# A multi-hazard cascading risk model for coastal rail infrastructure:

numerical modelling & engineering failure analysis

A thesis submitted for the degree of

Doctor of Philosophy

by

**Keith Atkinson Adams**

Brunel University
Department of Civil Engineering
College of Engineering, Design and Physical Sciences
Kingston Lane, London, UB8 3PH

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# A multi-hazard cascading risk model for coastal rail infrastructure

**Keith Atkinson Adams**

**Abstract**

The February 2014 extratropical cyclonic storm chain, that impacted the English Channel (UK) and Dawlish in particular, caused significant damage to the main railway connecting the southwest region to the rest of the UK. The incident caused the line to be closed for two months, £50 million of damage and an estimated £1.2bn of economic loss. This incident highlighted the urgent need to understand the cascading nature of multi hazards involved in storm damage and their impacts on coastal railway infrastructure.

This study focuses on the Dawlish railway where a seawall breach caused two months of railway closure in 2014. I used historical and contemporary data of severe weather damage and failure analysis to develop a multi-hazard risk model for the railway. Twenty-nine damage events caused significant line closure in the period 1846–2014. For each event, hazards were identified, the sequence of failures were deconstructed and a flowchart for each event was formulated showing the interrelationship of multiple hazards and their potential to cascade. The most frequent damage mechanisms were identified: (I) landslide; (II) direct ballast washout and (III) masonry damage. I developed a risk model for the railway which has five layers in the top-down order of: (a) Trigger (storm); (b) force generation; (c) common cause failure; (d) cascading failure and (e) network failure forcing service suspension.

Armed with the multi-hazard cascading risk model, I go on to collate eyewitness accounts, analyse sea level data, and conduct numerical modelling in order to decipher the destructive forces of the storm. My analysis reveals that the disaster management of the event was successful and efficient with immediate actions taken to save lives and property before and during the storm. Wave buoy analysis showed that a complex triple peak sea state with periods at $4-8$ s, $8-12$ s, and $20-25$ s was present, while tide gauge records indicated that significant surge of up to 0.8 m and wave components of up to 1.5 m amplitude combined as likely contributing factors in the event. Significant impulsive wave forces were the most likely the initiating cause of the damage. Reflections off the vertical wall caused constructive interference of the wave amplitudes that led to increased wave height and significant overtopping, our numerical simulations suggesting up to 16.1 $m^3/s/m$ (per meter width of wall). With this information and using engineering judgment I conclude that the most probable sequence of multi-hazard cascading failure during this incident was: wave impact force leading to masonry failure, loss of infill, and failure of the structure following successive tides.

The multi-hazard cascading risk model developed in this research is applicable for other infrastructure under a variety of natural hazards. Examples are presented in this research. Given the current global climate emergency and sea level rise, it is expected that the results of this work will provide an important contribution to infrastructure resilience to natural hazards.

Supervisors: Dr.Mohammad Heidarzadeh & Professor Mizi Fan

# Acknowledgements

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Undertaking a project in Coastal Engineering, with a background in Earthquakes and Disaster Management would, you think, prepare me for a disaster event - like for instance, a global pandemic. Suffice to say, studying an academic subject and living through a real world event are two totally different things. I would like to thank everyone that supported me through the middle section of my PhD study, during lockdown, with all the contingent stress that they too were having to deal with. Although the pandemic somewhat curtailed my plans for time abroad at other research groups, I feel that the output from the project is still academically strong and resilient.

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Keith Adams
Hatfield
October 2022

# Contents

# Declaration

The work in this thesis is based on research carried out at the Department of Civil Engineering, College of Engineering, Design and Physical Sciences, Brunel University, London, England. No part of this thesis has been submitted elsewhere for any other degree or qualification, and it is the sole work of the author unless referenced to the contrary in the text.

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# Abbreviations

**BL** British Library

**BODC** British Oceanography Data Centre

**CCO** Channel Coastal Observatory

**CFD** Computational Fluid Dynamics

**DM** Damage Mechanism

**DRR** Disaster Risk Reduction

**FPW** Failure Pathway

**ICE** Institution of Civil Engineers

**MSL** Mean Sea Level

**NOC** National Oceanography Centre

**NR** Network Rail

**SDR** South Devon Railway

**SLR** Sea Level Rise

**SWL** Still Water Level

**TNA** The National Archives

**UK** United Kingdom of Great Britain and Northern Ireland

**WWII** World War II - 1939-1945

Chapter 1

# Introduction

## 1.1 Background

The British Isles sit at the north-western tip of the European continent bounded to the west by the eastern North Atlantic Ocean and to the south-west by the Celtic Sea and the Bay of Biscay. The climate of the UK is characterised as temperate, without dry season, with warm summer according to the Köppen-Geiger climate classes (Beck [9]). A significant influence on the climate of western Europe is the Gulf stream which has the effect of keeping temperatures much warmer than the latitudes would suggest (O'Hare [95]). In winter, powerful storms form over the Atlantic Ocean and blow towards western Europe, these energetic extra-tropical cyclonic storms are often responsible for widespread flooding of coastal areas and sometimes significant infrastructure damage (Higgs [51]). Impending projected Sea Level Rise (SLR), increased storminess and rainfall (UKCP18 [129]) has the potential to overwhelm aging Victorian infrastructure along the UK coastal margins and increase vulnerability to meteorological induced hazards.

The United Kingdom has nearly 16,000 km of open rail routes [97] with a significant proportion of coastal alignment. Most of these are strategically important as they often are the only regional rail connection, or they provide logistical support to critical national infrastructure. For instance, the Cumbrian line in the lake district in north-west England (Fig.1.1c and d), is a vital link providing public transport as well as freight capacity to the nuclear reprocessing plant at Sellafield. The area is a UNESCO world heritage site and a major tourist destination [91]. In Wales, the south and west coastal railways (Fig.1.1d) were instrumental in providing infrastructure to support the coal mining and shipping businesses of the nineteenth century [80]. Where coastal railways are subject to direct wave action, they are particularly vulnerable to climate change effects including sea level rise (SLR) and increases in storminess and rainfall [79]. Recent studies have indicated that there is a 20% increase in the number and intensity of storms [98, 70] while Castelle et al. [20] showed that the winter-mean wave height has increased in recent years. The latest marine climate projections for the UK [129] predict mean sea level rise between 0.39 m and 0.70 m by 2100 dependant on emission scenarios. Network Rail, the infrastructure owner in the UK, has acknowledged weather resilience and climate change as a major risk to future operations, and in response has produced a series of adaptation plans. The latest is the “Second Climate Change Adaptation Report” [88], with a third due in 2021 [110]; the organisation has also contributed to the “Tomorrow’s Railway and Climate Change Adaptation”research programme [113].

The winter of 2013-14 saw extensive inland and coastal flooding in the UK and a series of storms in February, in particular, led to significant coastal infrastructure damage (Masselink et al. [75, 74]). The section of railway between Exeter and Newton Abbott, UK (Fig.1.1a) is particularly vulnerable to climate change effects. In 1845, a vertical seawall was built along the coastal margin to support the railway alignment in Dawlish [106]. Soft red sandstone cliffs were blasted along the coastline, with the unconsolidated material used to backfill the area between the cliff face and the frontage of the masonry seawall. Following the second report by Beeching [12], this section of railway became part of the Great Western mainline strategically connecting London to the south west of England. This sole vital economic link was broken during the February 2014 storm when successive deep extra-tropical cyclonic storms caused strong winds, violent waves [75] and storm surge effects to cause structural failure on the seawall (Fig.1.1, Fig.4.2, Fig.4.5d) and precipitated a route closure that lasted two months [87]. The cost of reinstatement was £50m with associated economic losses estimated at up to £1.2bn for the South West region [100]. The rebuilding and reinforcement of the seawall has persisted from the event in 2014 to today in 2022 and will extend beyond this timescale. It is this failure, and a desire to understand the processes involved that have led to this research project.

Contemporary reporting of the seawall failure by national press in the UK, and the contingent effects on the local and regional communities affected pointed towards a multi-factorial causation. Consequently, I decided to investigate the events leading to the failure of the seawall with the purpose of proposing a multi-hazard risk model with cascading failure pathways as a means of explaining the nature of the failure and the mechanisms involved. Such a model would be useful for other similar coastal transport infrastructure systems both in the UK and further afield.

I aim to extend the usefulness of the risk model by using it, in combination with historical archival research and contemporary eye-witness accounts, to explain the life cycle of the seawall particularly with regard to its history of significant failure events. I then use modern Computational Fluid Dynamics (CFD) methods and original engineer's records to model the sea conditions during the real life storm events of early February 2014 and their effect on the infrastructure.

The purpose of these efforts, is to understand the magnitude of forces exerted on the seawall and to postulate a likely cause of the failure event.

## 1.2 Objectives

This thesis presents research into the development and application of a multi-hazard cascading risk model for coastal railway transport infrastructure. The main aims of the research are:

1. Develop a qualitative understating of storm-related risks to coastal infrastructure through a critical evaluation of the existing literature.
    a) Evaluate the range of existing models for coastal defence structures.
    b) Assess the existing models for aspects of multi-hazard applicability.
    c) Review the current state of art for cascading risk and the integration of this concept in risk analysis.
2. Develop a multi-hazard risk model integrating the ideas of cascading failure for applicability to a case study site.
    a) To investigate the historical record of failures for the South Devon rail line especially with regards to the vertical seawall built by Brunel in 1845-46.
    b) To identify the full range of hazards that were activated during an example failure at the case study site.
    c) To investigate the cascading nature of these failures and how they interact to increase the risk.

d) Consider the applicability of the developed model for use in other contexts.

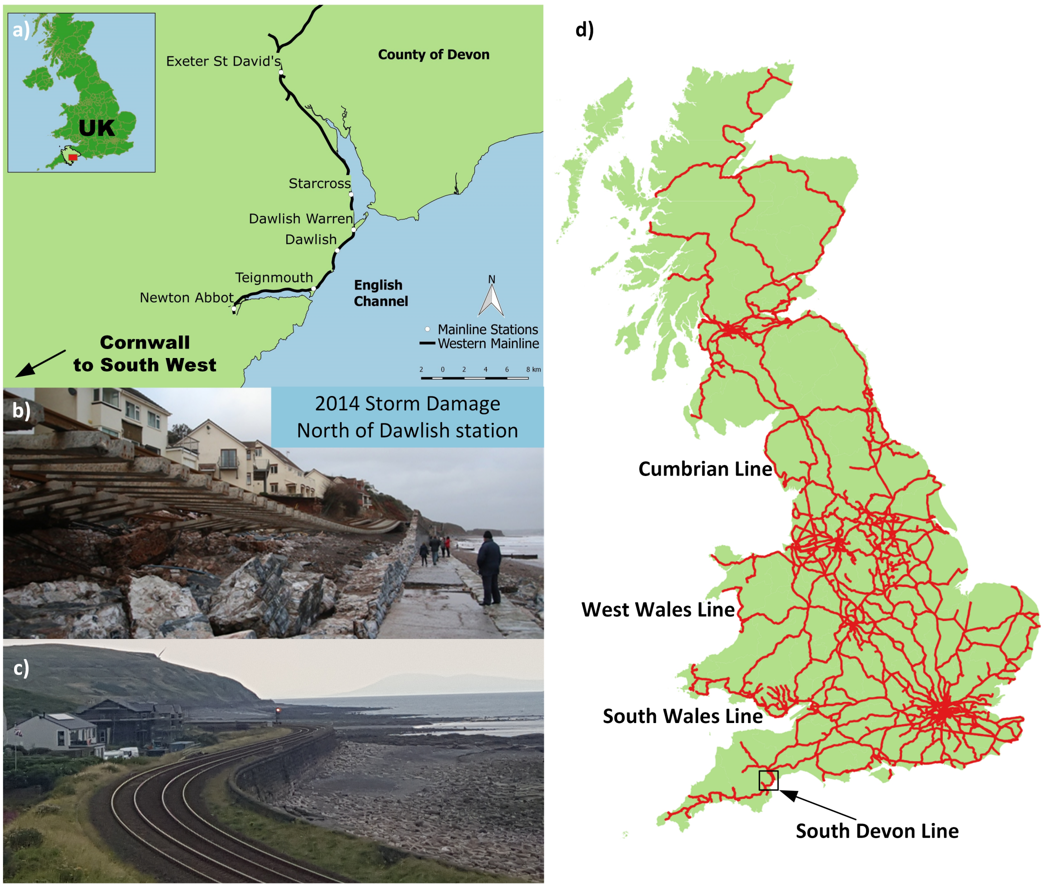



**Figure 1.1:** a) The location of the railway at Dawlish. b) Major damage after the February 2014 storm (©Matt Clark, Met Office UK). c) The coastal railway near Sellafield in Cumbria. d) Map of Great Britain showing the extent of coastal railways (red lines).

3. Investigate wave structure interaction for the case study site using the full range of data available through numerical modelling.

    a) Obtain, process and analyse realtime information for wave and tide levels pertaining to the case study site.

    b) Design a numerical model based on actual wall geometry and then to recreate wave and tide environment during a storm event.

    c) Evaluate the model outputs and compare with established empirical relationships in order to reconstruct the likely cause of critical infrastructure failure.

## 1.3 Structure of the Thesis

**Chapter 2** gives a critical review of the literature related to the main areas of research in this thesis. Section 2.1 addresses specifically the areas related to cascading risk models and their genesis and introduces the concept of risk as a product of the hazard, vulnerability and exposure for an engineered asset. Section 2.2 reviews the literature with regards to sea level data analysis, how I remove erroneous data, extract signals using frequency band filters and ensure security of the data. Section 2.3 looks at numerical modelling. A summary is given of the research needs I have highlighted in this project in Section 2.4 as a result of this critical review. In Section 2.5 These research needs are further distilled into a series of research questions and sub elements that will enable the production of a multi-hazard risk model and its application to a real life case study. I discuss the use of numerical modelling techniques to recreate the hydrodynamic pressures that a seawall was likely to experience during a specific storm event. I use these outputs to propose the likely damage mechanisms and failure pathways that were responsible for a network disruption.

**Chapter 3** details the data and methods used throughout the study. Section 3.2 looks at the historical and contemporary sources of data available and how they were used in this study in order to detail a complete history of failure of a vertical seawall in South Devon from construction to the failure in 2014. Section 3.3 details the methodology I used to produce a table of damage incidents detailing both qualitative and quantitative data for each event. Section 3.4 sets out how I used existing fault tree and failure mode and effect analysis to fit the observed damage patterns and how I used engineering judgement to infer intermediate failure paths consistent with the historical record. Section 3.5 gives the results of a data collection procedure for eye witness accounts of the 2014 seawall failure incident and a methodology for relating these observations into engineering analysis and probable causes. Section 3.6 details the data and methodology pertaining to sea level and wave climate data analysis and Section 3.7 goes on to explain the numerical modelling and validation approaches to the work.

**Chapter 4** focuses on the development of the cascading multi-hazard risk model for the railway at Dawlish in South Devon, detailing the analysis of historical records of damage in Section 4.2, the formulation of the risk model in Section 4.3 and an analysis of the damage mechanisms proposed in Section 4.4. Application of the proposed model is demonstrated for two incidents in the compiled history of the seawall in Section 4.5 where individual damage mechanisms and failure pathways are explained. Section 4.6 discusses the general application of the model along with its limitations and proposes the potential flexibility of the model for other hazard events. Finally in Section 4.7 I offer concluding remarks in the form of a synopsis of the model development and detail the main findings of the research.

**Chapter 5** is dedicated to the numerical modelling and reconstruction of the seawall failure event, in Section 5.2 I discuss the eye witness accounts and analyse their engineering correlations. Section 5.3 frames the sea level observations and spectral analysis of data to hypothesise the potential cause of observed wave profiles and concludes that the most probable cause of prolonged period waves observed in the data is a long swell wave coming from a distant source - consistent with a large scale storm event. Section 5.4 emphasises the numerical simulations I conducted on the seawall given the real time analysed data. I derive the wave loading and overtopping calculations and compare these with empirical relationships from other sources. I conclude with Section 5.5 where I detail the main findings of the simulations and analyse the evidence to suggest the most likely initiating cause of failure of the seawall.

**Chapter 6** concludes the report by giving an overview of the thesis in Section 6.1, detailing the main conclusions of the project in Section 6.2 and outlining limitations and opportunities for future work in the final Section 6.3.

## 1.4 Research Outputs

Some of the work presented in this thesis has been published in journals and conference proceedings - the relevant publications are listed below.

# Publications

**Peer-reviewed journal articles:**

1) K. Adams and M. Heidarzadeh. 'A multi-hazard risk model with cascading failure pathways for the Dawlish (UK) railway using historical and contemporary data'. *International Journal of Disaster Risk Reduction* 56.102082 (2021). DOI: doi.org/10.1016/j.ijdrr.2021.102082

2) K. Adams and M. Heidarzadeh. 'Extratropical cyclone damage to the seawall in Dawlish, UK: eyewitness accounts, sea level analysis and numerical modelling'. *Nat Hazards* (2022). DOI: doi.org/10.1007/s11069-022-05692-2

# Conference Proceedings

1) K. Adams and M. Heidarzadeh. 'A risk model for the vulnerability of UK's south Devon coastal railway due to storm-related hazards.' (2019, January). In *Geophysical Research Abstracts* (Vol. 21).

2) K. Adams and M. Heidarzadeh. 'Developing fragility curves for vital coastal infrastructure following extreme storms and sea level rise: A case study from Dawlish, UK.' (2021). *American Shore and Beach Preservation Association, 2021 National Coastal Conference "Geaux Resilent".* Hybrid In Person and Online.

