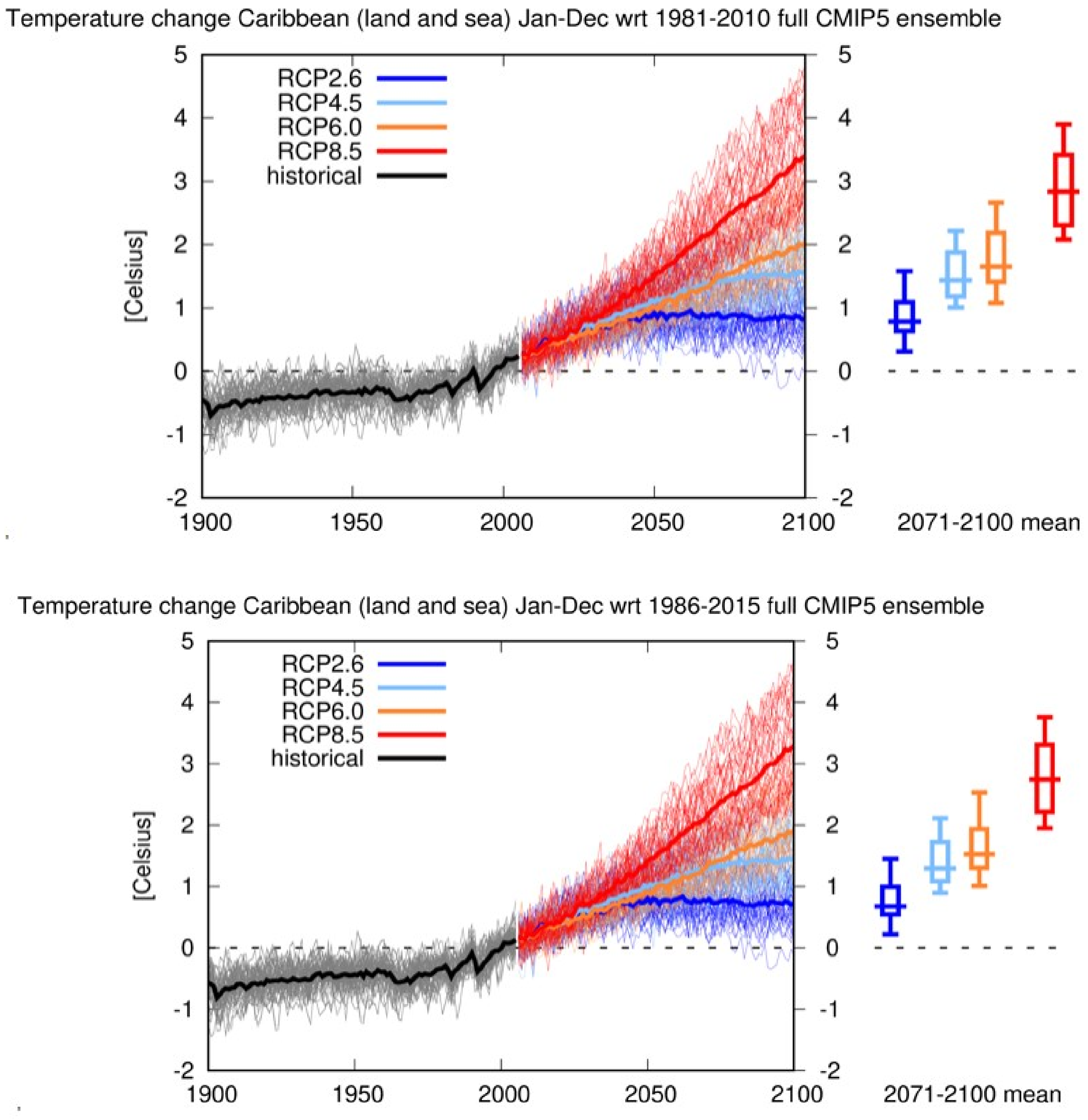


Figure D-1: Climate projections for the Caribbean based on RCP's generated using the full CMIP5 ensemble on from KNMI Climate Change Atlas. Diagrams show that the projections vary based on which time period is selected.