3) K. Adams and M. Heidarzadeh. 'Recreating a disaster: how extratropical storms finally buried Brunel's historic seawall' (2022) *Coastal Sediments 2023: Inclusive coastal science and engineering for resilient communities.*

Chapter 2

# Literature Review

## 2.1 Cascading Risk Models

The relatively young body of academic literature in multi-hazard studies and cascading failures has attracted a wide vocabulary for similar concepts as reviewed extensively by Tilloy et al. [127], in this work the authors discuss not only terminology but also methods of modelling and quantification of risk used by different academic disciplines. Differences of language used in Disaster Risk Reduction (DRR) studies by diverse academic disciplines has led to an effort for harmonisation in terminology as identified by Kappes et al. [60] and more recently Monte et al. [82]. For clarity I define the terms used in this thesis in Table 2.1.

Risk (R) is defined by the Intergovernmental Panel on Climate Change [57] as the product of hazard (H) and consequence (C):

$$R = H \times C \tag{2.1}$$

In this context consequence is the compound effect of the risk, expressed in context of the area of interest. So for example, the consequence of seismic risk maybe the extent of health effects, immediate and longer lasting or of business

**Table 2.1: Disaster Risk Reduction (DRR) nomenclature used in this thesis where not explicitly defined elsewhere in the text.**

| Terminology | Definition | Reference |
|---|---|---|
| Risk | Risk can be defined as a function between hazard and vulnerability, which can provide answers regarding the preparation (or not) of an individual, community, or system. | [82] |
| Multi-hazard risk | The term multi-hazard risk refers to the risk arising from multiple hazards. By contrast, the term multi-risk would relate to multiple risks such as economic, ecological, social, etc. | [60] |
| Cascading | "...one type of phenomena can clearly be distinguished: the triggering of one hazard by another, eventually leading to subsequent hazard events. This is referred to as cascade, domino effect, follow-on event, knock-on effect, or triggering effect." | [60, 28, 18] |
| Vulnerability | Vulnerability can be defined as the state of community fragility and the system in which it lives based on its physical, social, cultural, economic, technological, and political aspects, thereby diminishing all capacities. Whereas the vulnerability of transport systems is commonly assessed in terms of physical vulnerability of its components depending on the physical characteristics of the infrastructure assets, e.g. age, material, structural types, and functional vulnerability depending on the functional characteristics of the network, e.g. capacity and speed. | [82, 10] |
| Capacity | Capacity and coping capacity are defined as the ability of a system to be protected from a vulnerability by its stakeholders, through existing measures of prevention and mitigation etc. | [18] |
| Resilience | The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions. | [57] |
| Damage Mechanism (DM) | Each force generated by the triggering event or initiating hazard scenario gives rise to a damage mechanism, which links the force to the structural vulnerability (represented as a common cause failure and a cascading failure). Each Damage Mechanism (DM) consists of one or more failure pathways. | |
| Failure Pathway (FPW) | The path force is transmitted through the structural elements giving rise to failure which has the potential to cascade between separate damage mechanisms. | |
| Exposure | The presence (location) of people, livelihoods, environmental services and resources, infrastructure, or economic, social, or cultural assets in places that could be adversely affected by physical events and which, thereby, are subject to potential future harm, loss, or damage. | [82, 57] |
| Disaster | A disaster of natural origin can be considered the "materialization" of risk or the product of interactions between natural phenomena and individuals, communities, or systems in a given area and time that causes a rupture in social well-being and requires external assistance. | [82] |

interruption as a result of the hazard event. Civil and Structural Engineers often define risk by expanding the definition of consequence as the product of structural vulnerability (V) and exposure (E) [22, 132]:

$$R = H \times V \times E \tag{2.2}$$

Where vulnerability is considered, but not explicitly in the structural engineering context, the concept of capacity should be considered. The United Nation Development Programme (UNDP) define capacity as "... the existing strengths of individuals and social groups. They are related to people's material and physical resources, their social resources, and their belief and attitudes. Capacities are built over time and determine people's ability to cope with crisis and recover from it." [104] - in this way the relationship between a communities capacity to resist, plan and recover from a disaster and their vulnerability is implicitly linked.

Combining the hazard and vulnerability of engineering assets, respecting the intrinsic link between hazardous force generation and propensity for damage as represented by structural vulnerability, is an approach adopted by Cardona et al. [17] as a prerequisite for determining how meteorological extremes contribute to disasters. Indeed, Cardona et al. [17] highlight the dependence of varying temporal and spatial scales to the vulnerability and exposure metrics and highlight the dynamic nature of their interactions. The benefit of this approach, is that the exposure has been decoupled from the structural vulnerability. This allows multiple stakeholders to interrogate the model using their own exposure metrics to provide tailored evaluations of overall risk (e.g. insurance providers for loss quantification, Network Rail (NR) for maintenance and capital expenditure and local authorities for disaster risk planning).

The challenges of analysing multi-hazards have been comprehensively reviewed and discussed by Kappes et al. [60] and more recently Tilloy et al. [127]

who make the relation between multi-hazard analysis and the objective of risk reduction. In the first multi-hazard approach, the authors argue that the idea of relevance is of prime importance in a defined area (the all-hazards-at-a-place approach) [50] (Table 2.1). In their second "thematically defined" approach Kappes et al. [60] introduce the idea of multi-hazard as "one hazard that triggers a second process" and go on to argue that one event may cause multiple threats.

Holistic treatment of multi-hazard risk (Table 2.1) is important, not least because "hazards are related and influence each other" [60], hence the idea of hazard chains or cascades [124, 71, 59]. The idea of hazard events having a cascading effect on interlinked systems has recently been developed and reviewed by Pescaroli et al. [103] and Pescaroli [101] in the area of emergency risk management while Huggins et al. [56] has recently reviewed the cascading effects due to rain-related incidents. Climate change has been linked to increased severity of hazard events, an example being the 2022 work by Huang and Swain [55] where increased risk of mega-flood conditions are explicitly linked to extreme storm sequences, a phenomenon I have associated with the 2014 floods in the UK and the subject of this study.

For a transportation system such as a coastal railway, which is subject to multi-hazard risk scenarios, the potential for cascading effects is amplified - especially when the network is critical infrastructure. Recent work by Fekete [32] has analysed critical infrastructure and cascading effects and discusses the links with climate change adaptation with obvious links to my work where Sea Level Rise (SLR) on coastal margins has the potential to accentuate storm surge and flooding events. Indeed, elements of failure which may cascade have the effect of increasing the severity of a disaster event, this effect is explored extensively with respect to tsunami hazards and critical infrastructure by Suppasri et al. [121]

where diverse hazards are activated via the concept of escalation points during a hazard event.

In terms of civil engineering infrastructure, Gardoni and LaFave [36] assert that mitigation of risk must account for the impact of combined natural and anthropogenic hazards, and that remedial strategies should account for infrastructure life cycles taking into account aging and deterioration. This idea of a dynamic vulnerability, as the hazard evolves and the assets age, is developed by Gill and Malamud [39] who define cascades as interaction networks of hazard and detail the need to include these interactions in any multi-hazard risk framework.

A generalised multi-hazard risk model for coastal infrastructure damage was proposed by Heidarzadeh et al. [48] for Dominica in the aftermath of Hurricane Maria and for Japan following the 2016 Typhoon Lionrock [49]. Although these works included seawall and subsequent road damage, they did not deal with a complex interconnected and dense transport infrastructure like the UK rail network or detail the specific structural components of the infrastructure concerned. Similarly, Mase et al. [72] analysed the climate change effects on earthen dyke reliability and proposed a generalised model of Failure Pathway (FPW), however these were exclusively based on wave overtopping rates as a surrogate of total force generation and detailed only linear FPW. This approach may prove simplistic for a complex rail network built on an historic masonry structure.

For a cascading series of events, using only wave overtopping to describe force transfer means failure mechanisms not associated with wave energy maybe missed. Gill and Malamud [38] discuss the spatial overlap and temporal likelihood of natural hazard interactions.

Inherent in the approach of Pescaroli and Alexander [102] is the acceptance that cascading events may involve damage to many disparate naturally occurring and man-made networks so increasing their overall effect. Van Eeten et al. [131] discuss the multi-hazard nature of cascading failures across critical infrastructure and contend that their occurrence is much more common than originally thought. Zscheischler, Martius and Westra [139] recently introduced the idea of compound events defined as a combination of multiple drivers and hazards which are responsible for many of the most severe weather and climate related impacts. The formation of an integrated hazard and vulnerability model for the civil engineering infrastructure of the coastal railway at Dawlish is highlighted as a research need for the purposes of this study.

## 2.2 Sea Level Data Analysis

When studying hydrodynamic effects of sea on critical coastal infrastructure it is important to understand the constituent elements of sea state in order to take account of all the contributing factors that may have an effect on static and dynamic pressures felt by the structures impacted. For clarity I have defined the main terms relating to sea level in Table 2.2.

A critical review of the analysis of sea data for the purposes of this project has been split into two distinct and complimentary sections.

1. **Tide Gauge Records:** These are some of the oldest records of systematic sea-level monitoring in the world and consist of (a) historical paper records for a handful of UK ports from 1830 onwards and (b) digital records to present day. They aim to give a relative indication of water levels at a location at a particular point in time with the aim to study the patterns of tidal cycle variation (see Hogarth et al. [53]).

2. **Wave Buoy Data:** This typically high frequency real time data ($\approx 1Hz$) is produced as a result of instruments moored in the ocean and in coastal areas and provide wireless transmission of high quality wave environment data onshore. Modern wave buoys can monitor individual wave heights based on displacement measurements as well as directional information thanks to a set of accelerometers and magnetic compass.

## Tide Gauges

A brief history of the UK tide gauge network is available in Woodworth et al. [137] who additionally outline the main value of the tide gauge asset. In terms of civil engineering infrastructure and for this thesis, the main attributes can be defined as providing:

- Determination of the heights of extreme sea levels for coastal engineering design.
- Production of precise tidal prediction.
- Provision of flood warning during periods of high tide and storm surge.

The processing of tide gauge data is an important step in understanding the evolution of long trend changes such as sea level rise and storm surges with various projects having been recently undertaken to digitise and process historical data. Murdy, Orford and Bell [83] automatically digitised long duration analogue records from the Belfast (UK) harbour tide gauge with the aim of completing a 110 year record for the site. The aim of this work was to allow the study of decadal and century long changes in tide levels in order to document the variation in mean sea level and historical storm surges. The work produced a consistent annual-based legacy data series with over 2 million data points. More recently a UK tides citizen science project, organised by the National Oceanography Centre (NOC), utilised 3,800 volunteers to transcribe handwritten tide data from two sites in Liverpool with records dating from 1853-1903. The data is currently undergoing quality control processing with the computed tidal records being made available for future sea level change studies [136].

Long term tidal data can provide a useful tool in analysing historical storm surge and other long period wave phenomena. Indeed, Goring [41] has applied a methodology for separating long period waves from tidal signals and applied them to example applications for meteorologically generated long waves (rissaga), far infragravity waves and tsunami. For purposes of clarity, I refer to the definition of ocean waves given by Holthuijsen [54]. The processes used by Goring can be simplified as:

1. Detiding
2. Despiking
3. Degapping
4. High Pass Filtering
5. Denoising

Detiding involves removing the tide from the signal as typically it represents more than 90% of the variance of tidal data, the output from this step is a non-tidal residual which contains long period oscillations (>2 weeks), storm surges (>1.5, <14 days), remnant tides (4-24 hours) and short period oscillations (1 - 240 minutes).

Despiking - Spikes in tide gauge records are usually either transmission errors or reflections from targets in the sea other than the sea surface. It is important to detect and eliminate them since they are high frequency phenomenon that contaminate the record.

Degapping - where telemetry faults cause data dropouts, or where spikes have been eliminated, the gaps produced need to be filled for high-pass filtering and denoising. Linear interpolation between adjacent good data is the normal procedure. Indexes of gaps are recorded to allow subsequent reintroduction if the signal is required.

High-Pass Filtering involves, preferentially, the use of orthogonal wavelet decomposition for non-stationary data this ensures any remnant tide as well as longer period fluctuations are removed.

Denoising of the non-tidal residual is essential to ensure the long-wave signal is not being obscured by noise caused by instrument error and residual swell waves (Periods of 8s to 20s) aliased to the long wave signal.

These steps are similar to the adopted approach as outlined later (see figure 3.4) with two main differences - firstly since the data underwent a quality control procedure before publication I opted to despike and degap the data before the detiding step - I did this to ensure the tidal fitting package I used would have minimal error in estimating the tidal components and secondly instead of a separate denoising step, I analysed the detided residual signal for variations and estimated an error margin for the predictions (see Section 3.6).

Storm surge is a long period wave with approximate duration of a few hours to a few days ([73, 94]), and have been correlated to the duration of the storms that are responsible for their formation [54]. Typically these storms are characterised as tropical or extra-tropical cyclones in the northern hemisphere and are observed as a change in water levels rather than a surface water wave and in extreme cases can cause flooding, disruption to coastal activities and death (for example: Fritz et al. [35], Gerritsen [37] and Holthuijsen [54]).

In circumstances where small increases in still water levels are significant in relation to the available freeboard (that is the height of the crest of the wall above the Still Water Level (SWL)) at a coastal defence structure, such as a vertical seawall, it is important to quantify the observed surge component of a storm as it has a direct impact on the amount of seawater which may overtop the structure (wave overtopping). This calculated surge component is highlighted as a key research need for this project.

### Wave Buoys

The recent measurement of waves was catalysed in Europe following the damaging tidal surges of 1953, which claimed many lives in UK, Germany and Netherlands - it was this event which led to the development of the sea dykes in the Netherlands and the Thames Barrier in the UK (both still in operation 70 years later). Although rudimentary work had been conducted on wave measurements during World War II - 1939-1945 (WWII) by Sverdrup and Munk [122, 123] these focused on visual observations; meanwhile in the UK, at the same time, a series of pressure transducers moored at 40 feet water depth were used for measurement of dynamic pressures allied to wave height which led Cartwright and Longuet-Higgins [19] to postulate the theoretical statistical distribution of wave heights. Following the end of WWII and the devastating results of the 1953 North Sea storm surge, methods for automatic measurement of wave heights were developed. One of the first by C. M. Verhagen in the Netherlands led to the formation of Datawell BV in 1961, a company now producing directional wave buoys worldwide.

Wave buoys are sea borne moored instruments which record the passing of waves by measuring the vertical heave of the wave profile by using an ac-

**Table 2.2: Sea level nomenclature used in this thesis where not explicitly defined elsewhere in the text.**

| Terminology | Definition | Reference |
|---|---|---|
| Sea Level | Sea level refers to the vertical change in the height of the sea surface which occurs over all time and space scales from many different mechanisms (including waves, seiches, tides, storm surges, tsumamis, etc.), with tides being the most predictable and the dominant component of sea level variability in many parts of the world's oceans and coasts. | Haigh et al. [43] |
| Water Level | The term water level is used to refer to the height of the sea surface above some reference level or benchmark (i.e. a tidal datum). | [43] |
| Tide | Tides are the regular and predictable rise and fall of the sea caused by the gravitational attraction and rotation of the earth, moon and sun system. Tides are normally used to refer to the vertical change in sea level. | [43] |
| Storm Surge | A storm surge is large change in sea level generated by low atmospheric pressure and strong winds associated with an extreme meteorological event. Storm surges can elevate sea level over an area of hundreds to thousands of square kilometres. Storm surges affect low lying coastlines around the globe and are responsible for significant damage and loss of life. The most devastating coastal floods occur when surges coincide with high spring tides. | [43] |
| Mean Sea Level (MSL) | The average height of the sea over longer periods of time (usually a month or year), with the shorter-term variations of tides and storm surges averaged out. Eustatic (or absolute) mean sea level reflects only the change in sea height, whereas relative mean sea level represents the change in sea height and changes in the level of the land at a local or regional scale. | [43] |
| Still Water Level (SWL) | The average water level at any instant, excluding local variation due to waves and wave set-up, but including the effects of tides, storm surges and mean sea level. | [43] |
| Wave | Local or remote storms produce large wind or swell waves, which can overtop coastal defences/beaches and cause flooding and erosion. | [43] |

celerometer. In modern units, such as the ones deployed by Channel Coastal Observatory (CCO) in the English Channel (the area covered by this study), there are additionally two further accelerometers that measure movement in two other planes (Northing and Easting) which, when processed, allow a directional spectrum to be produced for the wave environment. The buoys are moored to the bottom of the sea bed on long elastic moorings and with the recent advent of improved battery life and communication technology provide an effective service for 6 months without servicing. The buoy measures the vertical acceleration due to gravity thanks to an artificial horizon which is a weighted stage inside the buoy. The stage is balanced on a liquid half sphere and is calibrated to have a natural frequency of 40s. In consequence, any waves above a period of 30s are not effectively captured and represent the limiting maximum wave period threshold of the instrument. Wave displacement is calculated by twice integration of the acceleration value with respect to time (as shown in Equation 2.3):

$$\int a\,dt \; = v, \int v\,dt \; = d \tag{2.3}$$

Where $a$ is the measured acceleration, $v$ is the velocity and $d$ is the buoy displacement.

The wave buoys collect data at a frequency of $3.84Hz$ which is subsequently filtered and down-sampled for transmission to shore via a high-frequency radio link in $1.28Hz$ increments. Packets of data are transmitted every thirty minutes along with on-board calculated wave parameters. Quality control of the data is both automated and manually inspected. No data is removed but suspect or poor data is flagged meaning the raw data can be processed by the user as a means of self quality control. Additional information on the quality control and calculation procedures are available in Bushnell [15] and [96, 31]. The review and analysis of the raw wave buoy data is highlighted as a research need for this project.

## 2.3 Numerical Modelling

In CFD, modern numerical modelling involves the use of a computer; typically with specialist software installed; that can iteratively solve the governing equations of the Conservation Laws. These are:

- the conservation of mass
- the conservation of momentum
- the conservation of energy

In terms of fluid flow, for a viscous fluid, the full Navier-Stokes equations govern the action of the fluid. When these equations are simplified to neglect the influence of viscous effects completely, and this is a valid assumption in systems with thin boundary layers compared to the dimension of the body, the simplified form of the governing equations are called the Euler equations (2.4). It was this simplification that allowed discretization methods and boundary conditions for the modelling domain to be developed.

$$\frac{\partial}{\partial t}\int_{\Omega}\vec{W}\,d\Omega + \oint_{\partial\Omega}\vec{F}_c\,dS = \int_{\Omega}\vec{Q}\,d\Omega \tag{2.4}$$

where, $\Omega$ is the finite-volume, $\vec{W}$ is the vector of the conservative variables, $\vec{F_c}$ is the vector of convective fluxes, $dS$ is the elemental surface area and $\vec{Q}$ is the vector of volume sources due to body forces and volumetric heating.

The finite-difference method was one of the first methods used to solve the Navier-Stokes/Euler equations (2.4). The numerical approximation of differential equations was probably undertaken by Euler in 1768 using hand methods employing a Taylor expansion (2.5) according to Blazek [11]. The finite-difference method is directly applied to the differential form of the governing equations, employing a Taylor series expansion for the discretisation of the derivatives of the flow variables. So, for instance to calculate the first derivative of a scalar function $U(x)$ at some point $x_0$, the developed Taylor series in $x$ is:

$$U(x_0+\Delta x) = U(x_0) + \Delta x\frac{\partial U}{\partial x}\bigg|_{x_0} + \frac{\Delta x^2}{2}\frac{\partial^2 U}{\partial x^2}\bigg|_{x_0} + \dots \tag{2.5}$$

using this expansion, we can see that an approximation of the first derivative is given as:

$$\left.\frac{\partial U}{\partial x}\right|_{x_0} = \frac{U(x_0 + \Delta x) - U(x_0)}{\Delta x} + O(\Delta x) \tag{2.6}$$

with $O(\Delta x)$ in (2.6) representing the truncation error in the first order, tending to zero with the first power of $\Delta x$. One of the major strengths of the finite-difference method is that this same procedure can be applied to derive more accurate finite-difference formulae and therefore to obtain higher-order derivatives. In contrast, one of the restrictions is that the method relies on a structured grid and as such it struggles to deal with complicated geometry, however this facet of the method makes it computationally efficient.

Numerical modelling of complex science and engineering problems became more common following the end of WWII, which saw a dramatic increase in the use of computing and modelling in the war effort, especially in the areas of code breaking (after Alan Turing OBE FRS used his computer to break the Enigma code at Bletchley Park [117]) and in atomic bomb explosion modelling (as part of the Manhattan Project based at the Los Alamos Laboratory in New Mexico headed by Dr J Robert Oppenheimer [111]). In the immediate post war years, the development of numerical modelling moved away from a military focus towards civilian use and with the advent of increasing computing power and availability of powerful computers in university departments (and much later personal computers), the ability to numerically model complex engineering problems became possible. With this came the development of the finite-element method first introduced by Turner et al. [128] in 1956 in aeronautical engineering as a method of estimating stiffness and deflection of components. The method is still commonly used in structural engineering projects but it has really only commonly been used for solution of the Navier-Stokes equations since the beginning of the 1990s [11].

The finite-element method requires an unstructured grid since the physical space is divided into triangular or tetrahedral shapes in 2D. This method can be computationally intensive but is especially useful for application in complex geometries and when dealing with non-Newtonian fluids. The increased complexity of the method stems from the unstructured grid having to possess a certain number of points at the boundaries and/or inside the elements where the solution to the flow problem must be found. The number of these points multiplied by the number of unknowns determines the degrees of freedom of the model. The variation of the solution inside an element is represented by a shape function and in practical applications, linear elements are usually employed. This means the shape function takes on a linear distribution with a zero value outside the corresponding element. The result is a second-order solution on a smooth grid. In contrast to the finite-difference method which is directly applied to the differential form of the governing equations, finite-element analysis relies on the transformation of the governing equations into the equivalent integral form (See Equation (2.4)).

The transformation can be achieved in two different ways. The variational principle can be used, where a physical solution is sought and for which a functional relationship possesses an extremum or, the preferred option for most applications is the weak formulation. In this process the weighted average of the residuals is zero over the physical domain, with the residuals akin to the errors of an approximation of the solution. This allows for discontinuous solutions such as shocks. The finite-element method is mathematically rigorous and can be shown to be equivalent to the finite-volume discretisation (discussed below), however, the numerical effort required is significantly greater. It is thought that this increased effort is the reason that finite-volume methods became more popular.

The finite-volume method sits conveniently between the structured, potentially inflexible finite-difference method and the much more computationally intensive finite-element method. It was developed much later than the other two methods, and was first documented by McDonald [77] in 1971 for the simulation of 2D inviscid flows. The method directly utilises the conservation laws which are the integral form of the Navier-Stokes/Euler equations. The equations are discretised by dividing the physical space into arbitrary polyhedral control volumes. This then allows the surface integral (right hand side of equation (2.4)) to be approximated as the sum of the fluxes crossing the control volume faces. The shape and position of the control volume within the grid can be defined as either a cell-centred scheme (where flow quantities are stored at the cell centroid) or cell-vertex schemes (where flow quantities are stored at grid points). The main advantage of the method is that the discretisation is related directly to the physical space and therefore no transformations are necessary between coordinate systems - this makes the method efficient for complex geometries. Since conservation of mass, momentum and energy is achieved by direct discretisation of the conservation laws it is possible to compute weak solutions to the governing equations accurately. However, since these solutions are non-unique in the Euler equations, an additional entropy condition must be employed. The entropy condition prevents unrealistic features like expansion shocks violating the second law of thermodynamics [11].

Around the same time as the development of the finite-volume method, scientists from the Los Alamos Scientific Laboratory were continuing to develop the finite-difference method for use in turbulent fluid dynamics - this method is much more computationally efficient due to its need for structured grids and has the advantage of being able to easily resolve the equations to obtain higher order approximations and therefore higher spatial discretization of the model domain [11]. To overcome some of the drawbacks of using a finite-difference model Nichols and Hirt [93], scientists at Los Alamos, proposed a method for calculating the transient free surface flows past stationary objects. This work was expanded later by both authors into the volume of fluid method for dynamics of free boundaries [52] and it was this work that resulted in the development and marketing of a CFD package called Flow-3D and a subsidiary application aimed at Civil and Coastal Engineering CFD problems (Flow Science [34]).

The volume of fluid (VOF) method for use in structured grids came about to overcome the inherent problems of convective flux approximations in Eulerian methods. The smoothing of flow quantities results in a smearing of surface of discontinuity such as at free surfaces. The problems of defining the free surface and how it is represented in a numerical model has been addressed by using height functions, line segments and latterly marker particles. The benefit of working with volumes occupied by fluid in the marker particle method has the advantage of eliminating all logic problems associated with intersecting surfaces that are inherent in height function and line segment solutions. The volume of fluid method extends the benefits of the marker particle method by defining a single step function $F$, whose value is unity at any point occupied by fluid and zero otherwise. The average value of $F$ in a cell would then represent the fractional volume of the cell occupied by the fluid. It logically follows that any cell with a fractional $F$ value must contain a free surface.

In addition to computing which cells contain a free surface, it is also necessary to compute where the fluid is located in the boundary cell. The normal direction to the boundary lies in the direction in which the value of $F$ changes most rapidly - therefore calculation of the derivatives of $F$ give the boundary normal. This information, along with the value of $F$, then allows a line to be constructed that approximates the interface. The boundary is then used in the setting of the boundary conditions.

Having identified which cells contain a free surface and the approximate position of the free surface, it is necessary to understand the evolution of the $F$ field, this relationship is defined as:

$$\frac{\partial F}{\partial t} + u\frac{\partial F}{\partial x} + v\frac{\partial F}{\partial y} = 0 \tag{2.7}$$

this equation shows that F moves with the fluid, it simplifies to $F$ remaining constant in a Lagrangian mesh but means that in an arbitrary Lagrangian-Eulerian mesh $F$ must be computed. Since $F$ is a step function, an approximation is made using the donor-acceptor method [58].

Flow3D-Hydro solves the transient Navier–Stokes equations of conservation of mass and momentum using a Finite Difference Method and on Eulerian and Lagrangian frameworks ([76]). The aforementioned governing equations are:

$$\nabla \cdot u = 0 \tag{2.8}$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = \frac{-\nabla P}{\rho} + \nu \nabla^2 u + g \tag{2.9}$$

where $u$ is the velocity vector, $P$ is pressure, $\rho$ is water density, $\nu$ is kinematic viscosity and $g$ is the gravitational acceleration. A Fractional Area/Volume Obstacle Representation (FAVOR) is adapted in Flow3D-Hydro, which applies solid boundaries within the Eulerian grid and calculates the fraction of areas and volume in partially blocked volume in order to compute flows on corresponding boundaries (Hirt and Nichols [52]).

The selection and development of an appropriate CFD package and design of model are highlighted as essential research needs for the purposes of this work.

## 2.4 Summary of Research Needs

This chapter has outlined the key aspects of the engineering objectives of this thesis. I have looked at the complex area of cascading risk models and their genesis, discussing the differences in multi-hazard and risk analysis, dynamic vulnerabilities and cascading effects which influence the understanding of engineering failures. In terms of understanding the physical conditions that contribute to failures of coastal infrastructure I have focused on the hydrostatic and hydrodynamic conditions that combine to increase forces on a structure and given that these conditions may be modelled I have highlighted the type of numerical model which would need to be created in order to demonstrate the magnitude of forces experienced by failing infrastructure during a storm event.

### 2.4.1 RN1 : Formation of a Cascading Multi-Hazard Risk Model for Coastal Railway Infrastructure

Many existing studies have focused on the vulnerability of coastal infrastructure solely from a flooding viewpoint where that infrastructure has a primary role of stopping a flooding event. Where discussion on failing infrastructure has taken place it is couched in terms of a failure of an engineered component, for example an earthen dyke, where simplified assumptions on the force generating mechanisms have been made. Previous studies have sometimes used a single surrogate for force generation, commonly wave overtopping. However, I have highlighted that in a complex engineered structure like a seawall supporting vital transport infrastructure such as a main railway with multiple additional uses of flood defence and amenity value, simply using one force surrogate may seriously under-estimate the risk associated with a particular storm event. I have highlighted the need for understanding the multitude of different force generating mechanisms in order to understand the global effects of a hazard. Work conducted before this study has rarely been focused on railway transport infrastructure. Various authors have highlighted the need to understand the relationship between multi-hazards and cascading effects and this has been highlighted as a task for this work.

### 2.4.2 RN2 : Application of tide gauge data for coastal risk studies

The manipulation and processing of real time tide gauge data is highlighted as a research need in order to quantify the effect of the quasi-static elements of structural loading that the target infrastructure experienced throughout the course of a storm event. By understanding this data I can estimate the values of SWL that were present throughout the storm and therefore estimate the magnitude of forces experienced by the seawall. In combination with information on wave climate (Section 2.4.3) tide data will be used as an input for effective numerical simulation of elements of the storm event.

### 2.4.3 RN3 : Application of real time wave climate data for coastal risk studies

The additional hydrodynamic forces created by waves impacting on the coastal infrastructure are vital to the understanding of the compound effect of quasi-static and dynamic forces experienced throughout the storm event. By isolating the specific dynamic components I expect to be able to quantify typical maximum forces which may provide an insight to the activating mechanisms of failure of the asset. This data stream which includes significant wave height, wave direction and period at 1Hz granularity will provide a feed to the input conditions for the numerical model.

### 2.4.4 RN4 : Numerical Simulation of failure events

Following successful development of a cascading multi-hazard risk model for coastal railway infrastructure, is it possible to recreate the forces that were inflicted on the seawall with a view to evaluating the contribution of quasi-static and hydrodynamic forces on the failure? Can I identify an activating failure pathway for the disaster and postulate a potential explanation for the initiating failure that cascaded eventually to complete service disruption on the line and significant losses to the local and regional economy?

## 2.5 Research Question

Given the type of damage observed to a vertical seawall after an extratropical cyclone can I construct a comprehensive multi-hazard risk model, including cascading elements for critical coastal engineering transport infrastructure, that could have wider application for other sites or other hazards?

With a multi-hazard cascading risk model, can I use real-time information to reconstruct the sea state and wave forces exerted on the wall during a particular storm to demonstrate a likely damage mechanism (DM) and failure pathway (FPW) that initiated and then cascaded to cause a complete network failure and significant losses?

I have subdivided this research question to answer the research needs highlighted in the literature review (Section 2.4) into three chapters of this thesis:

Chapter 3 provides the basis of the data and methods used in the study to support the following chapters. In chapter 4 I detail the work conducted to formulate the multi-hazard risk model and the complimentary cascading FPW which interact between separate DM to increase the severity of the event. Chapter 5 introduces the work conducted on the original Brunel drawings of the seawall and the numerical modelling used to estimate magnitude of forces acting on the infrastructure during the storm event.

The thesis answers the research question by splitting it into supplementary parts, for which I use the research needs as constituent elements.

1. In order to formulate a cascading multi-hazard risk model for critical coastal railway infrastructure:

    a) Can I identify the separate forces that impact on the rail infrastructure from a compound event such as a coastal storm? (RN1)

    b) Having identified these forces and labelled them damage mechanisms (DM) can I use historical failure information to sub-divide these into separate failure pathways (FPW) which affect different infrastructure elements? (RN1)

    c) After cross-referencing the complete historical record of significant failures on the coastal railway, is there a commonality in one or more of the failures which suggest a cascading effect which bridges separate damage mechanisms (DM)? (RN1)

    d) Given the specific development of the risk model can I apply it to other coastal railways in the UK for similar hazards, or even a different coastal railway in another country for a different initiating hazard? (RN1)

2. If I have a multi-hazard risk model for a particular critical coastal infrastructure, is it possible to recreate the disaster in order to hypothesise the likely failure sequence?

    a) Hydrostatic forces on a structure are components of tidal variation and quasi-static influences such as storm surge - can I isolate real time information on these components to reconstruct the force at a particular time? (RN2)

    b) Hydrodynamic forces are a function of sea state during a storm, which in themselves are a function of wind and pressure environment - can I reconstruct specific elements of a damaging storm in order to identify the wave characteristics that led to damage. (RN3)

    c) Can I construct a model of the seawall that is true to the original as designed and built structure and numerically model the wave environment in order to study the wave/structure interaction? (RN4)

    d) Can this information provide enough circumstantial evidence to suggest a forensic explanation for how the seawall collapsed? (RN4)

Figure 2.1 details a flowchart for the various thesis sections and interlinks these with the research needs and overarching questions.

Several novel concepts are developed and presented in this investigation:

- The enumeration of distinct and separate force generation steps from a triggering storm hazard event.
- The concept of separate Failure Pathway (FPW) bridging separate Damage Mechanism (DM) to form a cascading disaster.

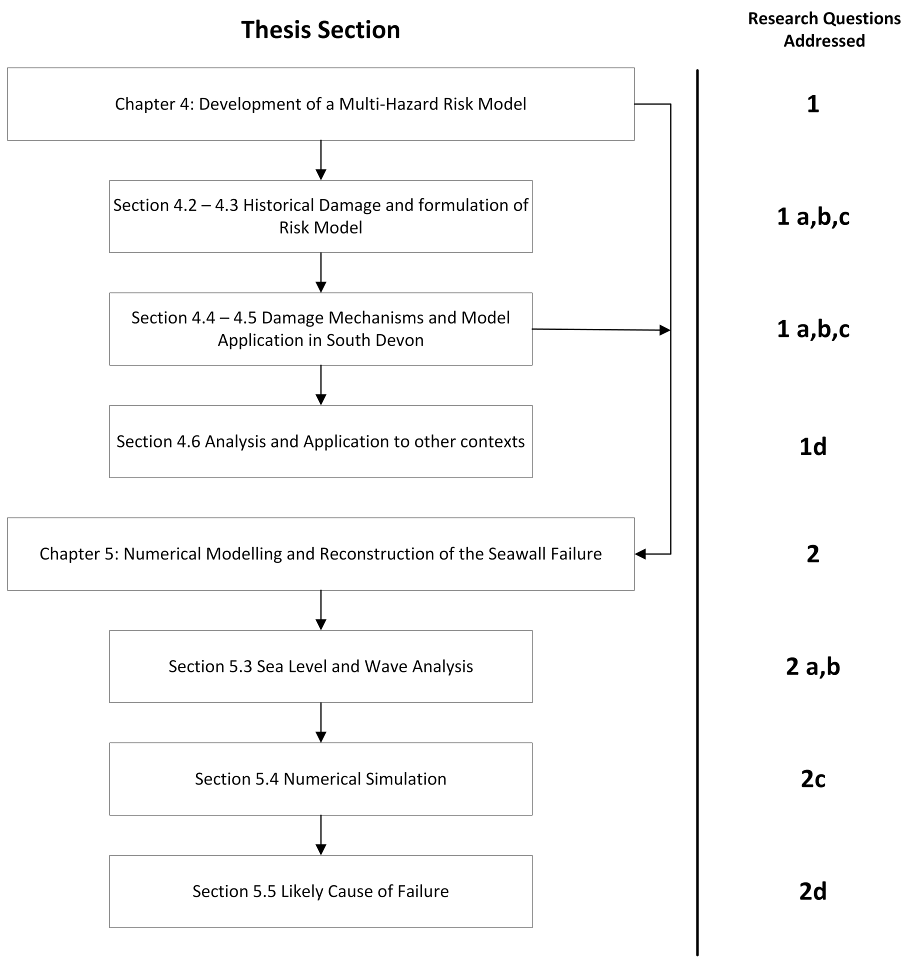



**Figure 2.1: Flowchart showing thesis sections addressing each research objective.**

- The formulation of a multi-hazard risk model which is proposed for use in other geographical locations and potential for use in diverse hazard events.
- Detailing the static, quasi-static and hydro-dynamic components of a specific storm and using these in numerical simulations of the wave/structure interaction in order to recreate the effects of a storm on a masonry seawall.
- From application of the risk model in combination with Computational Fluid Dynamics (CFD) modelling to reconstruct a disaster event and to use this information forensically to propose the likely initiating cause of failure.