Appendix E: Risk Matrix for the Impact of SLR Scenarios on G.A. of Selected Islands

E-1: Risk for G.A. Jamaica at SLR scenarios of 1.5°C and 2.0°C.

Zones	C.I.		SLR at 1.5° C					SLR at 2.0° C				
	No.	Type	Type of G.A. impacted	Potential Impact	Prob-ability	Conse-quence	Risk	Type of G.A. impacted	Description	Prob-ability	Conse-quence	Risk
J1	2	Airport (F&G, Em, Pv)	F&G; Em	Sea defense breached but runway not affected. Increased scour, erosion and water infiltration			Low	F&G, Em, Pv	Approx. 50% of the airfield and some other facilities inundated. Increase in scour, erosion, infiltration and slope instability.	High	Very High	High-Very High
		Seaport (F&G)					Very Low					Very Low
J2	6	Seaport (F&G; Em)	F&G; Em	Parts of the port are inundated; will affect slope stability. Increased erosion and scour			Medium	F&G; Em	Approx. 30% inundated; increased erosion, scour, overtopping and slope instability	High	Medium-High	Med-High
		5 Energy Facilities (F&G; Fdn)		Nearby sea defences not breached	Low	Very Low	Very Low	F&G; Fdn	Part of the refinery breached and one part inundated; 2 power plants inundated. Increased erosion and scour, saltwater intrusion and chemical attack on foundations. Stability of non-engineered fill at risk	Medium-High	Medium-High	High
J3	1	Airport (Pv; F&G; Em)	Pv; F&G; Em	Airport fully inundated	High	Very High	Very High	Pv; F&G; Em	Completely inundated. Increased pore pressures in subgrade, increased erosion, scour, slope stability issues	High	Very High	Very High
J4	3	Seaport (F&G; Em)	F&G; Em	Mostly inundated	High	Very High	Very High	F&G; Em	Completely inundated. Increased erosion, scour, slope stability issues	High	Very High	Very High
		2 Energy Facilities (F&G; Em)	Em	Not inundated but adjacent port is. Increased erosion and scour of sea walls. Potential for infiltration.	High	Low-Medium	Medium	F&G; Em	Completely inundated. Increased erosion, scour, slope stability issues, potential for contamination if not moved.	High	Very High	Very High
J5	1	Energy Facility (Fdn)		Not inundated.			Very Low		Not inundated.			Very Low

E-2: Risk for G.A. Jamaica at SLR scenarios of 3.0°C.

Zones	C.I.		SLR at 3.0° C				
	No.	Type	Type of G.A. impacted	Description	Probability	Consequence	Risk
J1	2	Airport (F&G, Em, Pv)	**F&G, Em, Pv**	**Completely inundated and cut off from the mainland**	High	Very High	**Very High**
		Seaport (F&G)	**F&G**	**Completely inundated and cut off from the mainland**	High	Very High	**Very High**
J2	6	Seaport (F&G; Em)	**Fdn; Em**	**Completely inundated**	High	Very High	**Very High**
		5 Energy Facilities (F&G; Fdn)	**F&G; Fdn**	**Approx. 50 % of the refinery inundated - Fdn subject to chemical attack; 2 power plants completely inundated. Increased erosion and scour, saltwater intrusion and chemical attack on foundations.**	High	Very High	**High to Very High**
J3	1	Airport (Pv; F&G; Em)	**Pv; F&G; Em**	**Completely inundated. Increased pore pressures in subgrade, increased erosion, scour, slope stability issues**	High	Very High	**Very High**
J4	3	Seaport (F&G; Em)	**F&G; Em**	**Completely inundated. Increased erosion, scour, slope stability issues**	High	Very High	**Very High**
		2 Energy Facilities (F&G; Em)	**F&G; Em**	**Completely inundated. Increased erosion, scour, slope stability issues, potential for contamination if not moved.**	High	Very High	**Very High**
J5	1	Energy Facility (Fdn)		**Not inundated.**			**Very Low**

E-3: Risk for G.A. St. Lucia and Barbados at SLR scenarios of 1.5°C and 2.0°C.