Chapter 3

# Data and Methods

## 3.1 Introduction

In this research, I study historical and contemporary data on the failure of the Dawlish railway by storm induced forces to establish a multi-hazard risk model with cascading failure pathways (FPW) which could be used with an exposure database to evaluate risk to the structural assets. I use primary historical accounts and identify damage mechanisms (DM) and FPW that cascade between separate DM.

Section 3.2 provides details of the methodology I developed to analyse the historical damage data and the methods for assimilating this data into a table of major incidents (Section 3.3 Table 3.1). These incidents affected the railway line since its inception in 1845 until the major incident in February 2014 which closed the line for 56 days. The latter event is estimated to have had a financial impact to the South West region of the UK of up to £1.2bn from a combination of loss of tourism, business interruption and loss of industrial output as well as the replacement costs of the railway network itself.

Detailed contemporary reports of damage from selected newspaper articles are presented in Appendix A. Additional cross-referenced damage data is also presented as Appendix B.

Section 3.3 sets out the rationale and definitions of significant failure events for the railway line and highlights the cut-off criterion I have used to exclude the numerous minor events which have not significantly impacted on the operation of the line. In some cases, otherwise major events have been excluded where cross-referenced secondary evidence is not available or where specific details of the duration of interruption were unavailable.

Section 3.4 details the methodology for disaggregating the failure events into a linear series of cause and effect relationships. The result of this process is a series of event tree analysis flowcharts presented in Appendix D for each historical major event. I then used each separate flowchart generated to aggregate the data into a dominant failure matrix (Appendix C) which in turn allowed me to generate the multi-hazard cascading model presented in Chapter 4.

The data sources used in the numerical modelling study comprises eyewitness accounts, sea level records from coastal tide gauges and offshore wave buoys as well as structural details of the seawall. As for methodology, I analyse eyewitness data, process and investigate sea level records through Fourier Transform and conduct numerical simulations using the Flow3D-Hydro software package [34].

Section 3.5 investigates and analyses personal accounts of the storm of 2014 and its effects on the local population of Dawlish in Devon. This was conducted through a research of published work by the local Dawlish museum and is cross referenced using social media postings and news broadcasting organisations both at national and regional level. This information allowed me to understand the development of the damage to the railway network, the sequence of failures that occurred and the approximate times when disaster mitigation measures were put into place by the civil contingency organisations.

Sea Level and Wave Data Analysis sources and techniques for processing the large amounts of data are presented in Section 3.6. It was important that I conducted the analysis on raw quality controlled data from the tide gauges and wave buoys to ensure that no data was truncated or otherwise lost in post-processing of long time period records. This allowed me to isolate the specific conditions observed before, during and after the storm in question.

Section 3.7 details the process of modelling the wave structure interactions using a commercial computational fluid dynamics package. Aspects of validation against vertical seawalls are explained as well as the underlying governing equations of conservation of mass and momentum used in the software.

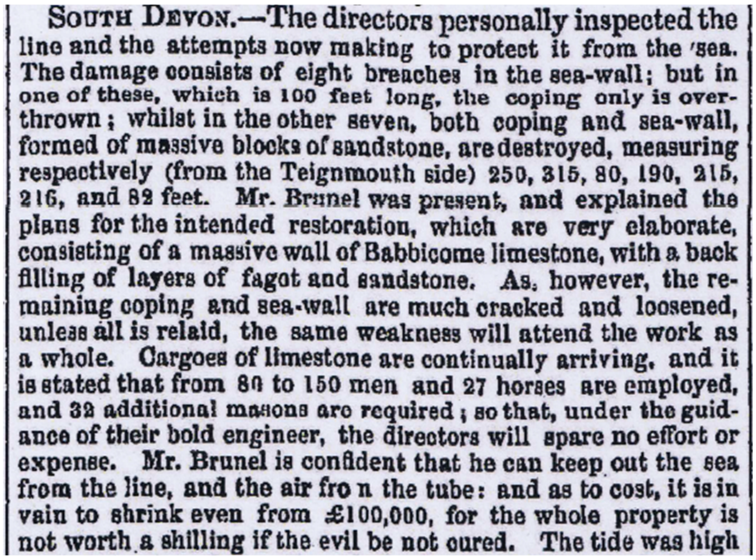
## 3.2 Seawall Damage Data

Archival research of historical damage data and interpretation of damage information was used in combination for this study. This approach has been widely applied in the past for natural hazard analysis, for example by Soloviev [118], Ambraseys and Melville [4] and Heidarzadeh et al. [47]. I establish DM associated with each event, detail the multi-hazards triggered (e.g. wave overtopping, wave impacts or excess soil pore pressure) and identify the cascading nature of the hazards. Research was undertaken to investigate the frequency of occurrence and nature of the damage suffered by the seawall in Dawlish from the date of work commencing in 1845 until the February 2014 storms. The British Newspaper Archive at the British Library (BL)[1] facilitated a comprehensive review of dam-

[1] https://www.britishnewspaperarchive.co.uk/

age reports with some details of prevailing weather and sea conditions that led to failure (Fig.3.1). A copy of this resource is appended at the end of this research as Appendix A. The historical records were cross referenced for accuracy with ad-

**a)**



SOUTH DEVON.—The directors personally inspected the line and the attempts now making to protect it from the sea. The damage consists of eight breaches in the sea-wall; but in one of these, which is 100 feet long, the coping only is overthrown; whilst in the other seven, both coping and sea-wall, formed of massive blocks of sandstone, are destroyed, measuring respectively (from the Teignmouth side) 250, 315, 80, 190, 215, 216, and 82 feet. Mr. Brunel was present, and explained the plans for the intended restoration, which are very elaborate, consisting of a massive wall of Babbicome limestone, with a back filling of layers of fagot and sandstone. As, however, the remaining coping and sea-wall are much cracked and loosened, unless all is relaid, the same weakness will attend the work as a whole. Cargoes of limestone are continually arriving, and it is stated that from 80 to 150 men and 27 horses are employed, and 32 additional masons are required; so that, under the guidance of their bold engineer, the directors will spare no effort or expense. Mr. Brunel is confident that he can keep out the sea from the line, and the air fro n the tube: and as to cost, it is in vain to shrink even from £100,000, for the whole property is not worth a shilling if the evil be not cured. The tide was high

**b)**

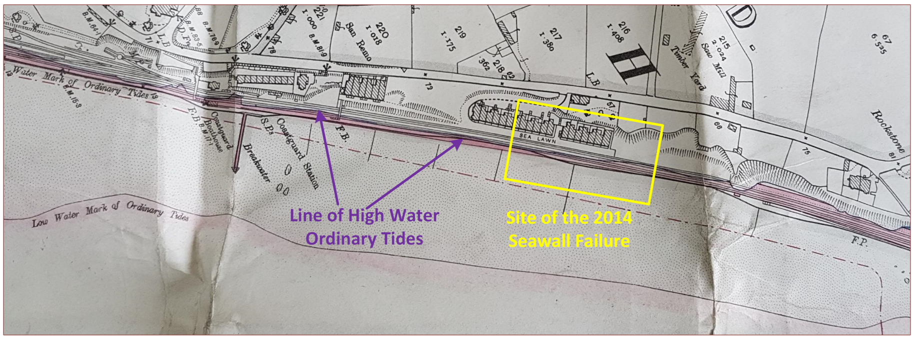



**Figure 3.1: a) Newspaper extract detailing damage to Dawlish seawall and engineering remedies [13]. b) Nineteenth Century Admiralty map of Dawlish showing ordinary tide high water and annotated with site of the February 2014 seawall failure [126]**

ditional resources provided by Brunel University London Special Collections[1], The National Archives (TNA) at Kew[2], University of Bristol Brunel Collection[3], the UK Institution of Civil Engineers (ICE)[4] and Network Rail[5]. The historical record

[1] https://www.brunel.ac.uk/life/library/Special-Collections
[2] https://www.nationalarchives.gov.uk/
[3] http://www.bristol.ac.uk/library/special-collections/strengths/brunel/
[4] https://www.ice.org.uk/knowledge-and-resources/ice-library
[5] https://www.networkrail.co.uk/

up to the late 1980's was comprehensively detailed in Kay's work on the history of the Exeter to Newton Abbott line which benefited from personal interviews with the dedicated 'seawall gang' of technicians and masons based at Dawlish station, whose job was to constantly survey and maintain the fabric of the seawall [61].

## 3.3 Risk Models

The railway damage information is compiled into Table 3.1. From a large list of numerous damage incidents, I study significant failure events. A significant event is defined as one which led to either the complete closure of the line for at least 12 h or required one of the lines to be closed for at least one day (single line closure; Table 3.1, Column 5). In total, 29 separate incidents of significant failure were discovered in the 169-year history of the line to 2014 and are listed in Table 3.1.

A more comprehensive list of events affecting the railway line was also compiled by Dawson, Shaw and Gehrels [26] although their interest was focussed on human geography and anticipated sea level rise. I limited the entries in Table 3.1 to events which demonstrated major failure mechanisms of the engineered assets using the criteria above since the objective is to establish a multi-hazard risk model. The result is that I do not include minor incidents which may, for instance, result in speed restrictions or delay on the line or those which are regularly corrected by the dedicated team of maintenance linesmen based at Dawlish station.

By adopting this approach, I have satisfied the criterion of "cut-off" [50] where the severity of an event is defined by its spatial scale and relevance – in effect I have defined the exposure by quantifying the extent of the network failure.

**Table 3.1: Significant damage events on the Dawlish Mainline from its construction in 1846 to February 2014 associated with weather induced failure.**

| Incident Date (d/m/y) | Asset | Location | Full Closure (days) | Single Line Closure (days) | Predominant Failure (FPW activated) |
|---|---|---|---|---|---|
| 05/10/1846 | Seawall | Breeches Rock | 3 | n/a | Masonry Damage (5) |
| 20/11/1846 | Seawall | Cockwood | 1 | n/a | Masonry Damage (5) |
| 26/12/1852 | Cliff Face | Breeches Rock | 0.5 | n/a | Slope Instability (1) |
| 28/12/1852 | Cliff Face | Breeches Rock | 7 | n/a | Slope Instability (1) |
| 04/02/1853 | Cliff Face | W Kennaway | 3 | n/a | Slope Instability (1) |
| 13/02/1853 | Cliff Face | W Kennaway | 0.5 | n/a | Slope Instability (1) |
| 16/02/1855 | Seawall | Smugglers Lane | 12 | n/a | Toe Scour (4) |
| 25/10/1859 | Seawall | Sprey Point | 3 | n/a | Flooding of Rails (2) |
| 31/01/1869 | Seawall | Sea Lawn | 5 | n/a | Toe Scour (4) |
| 25/12/1872 | Seawall | Rockstone | 1 | n/a | Masonry Damage (5) |
| 30/12/1872 | Seawall | Rockstone | n/a | 2 | Toe Scour (4) |
| 11/01/1873 | Seawall | Rockstone | 1 | 7 | Masonry Damage (5) |
| 01/02/1873 | Seawall | Rockstone | 3 | n/a | Toe Scour (4) |
| 01/12/1874 | Cliff Face | n/a | 3 | n/a | Slope Instability (1) |
| 01/12/1875 | Cliff Face | n/a | 1 | n/a | Slope Instability (1) |
| 03/02/1916 | Seawall | Rockstone | n/a | 1 | Toe Scour (4) |
| 12/03/1923 | Cliff Face | Sprey Point | 3 | 8 | Slope Instability (1) |
| 24/12/1929 | Seawall | Sea Lawn | n/a | 2 | Toe Scour (4) |
| 04/01/1930 | Seawall | Sea Lawn | 5 | n/a | Toe Scour (4) |
| 10/02/1936 | River Wall | Powderham | 3 | n/a | Toe Scour (4) |
| 01/03/1962 | Seawall | Rockstone | 0.5 | 8 | Coping & Parapet Walls (3) |
| 11/02/1974 | Station | Dawlish Station | 0.5 | 5 | Wave Debris Damage (-) |
| 26/02/1986 | Seawall | Smugglers Lane | 6 | 7 | Toe Scour (4) |
| 01/01/1996 | Seawall | Rockstone | 7 | n/a | Toe Scour (4) |
| 01/12/2000 | Seawall | Sprey Point | 3 | n/a | Masonry Damage (5) & Slope Instability (1) |
| 27/10/2004 | Seawall | Smugglers Lane | 5 | n/a | Masonry Damage (5) |
| 22/09/2006 | Track | Dawlish Station | n/a | 3 | Wind Damage (-) |
| 08/04/2013 | Seawall | n/a | n/a | 3 | Coping & Parapet Walls (3) |
| 05/02/2014 | Seawall | Sea Lawn | 56 | n/a | Masonry Damage (5) & Slope Instability (1) |

This allows stakeholders to use the model to determine the scale of loss for an individual event and to understand the probable FPW which contribute to loss of service.

## 3.4 Fault Tree Analysis

In this research I applied a multi-hazard risk assessment methodology, considering cascading failure paths to analyse historical failure events, previous work was undertaken by Marzocchi, Mastellone and Ruocco [71] and Egli, Hochwasserschutz and Raumplanung [30] with event tree analysis which provides a basis for the approach. In their work on multi-risk assessment the authors establish a ranking of different types of risk that takes into account possible interactions among them. As detailed these interactions may amplify the overall risk and in a significant difference to single risk assessment methodologies, a multi-hazard analysis index must take account of possible cascade or trigger related adverse events.

In the present study I modified a top-down Fault Tree Analysis (FTA) [68] and bottom-up Failure Mode and Effect Analysis (FMEA) [119] to fit the known observed damage events (Table 3.1). I then applied engineering judgement to infer any intermediate failure paths which led to a known network failure condition while being consistent with the historical record. For the most recent events, where detailed records are available, the FMEA route was chosen. Where the severity of the hazard data was postulated from contemporary newspaper reporting, the FTA was used.

FTA is a top down approach where reverse engineering is used to detail the potential failure of a component. A typical question to ask for this process is "how likely is it that this asset will fail". The process replicates how failure moves through a system and graphically shows how component failures lead to system wide failures. The process developed in the early 1960s specifically for the development of the intercontinental ballistic missile systems for the US air force. The method allows systematic fault assessment and interrelationships to be accounted for - this top down approach allowed me to define the triggering event, look at each individual potential force generating step, its effect on large scale engineering component (the common cause failure) and then the effect on subsidiary engineering components, which in themselves would then have a potential to cascade across each other. The idea of low level cascading effects is the major development to the method that I introduced. It is the method used to construct the failure sequences shown in Appendix D for the older events (D.1 to D.13).

The FMEA was used in a bottom up approach where recent events were detailed in a comprehensive civil engineering methodology. This approach focuses on the failure modes of a component and additionally on the domino effect that particular failures have an the system as a whole. It is commonly used in the reliability, safety and quality control industries. The bottom up approach is used on existing assets - looking at each component individually with the aim of assessing it as part of a bigger system. A typical question to ask at the start of this process is "Given that the seawall has collapsed, which elements were responsible for the failure". The final step is the definition of the hazard responsbile. This method was used to construct the modern examples of failure shown in Appendix D specifically D.14 to D.25.

I justify the judgements made through temporal alignment of the failure events over successive decades. For each incident I produced a diagram detailing the specific elements of common cause failure (a FPW within a DM) and cascading failure (a FPW linking different DM) leading to network failure (an exposure) stemming from an initiating triggering hazard, in this case a storm (Appendix D).

I then aggregated these into a model following the structure of Lee et al. [67] and developed it by adding an intermediate force generating step in the DM between the trigger and common cause failure lanes. The triggering event encapsulates the initiating hazard which in the model is a storm which leads to service suspension. In reality, the hazard is a complex combination of extra-tropical cyclonic weather systems, sometimes appearing as series of discrete events, temporally aligned with high spring tidal cycles, prolonged rainfall and easterly or south-easterly prevailing winds. In combination, they generate large and violent waves which can impart destructive energy onto the railway infrastructure. The forces that are generated because of this hazard sequence are divided broadly into wind dominated, hydrodynamic (or wave) and geotechnical effects which in turn initiate a primary common cause failure. I define a common cause failure here as a series of simultaneous multiple failures that result from a single event [29, 134], which can subsequently cascade across DM, increasing the severity of the disaster and precipitating a service suspension.