Zones	C.I.		SLR at 1.5° C					SLR at 2.0° C				
	No.	Type	Type of G.A. impacted	Potential Impact	Prob-ability	Conse-quence	Risk	Type of G.A. impacted	Description	Prob-ability	Conse-quence	Risk
L1	2	Airport (PV, F&G), Seaport (F&G; Em)		Potential erosion of the beach and raised area in front of the airport	Very Low	Very Low	Very Low	F&G & Em	Airport: Coastline breached but pavement not affected. There may be saltwater intrusion. Wave action and erosion probably increased. For the seaport around 10% of the loading and unloading area was breached and is inundated. The cargo terminal appears to be safe. Increased load on part of the F&G. Potential to introduce protection/move inland	High	Low-Medium	Medium
L2	4	Airport (Pv; F&G		Potential increase in erosion but not near the airport	Low	Very Low	Very Low	F&G	Sea defences breached and a small part of the southwest is inundated. Pore pressures, overtopping and erosion may increase and affect the subgrade nearby	High	Medium	Med-High
		Seaport (Em; F&G)	Em; F&G	Water breaches a small part (~5%) of the cruise and container terminals. Potential increase in infiltration, pore pressures, erosion, toe instability and scour.	High	Medium	Med-High	Em; F&G	Over 50% of the container terminal is inundated but about 10% of the cruise terminal is inundated. Greater potential for increase in infiltration, pore pressures, toe instability, erosion and scour.	High	Med-High	High
		2 Energy Facilities (Fdn)		Potential increase in erosion at the coastline but facilities at a higher elevation. Potential for saltwater intrusion and chemical attack but unknown.	Low-Medium	Very Low	Very Low - Low		Same as at 1.5°C.	Low-Medium	Very Low	Very Low
B1	1	Airport (Pv)		Increased erosion of the coast but far from the airport and the high elevation of the airport (52m) prevents the pavement from being affected.	Very Low	Very Low	Very Low		Same as at 1.5°C.	Very Low	Very Low	Very Low
B2	4	Seaport (Em; F&G)	Em; F&G	Approx. 10% of seaport terminal inundated. Overtopping Em; increased scour and erosion and pore pressures. Can affect slope stability.	High	Low-Medium	Medium	Em; F&G	Approx. 20% of seaport terminal and pier inundated. Increased pore pressures, erosion, scour; can affect slope stability	High	High	High
		3 Energy Facilities (Fdn)		Potential infiltration of seawater but not near the plants from visual observation	Very Low	Very Low	Very Low		Same as at 1.5°C.	Very Low	Low	Very Low

E-4: Risk for G.A. St. Lucia and Barbados at SLR scenarios of 3.0°C.

Zones	**C.I.**		**SLR at 3.0° C**				
	No.	**Type**	**Type of G.A. impacted**	**Description**	**Probability**	**Conse-quence**	**Risk**
L1	2	Airport (PV, F&G), Seaport (F&G; Em)	**Pv, F&G, Em**	**Approx. over 50% of the cargo terminal is inundated. Increased load from sea water. Potential groundwater intrusion that may affect foundations of port buildings located further inland. Potential for cargo terminal to be moved**	High	High	**High**
L2	4	Airport (Pv; F&G	**Pv; F&G**	**Approx. 50% of the runway is inundated**	High	High	**High**
		Seaport (Em; F&G)	**Em; F&G**	**All container facilities inundated. Only 30% of the cruise terminal is inundated. High increase of infiltration, toe instability, erosion and scour.**	High	Very High	**Very High**
		2 Energy Facilities (Fdn)		**Same as at 1.5°C.**	Low-Medium	Very Low	**Very Low**
B1	1	Airport (Pv)		**Same as at 1.5°C.**	Very Low	Very Low	**Very Low**
B2	4	Seaport (Em; F&G)	**Em; F&G**	**Completely Inundated. Pore pressures increase. Potential increase in erosion and scour; can affect slope stability.**	High	Very High	**Very High**
		3 Energy Facilities (Fdn)	**Fdn**	**Water nearby but most C.I. not touched; 1 power plant inundated. Will need to be moved. Potential damage to foundations**	Low	Low-Medium-High	**Medium**

Appendix F: Conventional Plans to mitigate SLR

Current conventional plans for coastal infrastructure in response to C.C., namely SLR, include using climate projections to construct higher land, increasing worst-case scenario events designed, building protective sea walls, introducing better and higher capacity drainage systems and constructing physical barriers (Agravante, 2019). Even though these solutions would utilize climate projections, they are still based on using the features of conventional design. Some of these solutions have also already been introduced in the Caribbean. Implementation of these plans include:

1. **Constructing higher land/raising embankments** – e.g. Jamaica where the in-road to the N.M.I.A. was raised from 0.5-1m to 3–4m and added 3.7km "revetments" boulders and barricades to protect the raised road as a response storms damage 2004 to 2007. This was to protect the airport as well as C.I. within Zones J1 and J2 (CL Environmental Co. Ltd., 2014).
2. **Increasing Worst-Case Scenario Design Lives** – e.g. Norway where the minimum acceptable safety standard for coastal flooding is a 1 in 10,000-year event unlike the normally used 1 in 50-year or 1 in 100-year events (Anon, 2020).
3. **Building Protective Sea Walls** – e.g. San Francisco International Airport in 2019 where a protective seawall and interlocking steel sheet piles to accommodate 3 feet of sea level rise, plus another two feet for storm waves.
4. **Introducing Better and Higher Capacity Drainage Systems and Constructing physical barriers** – e.g. Singapore’s Changi Airport where draining facilities are being upgraded. Levees, tidal gates, holding ponds and pumping stations will be used as barriers as well as raising the road level surrounding the airport to act as a levee for district level flood protection, and act as a fixed flood barrier (Airports Council International, 2018).

These four methods would utilise and/or impact all the types of G.A. mentioned and could be useful in addressing the at-risk areas. However, the feasibility is questionable in the Caribbean context. First, all solutions would be very expensive for Caribbean economies and would most likely require external funding. Additionally, using the listing of additional considerations in Section 4.7 their feasibility may be limited. The Table below compiles the possible application and suitability of these plans.

Table: Potential application of current methods for C.I. and G.A. investigated.

Recommended Conventional measures to design for SLR	Where possibly NOT NEEDED	Where it possibly COULD WORK	Where it possibly COULD NOT WORK
Construct Higher Land	At 1.5°C - Nearly all zones except J3, J4 and the Seaport at J2. At 2.0°C - Most C.I. in Zones L1, L2, B1 and B2 except seaports, and Zone J5	Potentially at all seaport terminals with medium or higher risk and at airports in zones L1 and L2.	• Potentially at J2, J3, J4, B2. J2 and J4's engineered fill overly organic material with some indication of subsidence recorded at J4. As J3 was reclaimed wetland there is the potential of organic material the foundation soil. • All within and underground structures e.g. drainage, foundations, etc. would have to be redesigned. • J2 and B3 is located within capital cities and any changes may have to be implemented for the entire city.
Increasing Worst-Case Scenarios in the design		For the expansion/upgrading of all C.I. and their G.A. This will be dictated by policy, cost, technical feasibility and information available to determine what event can be designed.	
Building Protective Sea Walls		For all facilities with Medium-High risk in Table. However, as all islands are surrounded by the sea, the feasibility of this may not be practical in the long-term and may have a negative impact on the natural environment.	
Introducing Better and Higher Capacity Drainage Systems		For all medium or higher risk facilities though cost and practicality will determine feasibility. Information is needed on the current and expected capacity to and maintenance of the drains are important for its functioning.	
Constructing Physical Barriers		For all medium or higher risk facilities though cost and practicality will determine feasibility. The physical barrier may also have an impact on the surrounding coastline and ecosystem and may be problematic for Zones J1-4 which are in Marine Protected Areas.	