## 3.5 Eye Witness Data

The scale of damage to the seawall and its effects led the local community to document the first-hand accounts of those most closely affected by the storms including residents, local businesses, emergency responders, politicians and engineering contractors involved in the post-storm restoration work. These records now form a permanent exhibition in the local museum in Dawlish and some of these accounts have been transcribed into a DVD account of the disaster [25].

I have gathered together data from the Dawlish Museum, national and international news reports, social media tweets and videos. Table 3.2 provides a summary of the eyewitness accounts. Overall, 26 entries have been collected around the time of the incident. The analysis of the eyewitness data is provided in the third column of Table 3.2 and is expanded in Chapter 5.

**Table 3.2:** Eyewitness accounts of damage to the Dawlish railway due to the February 2014 storm and my interpretations.

| **Date (d/m/y)** | **Eyewitness accounts** | **Analysis and observations** | **Reference** |
|---|---|---|---|
| 04/02/2014 | Flooding of town centre, river overflowing, wind and waves inundating at various points along the seawall especially near centre of town. (1400 hrs) | Surge and waves were intensive causing overtopping of the wall. | Dawlish Museum [25] |
| | Network Rail shuts the mainline down. First Great Western (the railway company) cancel all trains after some engines get stranded and battered on the down line by large storm waves. (1515 hrs) | Severe overtopping of the seawall and inundation. | Dawlish Museum [25] |
| | Town centre damage reported | Strong wave actions and inundations. | BBC [5] |
| | The road "Sea Lawn terrace"– report of house flooding by resident to fire service due to high wind and waves. A car is stranded and has water inundation along Marine Parade (the coastal road) | Severe coastal flooding along Marine Parade. | Dawlish Museum [25] |
| | "Roof rattling, roof tiles, doors and windows leaking water". (Sea Lawn Terrace, 1800 hrs) | Winds and wave overtopping cause structural damage to houses fronting the sea at Sea Lawn Terrace. | Chris Saich, local resident [7] |

| Date (d/m/y) | Eyewitness accounts | Analysis and observations | Reference |
|---|---|---|---|
| | Fire station manager reports the cliffs being threatened at various points east of Dawlish towards the Warren due to large waves. | The storm cascades to other hazards such as coastal landslides. | Robert Porch, Dawlish Fire Station Manager [25] |
| | Road already collapsed, gas mains have been broken, smell of leaking gas by fire service along Sea Lawn Terrace. | Cascading hazards of energy line failures and damage to infrastructure along Sea Lawn Terrace. | Robert Porch [25] |
| | Sea Lawn Lodge Guesthouse, signs blown down. (2100 hrs) | Strong gusting wind, as a result of the storm, causing damage. | Gerard Belcher, Sea Lawn Lodge [25] |
| | Rivera terrace is evacuated, concern over houses being vulnerable. (2115 hrs) | Local police declare major incident and arrange evacuation of local residents. | Dawlish Museum [25] |
| | Reports of ballast having been washed away, rail line hanging in mid-air at Sea Lawn Terrace. | Severe damage to railway infrastructure at Sea Lawn Terrace. | Dawlish Museum [25] |
| | Police ask Sea Lawn Lodge (a local hotel) to act as clearing house for evacuated residents, police in attendance to take registration of all residents and search for missing persons. (2300 hrs) | Temporary evacuation centre for local people. | Gerard Belcher [25] |
| | "Water coming through windows, down the chimney into our lounge" at Sea Lawn Terrace. Evacuation by local police. (2300 hrs) | Wave overtopping and impact forces so severe, ballast is breaking windows and water ingress down chimney suggests water reaching in excess of 10m above wall base level along Sea Lawn Terrace. | Chris Saich, local resident [8] |
| | Police evacuation for River Terrace – "it was like an earthquake, the houses were jumping up and down on their footings ... it wasn't a storm, it was a hurricane". (2345 hrs) | Local residents, used to coastal storms, identify this event as extreme and liken it to a hurricane. | Robert Parker, local resident [8] |

| Date (d/m/y) | Eyewitness accounts | Analysis and observations | Reference |
|---|---|---|---|
| 05/02/2014 | Local Leisure Centre re-purposed for resident evacuation. (0200 hrs) | Temporary evacuation centre for local people. | Gerard Belcher, [25] |
| | 80 mph winds. (0700 hrs) | Strong gusting wind. | |
| | Riviera Terrace seawall gone; 1st storm was abating. Took some pictures pre-dawn. (0744 hrs) | Report by David Crome (First Great Western General Manager – West). | Steve Briers, [25] |
| | As morning went on, the hole in the wall got bigger and bigger as waves wash away more infill material and undermine road asphalt etc. | The storm has caused major damage to the railway and line was washed away. | Steve Briers [25] |
| | Station platform, structure being seriously damaged by wind and waves. | Damage to the station. | Dawlish Museum [25] |
| | Coastal Road flooded due to storm surge | Continuing coastal flooding. | Dawlish Museum [25] |
| | Marine Parade (a coastal road), shifting ballast traps cars and knocks down railings on town side. | The debris from railway damage impacted the nearby road and caused damage. | Dawlish Museum [25] |
| | Seawall along the frontage near the viaduct is breached in many sections. | Wave impact damage to the seawall. | Dawlish Museum [25] |
| | Marine Parade (a coastal road) extensive damage to tracks and ballast. | Wave overtopping damage. | Dawlish Museum [25] |
| | Boat Cove – many beach huts destroyed, blocking the access to the cove. | Wave Impact Damage. | Dawlish Museum [25] |
| | 5000 t concrete poured, 150 t steel. Pumping through 100 mm pipes from town to site of damage. | Initial temporary repair work. | Gerard Belcher [25] |
| | Breaches of wall reported from Dawlish Warren to Coryton Cove. 300 engineers working costing a total of £15m. | Continuing damage due to wind and wave overtopping. | Dawlish Museum [25] |

| Date (d/m/y) | Eyewitness accounts | Analysis and observations | Reference |
|---|---|---|---|
| | "Biggest structural engineering feat in the southwest in the last decade ... worst damage ever seen to the seawall in the local engineers' careers". | Evaluation of the storm suggests this was an extreme event with multiple cascading hazards activated. | Patrick Hallgate, Network Rail Engineer [5] |

## 3.6 Sea Level and Wave Data Analysis

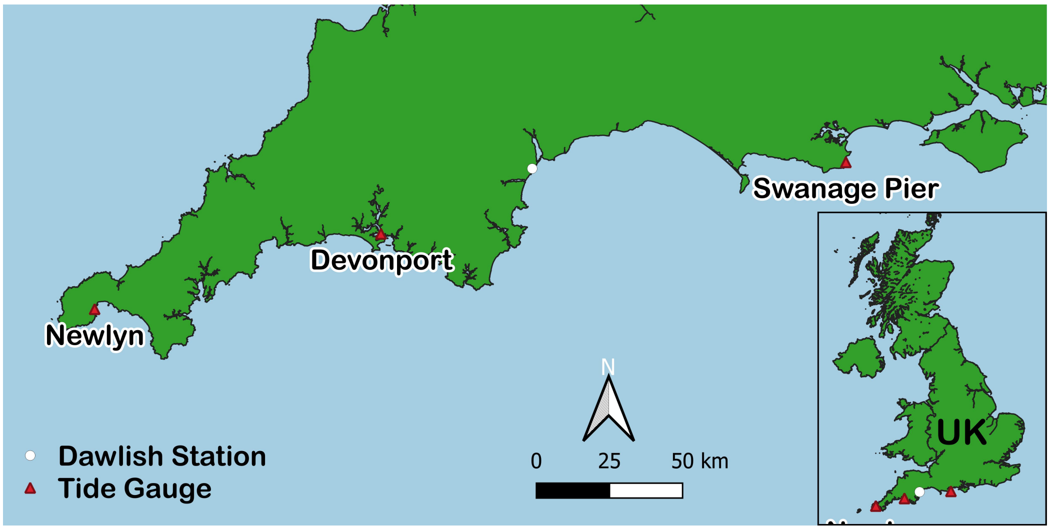



**Figure 3.2:** Location of Tidal Gauges on Channel Coast used in this study.

The sea level data is a collection of three tide gauge stations (Newlyn, Devonport, and Swanage Pier, Figure 3.2) owned and operated by the UK National Tide and Sea Level Facility for the Environment Agency [1] and four offshore wave buoys (Dawlish, West Bay, Torbay, and Chesil Beach, Figure 3.3). The tide gauge sites are all fitted with POL-EKO[2] data loggers. Newlyn has a Munro float gauge with one full tide and one mid-tide pneumatic bubbler system. Devonport has a three-channel data pneumatic bubbler system and Swanage Pier consists of a pneumatic gauge. Each have a sampling interval of 15 min, except for Swanage

[1] https://ntslf.org/
[2] www.pol-eko.com.pl

Pier which has a sampling interval of 10 min. The tide gauges are located within the port areas whereas the offshore wave buoys are situated approximately 2 - 3.3 km from the coast at water depths of 10–15 m. The wave buoys are all Datawell Wavemaker Mk III[1] units and come with sampling interval of 0.78 s. The buoys have a maximum saturation amplitude of 20.5 m for recording the incident waves which implies that every wave larger than this threshold will be recorded at 20.5 m. The data are provided by the British Oceanography Data Centre (BODC)[2] for tide gauges and the CCO[3] for wave buoys.

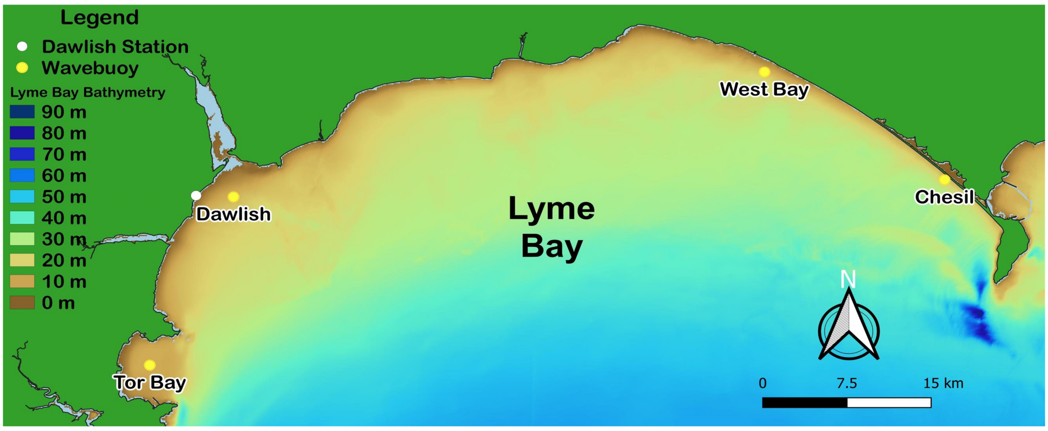



**Figure 3.3:** Location of Wave Buoys in Lyme Bay used in this study.

The sea level data underwent quality control to remove outliers and spikes as well as gaps in data (Figure 3.4). I processed the time series of the sea level data using the Matlab signal processing tool [76]. For calculations of the tidal signals, I applied the tidal package TIDALFIT (Grinsted [42]), which is based on fitting tidal harmonics to the observed sea level data. To calculate the surge signals, I applied a 30-min moving average filter to the de-tided data in order to remove all wind, swell and infra-gravity waves from the time series. Based on the surge analysis and the variations of the surge component before the time period

[1] https://www.datawell.nl/Products/Buoys/DirectionalWaveriderMkIII.aspx
[2] https://www.bodc.ac.uk/
[3] https://coastalmonitoring.org/

of the incident, an error margin of approximately ±10 cm is identified for the surge analysis. Spectral analysis of the wave buoy data is performed using the Fast Fourier Transform (FFT) package in Matlab [76].

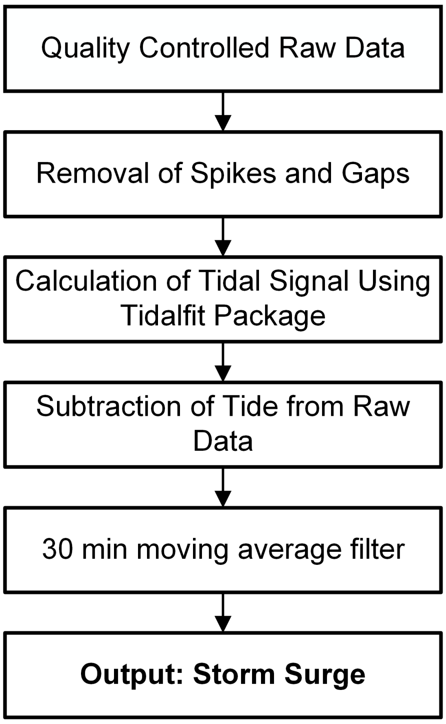



**Figure 3.4:** A flowchart of sea level data analysis conducted in this research.

## 3.7 Numerical Modelling and Validation

Numerical modelling of wave-structure interaction is conducted using the computational Fluid Dynamics package Flow3D-Hydro version 1.1 [76]. I validated the numerical modelling through comparing the results with analytical equations of Sainflou for design of vertical seawalls (Sainflou [114], Ackhurst [2]). I validated the numerical modelling through comparing the results with Sainflou's analytical equation for the design of vertical seawalls (Sainflou [114] and Ackhurst [2]), which is as follows:

$$p_d = \frac{\rho g H \cosh k(d+z)}{\cosh kd} \cos \sigma t \tag{3.1}$$

where $p_d$ is the hydrodynamic pressure, $\rho$ is water density, $g$ is the gravitational acceleration, $H$ is the wave height, $d$ is water depth, $k$ is the wavenumber, $z$ is the difference in still water level and mean water level, $\sigma$ is the angular frequency and $t$ is time. Sainflou's equation (Equation 3.1) is used to calculate the dynamic pressure from wave action, which is combined with static pressure on the seawall.

Using Flow3D-Hydro, a model of the Dawlish seawall was made with a computational domain which is 250.0 m in length, 15.0 m in height, and 0.375 m in width (Figure 3.5(a)). The computational domain was discretised using a single uniform grid with a mesh size of 0.1 m. The model has a wave boundary at the left side of the domain (x-min), an outflow boundary on the right side (x-max), a symmetry boundary at the bottom (z-min) and a wall boundary at the top (z-max). A wall boundary implies that water or waves are unable to pass through the boundary whereas a symmetry boundary means that the two edges of the boundary are identical and therefore there is no flow through it. The water is considered incompressible in the model. For volume of fluid advection for the wave boundary (i.e., the left-side boundary) in the simulations, I utilised the "Split Lagrangian Method", which guarantees the best accuracy [34].

The stability of the numerical scheme is controlled and maintained through checking the Courant number ($C$) as given in the following:

$$C = \frac{V \cdot \Delta t}{\Delta x} \tag{3.2}$$

where, $V$ is the velocity of the flow, $\Delta t$ is the time step and $\Delta x$ is the spatial step (i.e., grid size).

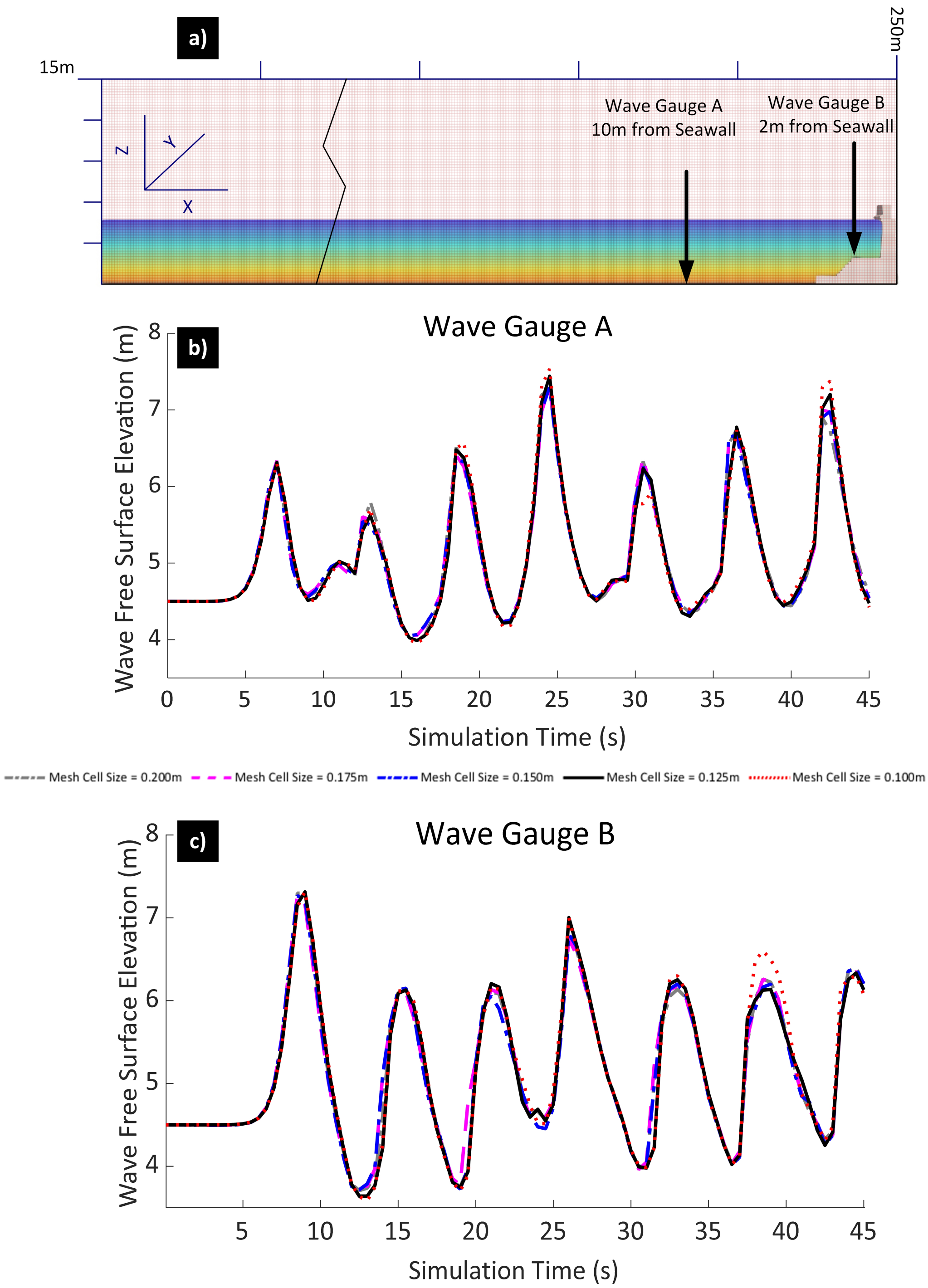



**Figure 3.5:** a) The model seawall showing the location of two gauges A and B, where wave time series are recorded (not to scale). b) and c) Time series of wave oscillations at the gauges A and B considering different mesh cell sizes.

The Courant number is a non-dimensionless group used in CFD simulations to evaluate the time step requirements of a transient simulation for a given mesh size and flow velocity. In a simulation the number broadly indicates how much information travels across a computational grid cell per unit time. Any number greater than one would mean information is propagating over more than one cell at a time, making the solution inaccurate and potentially leading to nonphysical results or divergence of the solution. For stability and convergence of the numerical simulations, the Courant number must be sufficiently below one (Courant, Friedrichs and Lewy [21]). This is maintained by a careful adjustment of the $\Delta x$ and $\Delta t$ selections. In transient and pseudo-transient approaches to solutions the time step implemented does not nee to constant. Flow3D-Hydro applies a dynamic Courant number, meaning the program adjusts the value of time step ($\Delta t$) during the simulations to achieve a balance between accuracy of results and speed of simulation. In the simulation, the time step was in the range $\Delta t =$ 0.0051 - 0.051 s.

In order to achieve the most efficient mesh resolution, I varied cell size for five values of $\Delta x =$ 0.1 m, 0.125 m, 0.15 m, 0.175 m, and 0.20 m. Simulations were performed for all mesh sizes and the results were compared in terms of convergence, stability and speed of simulation (Figure 3.5). A linear wave with an amplitude of 1.5 m and a period of 6 s was used for these optimization simulations. I considered wave time histories at two gauges A and B and recorded the waves from simulations using different mesh sizes (Figure 3.5). Although the results are close (Figure 3.5), some limited deviations are observed for larger mesh sizes of 0.20 m and 0.175 m. I therefore selected mesh size of 0.125 m as the optimum, giving an extra safety margin as a conservative solution.

The pressure from the incident waves on the vertical wall are validated in the model by comparing them with the analytical equations of Sainflou [114], Equation 3.1, which is one of the most common sets of equations for design of coastal structures (Figure 3.6). The model was tested by running a linear wave of period 6 s and wave amplitude of 1.5 m against the wall, with a still water level of 4.5 m. It can be seen that the model results are very close to those from analytical equations of Sainflou [114], indicating that the numerical model is accurately modelling the wave-structure interaction (Figure 3.6).

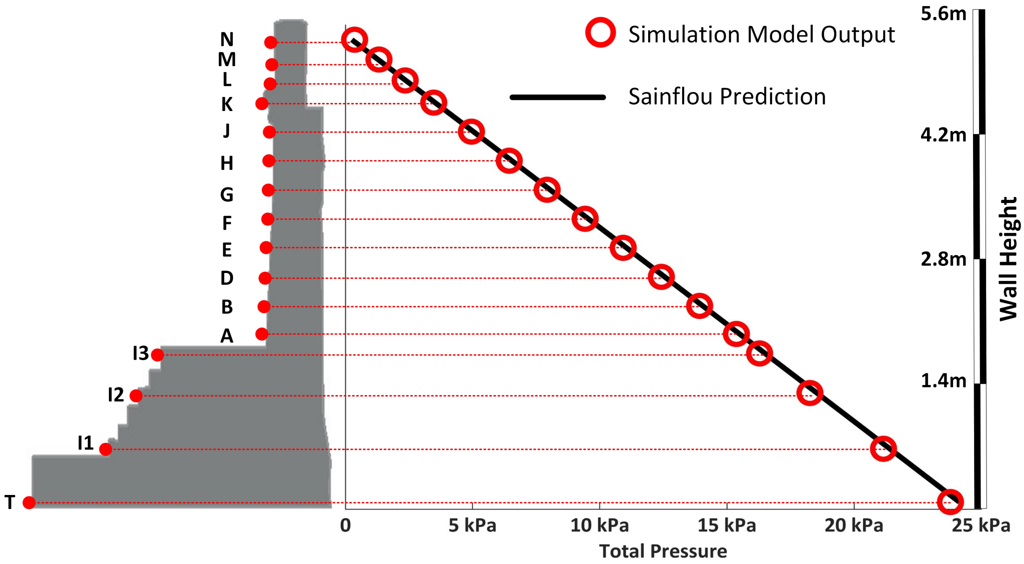



**Figure 3.6:** Validation of the computer model seawall showing the probe locations (with identifiers) where pressures are recorded and comparison of the simulated pressures for a linear wave (red circles) with those calculated using the theoretical equations of Sainflou [114]

## 3.8 Synopsis

This chapter has collated, compared and expanded on the current state-of-the-art data and methods for the formation of a multi-hazard cascading risk model for vital coastal infrastructure. I have achieved this through research and analysis of contemporary reporting of disaster events on the railway line since its inception in

1845 up to, and including, February 2014 when a catastrophic event took place on the line and resulted in an unprecedented service suspension.

A mechanism for disaggregating damage data reporting has been developed and the process of using failure tree analysis for civil engineering application has been improved and described.

Novel use of raw, quality controlled data from both tide gauges and wave buoys have allowed me to develop an understanding of the underlying sea-state conditions in the preceding hours before a catastrophic storm struck the seawall at Dawlish in Devon. Using eye witness accounts and cross-referencing these to social media reports has allowed me to understand the genesis of a disaster in real time.

I describe a process for validating the wave-structure interactions for a vertical seawall, like that in Dawlish, during a storm. Using a commercial CFD package validated against the equations of Sainflou, I was able to show excellent agreement between predicted model pressures and those analytically derived.

Chapter 4

# Development of a Cascading Multi-Hazard Risk Model

## 4.1 Introduction

In this research, I study historical and contemporary data on the failure of the Dawlish railway by storm induced forces to establish a multi-hazard risk model with cascading failure pathways (FPW) which could be used with an exposure database to evaluate risk to the structural assets. I use primary historical accounts and identify damage mechanisms (DM) and FPW that cascade between separate DM. The innovation in this study is the identification of storm initiated multi-hazards and the development of cascading structural vulnerabilities of rail network infrastructure in the UK. To my knowledge, this is one of the pioneering multi-hazard risk models with cascading FPW for rail networks in coastal settings. The combination of historical damage data with contemporary engineering understanding of cascading risk is a particular strength of this research. A multi-hazard risk model such as this would be beneficial for improving the resilience of the railway network to severe weather events by providing a tool that predicts possible FPW to inform future engineering interventions.

## 4.2 Analysis of Historical Records of Railway Damage

Despite Victorian (1837-1901 AD) engineering determination that man could curtail the action of the seas, 'Mr Brunel [the chief engineer] is confident that he can keep out the sea from the line' (Figure 3.1a), damage to the railway's seawall and associated engineering assets were a feature of constructing and operating the railway in Dawlish from the beginning in 1845. Initial damage was to the wall structure since it was constantly bombarded by energetic coastal waves whilst being built. Early recognition that stronger materials were needed is reported in the press: 'coping and seawall, formed of massive blocks of sandstone, are destroyed', while the engineering team searched for a local supply of stronger stone: '... massive wall of Babbicome limestone, with a back filling of layers of fagot and sandstone.' The cost of the remedial works to decrease the vulnerability of the seawall were estimated: 'in vain to shrink even from £100,000' [13], which in present-day value is equivalent to £6m [125].

However, it was only a few years later that a second hazard was to be identified. The soft sandstone cliffs that were blasted and used to build the seawall, and subsequently used to backfill the stronger sections, gave way in the winter of 1852 on two occasions and a few months later in 1853 [61]. In the historical records of significant damage events (Figure 4.1), 29% of occurrences involved slope instability or cliff face failure above the railway line, while 62% involved seawall failure (masonry, coping and toe scour). Successive newspaper reports and technical records show that damage was sustained in a similar manner

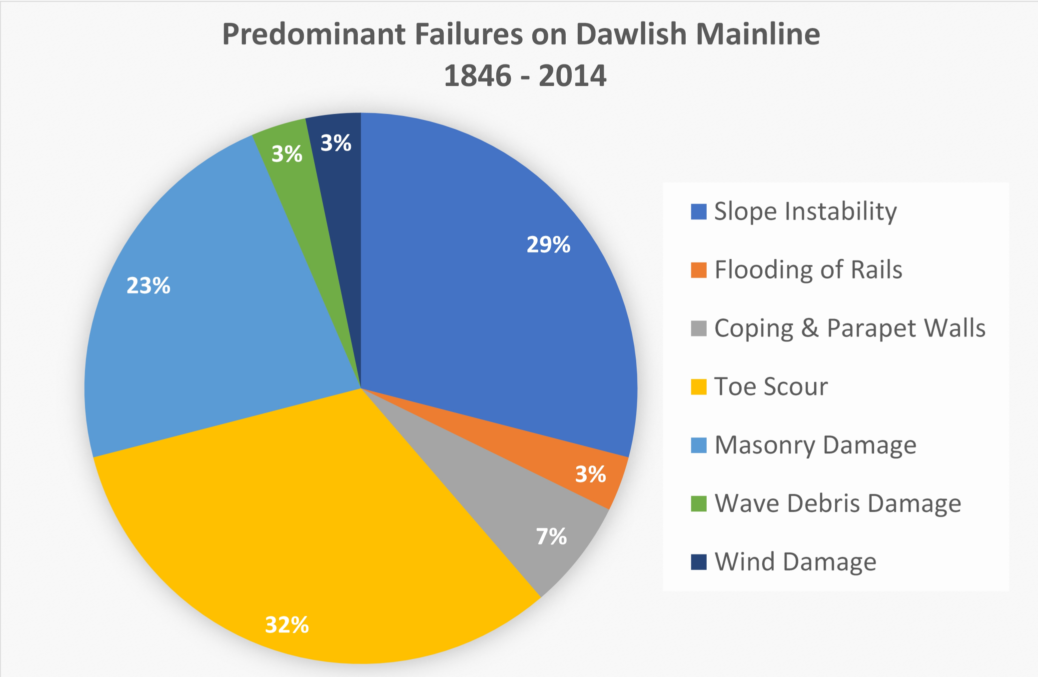



**Figure 4.1:** Relative predominance of cause of failure on the Dawlish Mainline derived from data in Table 3.1

throughout the life of the railway on average every decade or so (Table 3.1). In the few occurrences where seawall failure or geotechnical considerations are not explicitly mentioned, the force of water due to excessive overtopping has been responsible for flooding of the rails (3%) while wave debris damage accounted for 3% and direct wind damage a further 3%. Figure 4.2 presents some images of major historical damage of a few of the incidents listed in Table 3.1.

In all cases of significant damage, weather considerations were implicitly implicated. The easterly facing embayed nature of the Dawlish coastline makes it vulnerable to high spring tides, supplemented by storm surge when accompanied by deep cyclonic storms blowing south-easterlies landwards. Heaps [44] points out that along the southern coastlines of the UK, the tidal conditions at the time of a storm surge are often the most important factor – high spring tides coupled with hydrodynamic forcing can result in high water levels risking flooding as well as large waves which impart strong forces on coastal infrastructure. Figure

3.1b shows the line of high-water ordinary tides as being at or above the wall footings. To the east of the site of the 2014 damage at Rockstone, high-water ordinary tide is shown as being beyond the track bed and seawall. In these circumstances it is not surprising that 11 separate incidents from a total of 29 ($\approx$38%) can be attributed to the Sea Lawn and Rockstone areas (Table 3.1). Dawlish's soft red sandstone geology and the weathering of the cliffs in this bay has historically provided material for beach nourishment. The historical and contemporary accounts are consistent; during extended periods of stormy weather such as encountered during winter months (November to March), beach levels can be significantly eroded leading to the toe sections of the wall being uncovered. The lower beach levels lead to higher significant wave heights which in turn exert higher impact forces on the structure and in turn increased toe scour.

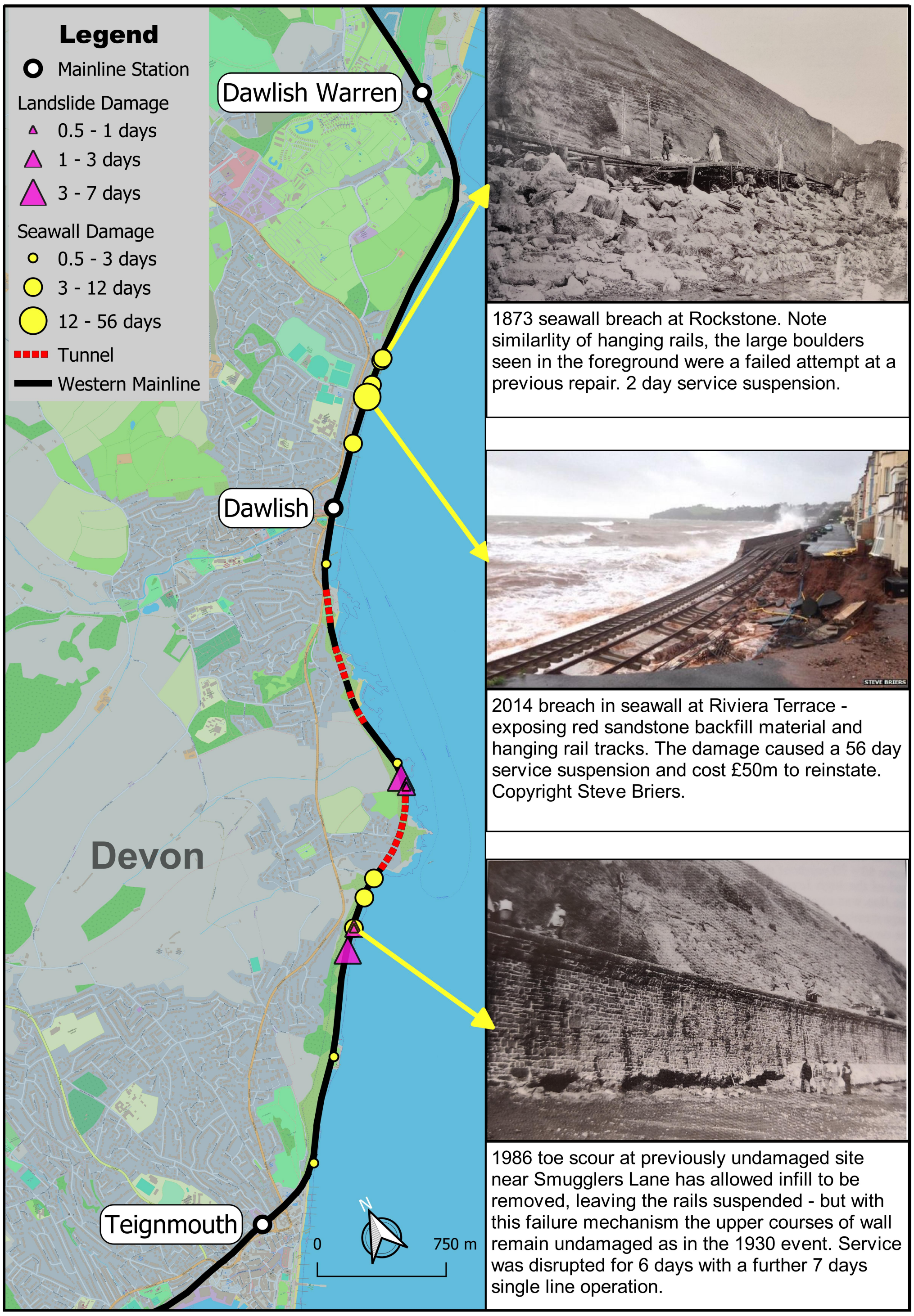



**Figure 4.2:** Position and magnitude of historical damage events on the coastal section of the Western Mainline between Exeter and Newton Abbott. The size of the circles and triangles are proportional to the number of closure days.

## 4.3 Dawlish Railway Risk Model

Based on the data in Table 3.1 and the damage descriptions in historical and contemporary accounts, I established the multiple hazards contributing to railway failure, their cascading order, DM and FPW. For each of these I developed a separate flowchart. In terms of railway resilience to storms and weather incidents, such flowcharts are helpful towards identifying the weak links in the infrastructure system and to the strengthening of those elements to reduce vulnerability.

I combined the separate flowcharts to form the proposed risk model consisting of five layers of precedence (Fig.4.3):

1. A triggering event (see Pescaroli [101]) which contributes to the hazard element of the risk equation (in this case a storm). The initiating hazard is temporally coincident with strong easterly to south easterly winds, sustained rainfall and high spring tides. The combined effect is to significantly increase energy delivery to the coastline.

2. Hazard force differentiation where discrete energy transfer processes encompassing wind, wave and excess soil pore pressure are generated. Each of these represent a DM which consequently initiates:

3. A series of common cause failures (FPW) which can occur simultaneously, are related to structural vulnerability and lead to:

4. Cascading failures which can link separate DM and has the effect of increasing the severity of the event, and ultimately:

5. Network failure and resulting railway service suspension – exposure.

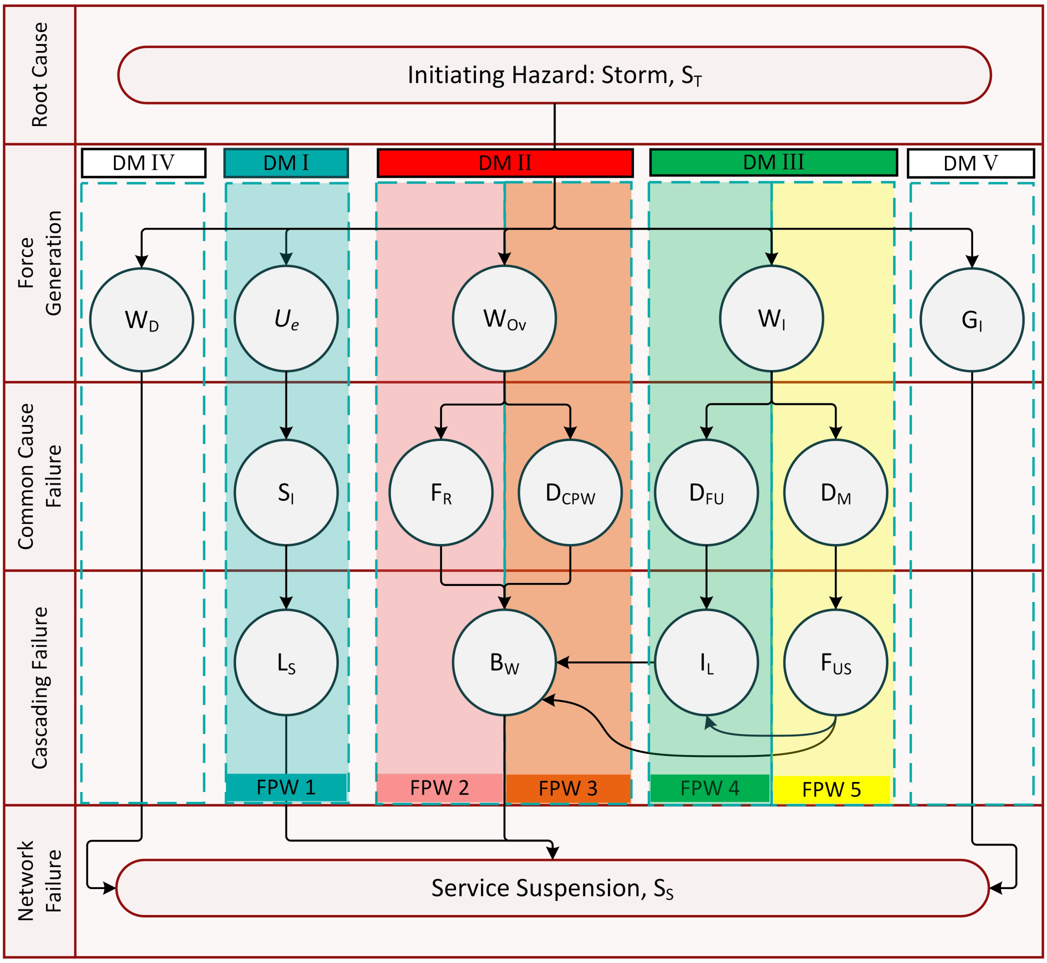



**Figure 4.3:** Risk model for the Dawlish railway network. Where: $\mathrm{S_T}$: storm; DM: damage mechanisms; $\mathrm{W_D}$: wave debris impact force; $\mathrm{U_e}$: excess pore pressure in the soil; $\mathrm{S_I}$: slope instability; $\mathrm{L_S}$: landslide; $\mathrm{W_{Ov}}$: wave overtopping force; $\mathrm{F_R}$: flooding of rails; $\mathrm{D_{CPW}}$: damage to coping stones and parapet walls; $\mathrm{B_W}$: ballast washout; $\mathrm{W_I}$: wave impact force; $\mathrm{D_{FU}}$: foundations undermined due to toe scour; $\mathrm{D_M}$: damage to masonry elements; $\mathrm{I_L}$: loss of infill material; $\mathrm{F_{US}}$: failure of upper sections of wall; $\mathrm{G_I}$: Wind impact force; FPW: failure pathway; $\mathrm{S_S}$: service suspension.

The three most common damage mechanisms (DM I to DM III) develop five separate failure pathways (FPW 1 to 5) each one associated with a common cause failure in the third layer of the risk model.

## 4.4 Analysis of Damage Mechanisms

The risk model identifies five damage mechanisms, each with their own generating force, these are:

**DM I:** Excess pore pressure $(\mathrm{U_e})$ in the shear faced cliff soils generated by prolonged rainfall leading to slope instability and landslide (Fig.4.4b).

**DM II:** Overtopping forces $(\mathrm{W_{OV}})$ generated by wave heights incident on the front face of the seawall energetic enough to propel water above the top surface of the seawall and onto the back side of the structure, initiating direct ballast washout due to rails flooding or damage to the coping stones and parapet wall separating the railway from the seawall frontage (Fig.4.5).

**DM III:** Hydraulic impact forces $(\mathrm{W_I})$ which involve the transfer of energy from the incoming waves (whether breaking or not) onto the vertical surface of the seawall, causing failure of main seawall elements due to masonry damage usually affecting the upper sections of the wall or due to loss of infill material after foundation failure initiated by toe scour (Fig.4.8c).

**DM IV:** Wave debris impact $(\mathrm{W_D})$ which involves the transport of material in the water column and subsequent impact of that on network infrastructure requiring service suspension.

**DM V:** A wind-dominated impact force $(\mathrm{G_I})$ which can damage and destroy elements of the network due to the speed and gusting of the prevailing winds and precipitate a service suspension.

The first three DM represent 94% of all recorded significant events (Fig.4.1). These three main DM are discussed in more detail following. Cascading failure between DM II and III result in indirect ballast washout and ultimate service suspension. I observed that more than one mechanism can be activated in an event.

### 4.4.1 DM I: Landslide

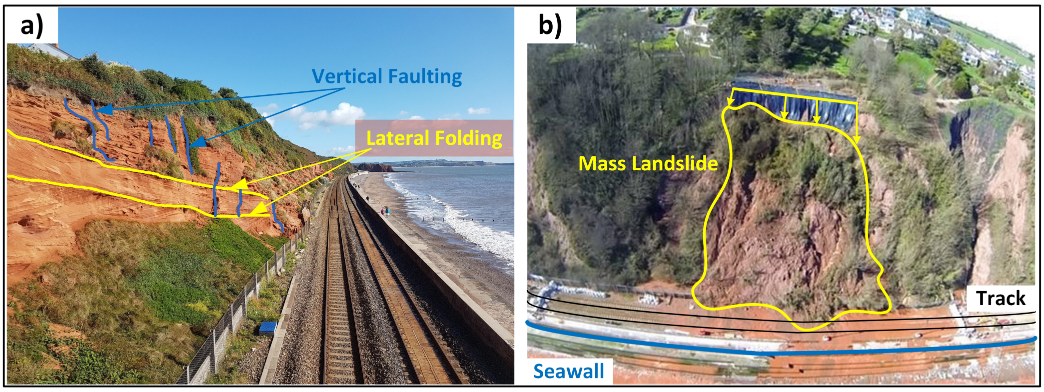



**Figure 4.4:** a) Highly folded and faulted shear faced red sandstone cliffs separated from English Channel by the Railway line near the Dawlish railway station. b) 20,000 tonne landslides at Holcombe near Dawlish [85]

Landslides typically have multiple causes, but only one trigger. The trigger is an external stimulus such as storm waves, increased hydrostatic water pressure or rainfall that causes a response in the form of a landslide by increasing stresses or by reducing the strength of slope materials. Sometimes, there appears to be no trigger due to long term action of gradual slope deterioration due to, for instance, chemical or physical weathering of soil components. Excess pore pressure builds in the soil and leads to slope instability in the shear faced cliffs, which then activates a landslide – this is a linear DM which can, of itself, result in network failure.

The soft red Permian breccias and sandstone rock-faces in south Devon have provided beach material for the coastline through natural erosion for centuries. When the seawall was erected 170 years ago, a vital supply of material was isolated from the foreshore; in addition, the blasting of the cliffs to provide even alignment and backfill, exposed shear faces and steep inclines to weathering by precipitation. Despite efforts especially in the 1920s to regrade the slopes to make them more stable, the typical slope angles observed along the coastal railway are often in excess of $65°$ and in some instances approach $90°$ shear faces. The sandstone is widely folded and faulted along the coast (Fig. 4.4a), and this makes it particularly unstable when there is a period of extended rainfall. The steep gradients result in frequent shallow landslides of the soil and weathered rock during the winter storm season caused by slope instability as excess pore pressure is released. This mechanism is well documented and involves the exceedance of combined thresholds of intensity and duration of storm related rainfall. For instance Cannon [16] successfully identified landslide triggering rainfall thresholds for more than 18,000 shallow landslides involving soil and weathered rock. These movements were often similar in nature to the events seen in Dawlish and were triggered at thresholds which ranged from 20mm/hr rainfall for 4 hours, to 8mm/hr for 24 hours. This difference in duration explains the temporal displacement of landslide events. It should be noted that these thresholds are regional, depending on geologic, geomorphic and climatological conditions.

The rapid infiltration of rainfall, causing soil saturation and a temporary rise in pore water pressures is generally believed to the mechanism which most shallow landslides are generated during storms according to Wieczorek [135].

Although landslides (Fig. 4.4b) may accompany wave damage of the seawall, they are seldom reported separately in the historical reports.

### 4.4.2 DM II: Wave Overtopping

Ballast washout is the terminal cascading failure which causes service suspension in all cases of masonry damage from wave overtopping. Despite the engineers' assertion that they could 'keep out the sea from the line' (Fig.3.1a), at times of normal high tide, the water surface is barely 0.5 m from the top of the coping stones of the seawall near the site of the 2014 collapse (Fig.4.5a) and this often leads to preventative line closures when high tide and weather risks coincide [90]. With easterly wind direction and large waves incident on the seawall [74], the railway has often suffered from wave overtopping forces which, when significant, can flood the tracks and wash the ballast away (Fig.4.5c), leaving the railway inoperable. This FPW 2 occurs often and is generally accompanied by masonry damage or undermining of foundations of the seawall (Fig.4.5d).

Wave overtopping often results in enough force transfer to activate FPW 3 causing coping stones at the top of the seawall to be removed or broken (Fig.4.5b). These large stones, typically granite, are then propelled against the adjacent 1 m high parapet wall that separates the track bed with the promenade (Fig.4.5e). The damaged parapet then fails with successive wave overtopping and blocks the rail line. This can occur over a significant distance along the coastal railway and is usually repaired by the dedicated line gang based at Dawlish railway station.

### 4.4.3 DM III: Wave Impacts

FPW 4 involves wave impact forces causing damage to the foundations of the seawall due to toe scour and loss of infill material.

This is a bottom-up mechanism, where sections of the wall will often be affected by lower masonry being removed following destruction of the toe protection (Fig.4.6). Here the backfill material behind the upper sections of the wall are not removed so protecting them from collapse; however, backfill is removed near the toe by suction from successive waves and eventually the lower masonry sections yield. This is the most common and significant failure mechanism among

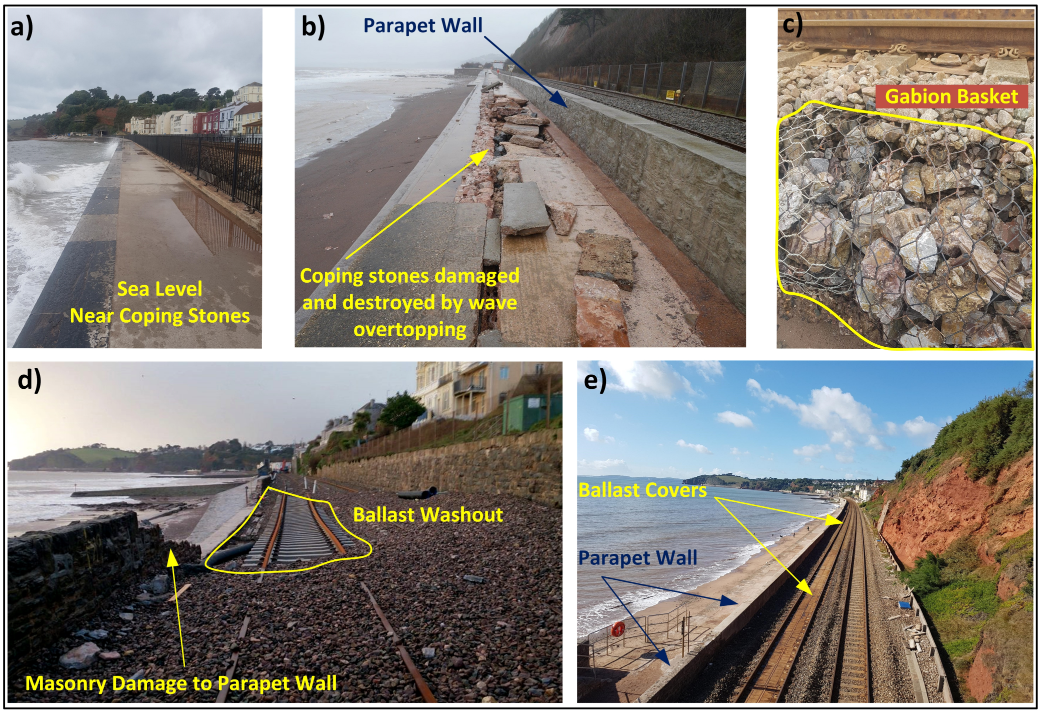



**Figure 4.5:** a) Ordinary high tide close to coping stone level, 2018. b) Wave overtopping damage to coping stones [138]. c) Ballast protection using gabion wire mesh baskets. d) Washout due to overtopping accompanied by parapet wall masonry damage in 2014 [109]. e) Ballast covers on the line closest to the sea as mitigation for wash-out. Pictures a,c,e by author (2018).

the damage incidents studied in this research accounting for 55% of all events (masonry damage 23% and toe scour 22%) (Fig.4.1).

Wave impact removes large amounts of sand cover during storms, thereby exposing the footings of the foundations of the main seawall. Toe scour due to successive wave trains leads to accelerated erosion at the interface of the soft red sandstone foundation and the more durable rock forming the frontage of the railway seawall. Waves wear away the foundation and then backfill material is sucked out of the cavity behind the frontage. In the absence of infill material, masonry damage to the wall fascia is sustained either at low or high level by wave impact force. This can lead to the rail tracks being left suspended in mid-air (Fig.1.1, 4.2, 4.8).

Whereas toe scour is initiated through a bottom-up mechanism, masonry damage is a top-down wave impact failure, initiated in the seawall by removal of upper courses of masonry. Although this FPW 5 is not the most common it has the potential to be the most expensive and disruptive, it often accompanies the top sections of coping and parapet walls failing due to overtopping of waves (FPW 3). Subsequently flooding of the rail bed occurs and ballast is washed away exposing backfill material. Wave impact forces then remove the upper courses of masonry allowing washback of overtopped water and infill material to the sea. Repeated actions over a high tide then accentuates the mechanism and causes further masonry to be removed. The cascading nature of the failure of the upper courses of masonry and ballast washout significantly increases the severity of the event.

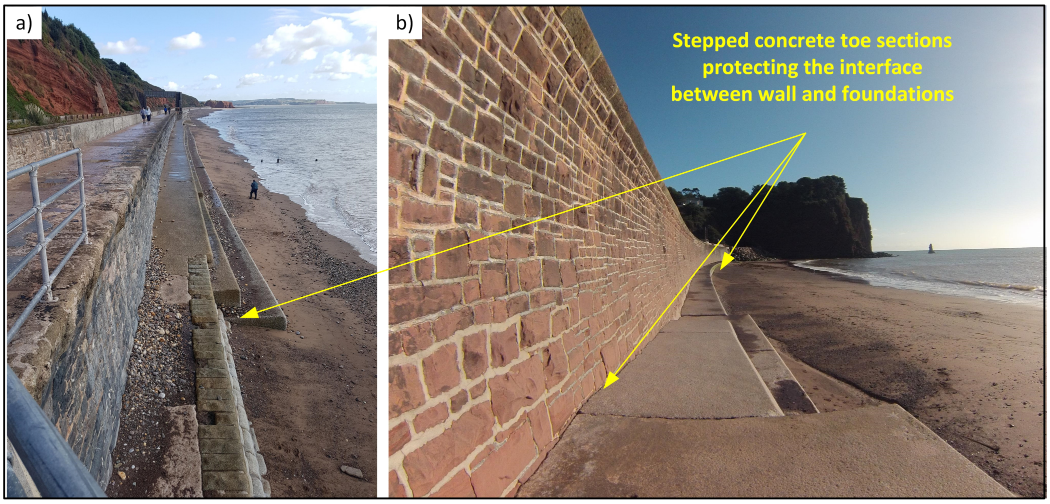



**Figure 4.6:** Stepped toe protection keyed into existing wall foundations providing increased resistance to scour. a) Granite faced wall near the site of the 2014 storm damage in Dawlish. b) A section of original sandstone seawall near Holcombe, Dawlish.

## 4.5 Model Application in South Devon

Two applications of the multi-hazard risk model are presented as case studies for the Dawlish railway below.

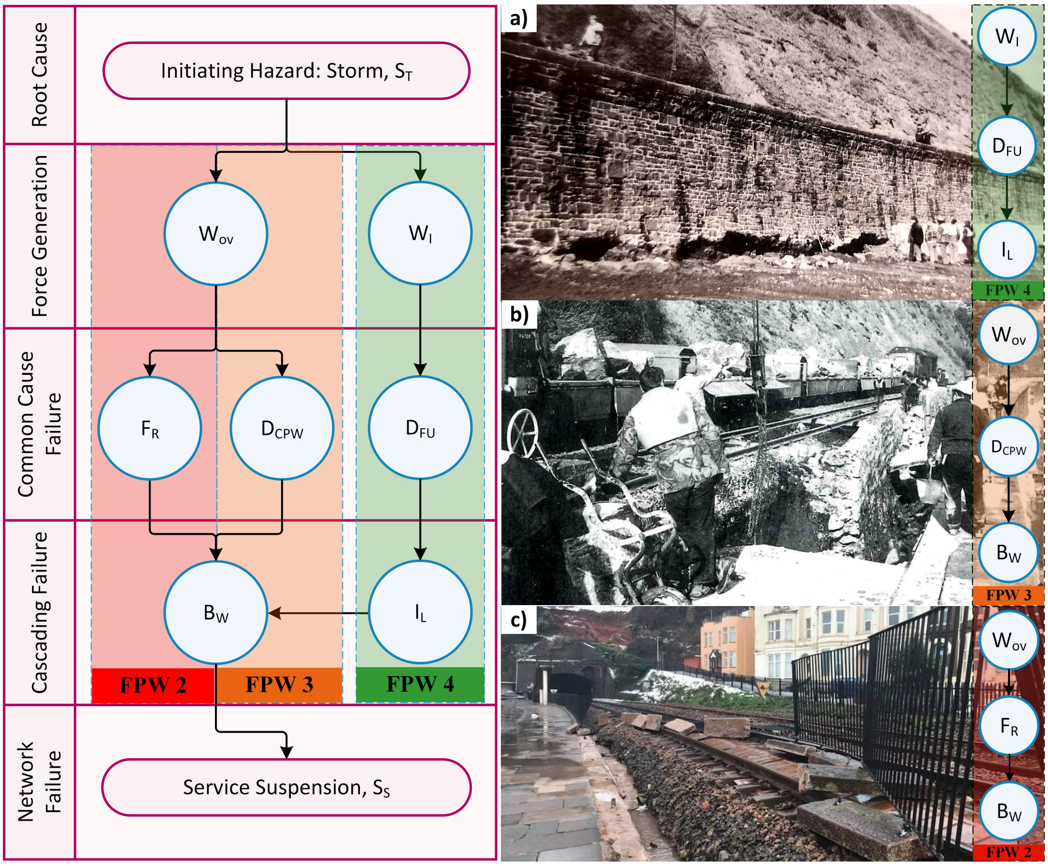



**Figure 4.7:** Event flowchart for the 1986 seawall failure. a) Railway engineers inspecting the foundation failure due to toe scour after wave impact damage. b) The result of overtopping is shown here: removal of coping and parapet walls. c) Recent example of damage after rail flooding and ballast washout due to wave overtopping. Where: $\mathrm{S_T}$: storm; $\mathrm{W_I}$: wave impact force; $\mathrm{D_{FU}}$: foundations undermined due to toe scour; $\mathrm{I_L}$: loss of infill material; $\mathrm{W_{OV}}$: wave overtopping force; $\mathrm{F_R}$: flooding of rails; $\mathrm{B_W}$: ballast washout; $\mathrm{D_{CPW}}$: damage to coping stones and parapet walls; $\mathrm{S_S}$: service suspension; FPW: failure pathway.

### 4.5.1 The 1986 incident

Evidence was collated for an incident that occurred on February 26, 1986 following a violent storm. Dawson, Shaw and Gehrels [26] used information gathered from Rogers and O'Breasail [112] to detail the remedial works required following a failure to the seawall (Fig.4.7a). I cross referenced this material with Network Rail [87] and Kay [61] to detail the specific failure paths that were activated. I identified the involvement of DM II and III (as described above) through three FPW as shown in Fig.4.7. The storm generated wave impact and overtopping forces on a previously undamaged section of the original seawall between Dawlish and Teignmouth. Impact damage caused toe protection to be stripped away (Fig.4.7a) and led to a common cause failure of the foundations due to undermining. A cascading failure of loss of infill material behind the wall and ballast washout followed (Fig.4.7b). At the same time, wave overtopping forces caused flooding of rails and damage to the coping stones and parapet walls cascading to a ballast washout (Fig.4.7c). Service was suspended for six days and for a further seven days of single line closure (Table 3.1).

### 4.5.2 The 2014 incidents

During February 2014, a series of storms coincided with high tides to cause severe damage to the rail network in the South West of England. The events were extensively reported in the press and were the subject of academic articles [75, 26, 74] as well as technical and impact assessments by the network operator [88, 110, 87] and local community and business groups [100]. I collated this information into a database of articles, pictures and videos to obtain a clear view of the timeline of the events and their sequencing specifically in terms of damage to the engineering assets of the railway. A field survey was conducted in September 2018 to examine the site of the damage and to evaluate the restoration works undertaken. The local museum in Dawlish [25] provided extensive information on the disaster, augmented by interviews with residents, engineers and emergency workers involved in the first response and subsequent rebuilding.

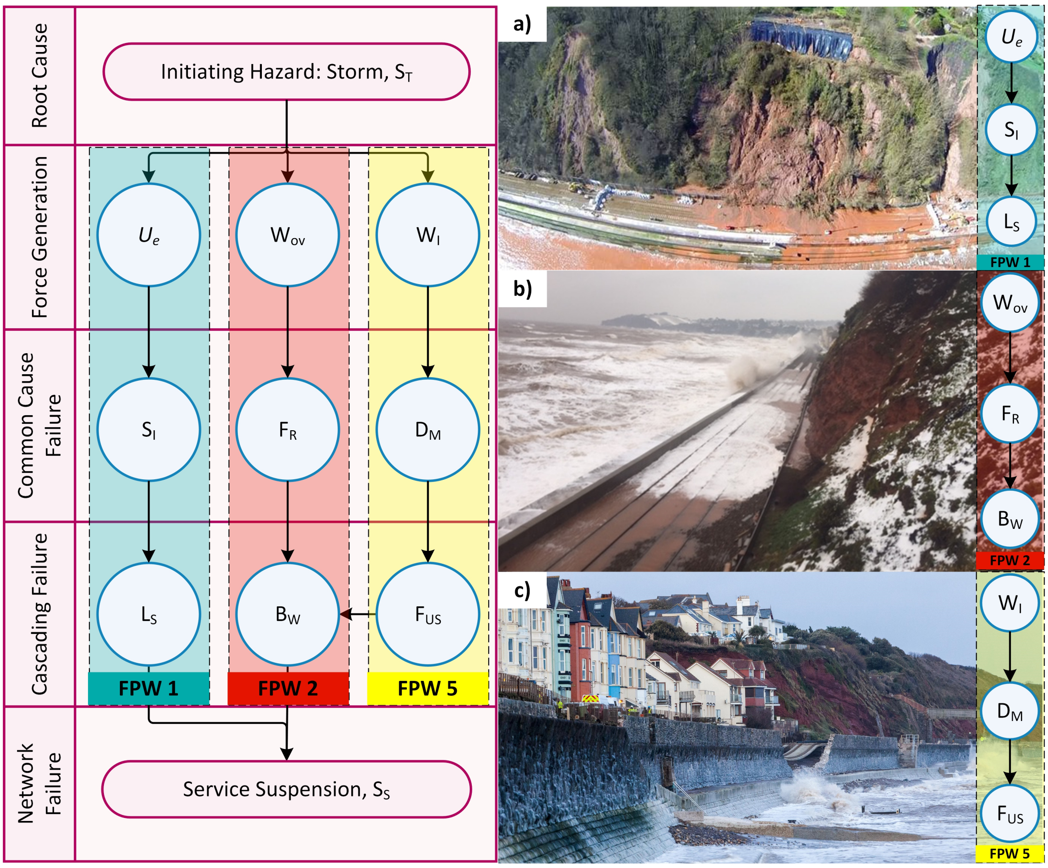



**Figure 4.8:** Event flowchart showing multi-hazard and cascading failures that led to the Dawlish network failure of February 2014. a) 20,000-tonne landslide between Dawlish and Teignmouth activating first failure path [85]. b) Failure path with significant wave overtopping flooding rails and leading to ballast washout. [89] c) Failure path of the upper sections of the seawall due to wave impact forces [84]. Where: $\mathrm{S_T}$: storm; $\mathrm{U_e}$: excess soil pore pressure; $\mathrm{S_I}$: slope instability; $\mathrm{L_S}$: landslide; $\mathrm{W_{OV}}$: wave overtopping force; $\mathrm{F_R}$: flooding of rails; $\mathrm{B_W}$: ballast washout;$\mathrm{W_I}$: wave impact force; $\mathrm{D_M}$: damage to masonry elements; $\mathrm{F_{US}}$: failure of upper sections of wall; $\mathrm{S_S}$: service suspension; FPW: failure pathway.

The seawall was reported to have failed during storms on the February 4, 2014, although I have studied reports and interviews with witnesses which prove the damage was initiated on the 3rd of February. Evidence suggests that three FPW were activated which led to the two-month suspension of service as shown in Fig.4.8. I identified the involvement of DM I, II and III with the following FPW for the 2014 event:

**FPW-1**: Long periods of high rainfall were sustained in the area prior and subsequent to the February damage to the seawall; this had the effect of causing a large landslide on 21st March due to slope instability brought on by excess pore pressure in the shear faces of the sandstone cliffs above the railway line (Fig.4.8a). This increased the severity of the disaster and represented a multi-hazard aspect to the event, lengthening the period of reconstruction and significantly impacting on the costs of recovery.

**FPW-2**: Wave overtopping and flooding of the rails led to significant amounts of direct ballast washout (Fig.4.8b); this flooding has the effect of displacing the ballast which supports the rails and uncovers the backfill material underneath. When overtopping and wave impact forces combine, further waves incident on the structure cause the infill to fluidise and become more mobile – hence material is washed out to sea and additional damage to the masonry structure is sustained. The result is V-shaped damage to the wall and hanging rails over a void space (Fig.1.1, 4.2, 4.8c).

**FPW-5**: The storm generated wave impact forces which initiated a common cause failure, damaging masonry elements in the wall structure cascading to failure of the upper sections of wall and ballast washout (Fig.4.8c).

## 4.6 Model Application in other contexts

The resilience of coastal railways to natural hazards such as storms and surges is an important aspect of disaster risk mitigation in those countries with vulnerable transport infrastructure. The present risk model (Fig.4.3) is spatially specific to the Southwest England rail mainline through Dawlish but has application in other coastal railway alignments throughout the UK, such as in Cumbria, west and south Wales (Fig.1.1) where similar hazards are encountered and the engineering assets were constructed during the same era and using similar design methods. Adaptation of the hazard elements to include local meteorological and wave environments would allow direct usage of the model in those regions. An example application would be for the analysis of damage events such as the January 3, 2014 incident in Cumbria [86, 6]. High spring tides, storms and landward winds caused extensive damage to the embankments, ballast and track and forced a week long suspension of service near Flimby (Fig.1.1). Reports of this event would suggest DM II and III were activated with FPW 2,3 and 5 being involved in the cascading failure evident as shown in Fig.4.9.

This type of model may also be applicable to other countries. Koks, Rozenberg and Zorn [63] in their global risk analysis report that approximately 27% of all road and rail assets are exposed to at least one hazard worldwide. In Italy, coastal infrastructure has been shown to be vulnerable to wave action and severe erosion [27] and specifically railway infrastructure along the Battipaglia-Reggio Calabria coastline [1]. For sea level rise and increased storminess, Dawson, Shaw and Gehrels [26] report potentially vulnerable coastal transport infrastructure in several major international cities. A key facet of the proposed model is the adaptive nature of its elements. Kazama and Noda [62] discuss the effects of the Japan

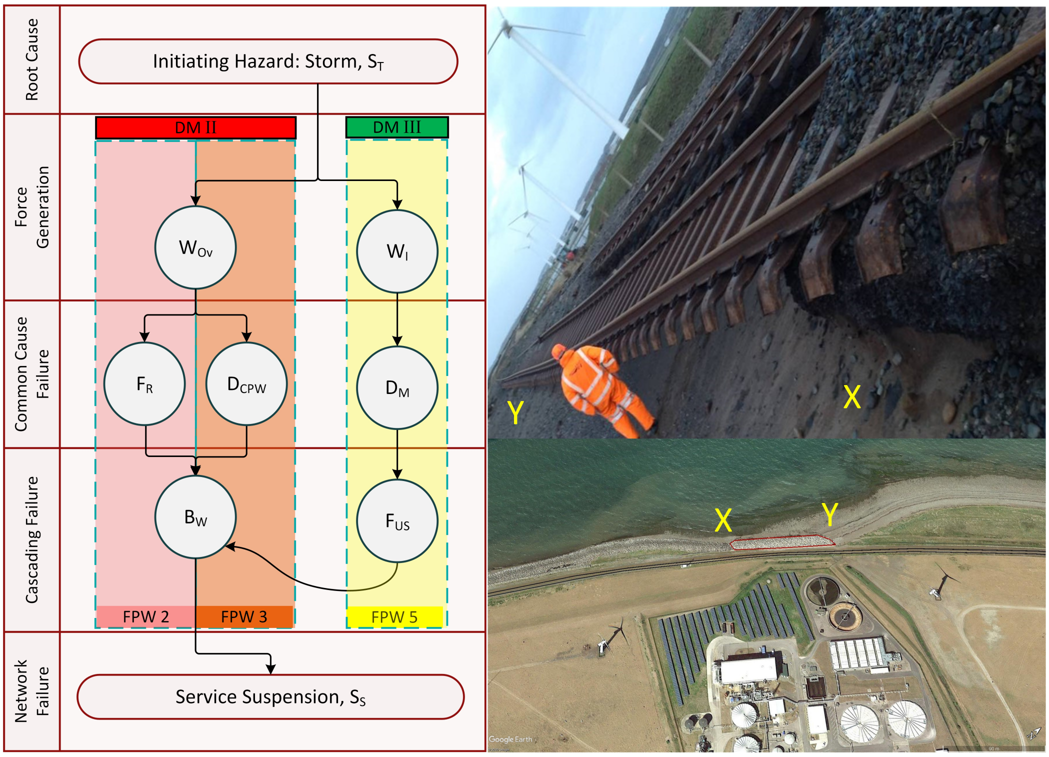



**Figure 4.9:** Event flowchart showing multi-hazard and cascading failures that led to the Cumbria network failure of January 2014. a) Network Rail inspecting rail bed failure near Flimby. b) Google Earth picture (2020) showing new rock armour reinforcement at same position. Where: $\mathrm{S_T}$: storm; $\mathrm{W_{OV}}$: wave overtopping force; $\mathrm{F_R}$: flooding of rails; $\mathrm{B_W}$: ballast washout; $\mathrm{D_{CPW}}$: damage to coping stones and parapet walls; $\mathrm{W_I}$: wave impact force; $\mathrm{D_M}$: damage to masonry elements; $\mathrm{F_{US}}$: failure of upper sections of wall; FPW: failure pathway; $\mathrm{S_S}$: service suspension.

2011 earthquake and subsequent tsunami event, reporting widespread rail network disruption in over 1700 locations. AIR international [66] in their modelling report of the 2011 great earthquake and tsunami also point out that water induced damages can outweigh the costs of earthquake and liquefaction in transport systems over a large spatial scale. Although this risk model has been developed for extratropical storms with hydrodynamic forcing, it has common DM and FPW that could be used for evaluation of risk following tsunami events. An example of this is for the Japan 2011 event where DM II - wave overtopping, FPW 2 and 3 are activated leading to flooding of rails and ballast washout [64]. These pathways were positively identified along with DM I leading to landslide, DM III leading to toe scour and loss of infill material behind earth retaining walls [65, 116] and DM IV – wave debris force, which is a rare occurrence for UK rail networks but a much more important, costly and common DM in tsunami induced failures [120].

One of the major strengths of this study and conversely challenges in implementing this approach to other settings is its reliance on long term records of damage incidents. The Victorian rail network in the UK and the coastal alignments are some of the oldest in the world and represent the first attempts at coastal engineering for vital transport infrastructure. The historical record stretches for 170 years with significant contributions in newspaper articles, books and company records. This research suggests that significant failure occurs on average every 8 years. Despite this comprehensive and long-term record there remains some epistemic uncertainty in the exact nature of the damage and sequence of events, increasing with older records – this is considered a limitation of the study. The amalgamation of the separate rail companies into GWR and then British Rail in the 1950's and the rationalisation of records means some details of engineering interventions have been lost and newspaper articles by their nature are non-technical so accentuating the uncertainty. The model is based on the hazard-vulnerability of the Dawlish railway, characterised by a vertical masonry seawall elevating the rail alignment above normal high tide level. The line is built along a coast characterised by soft sandstone deposits which readily weather and have historically provided nourishment for the beach. The age of the asset will affect its vulnerability and the application of the model to other Victorian coastal railways will be dependent on these criteria. However, the methodology and systematic identification of separate force mechanisms from a single initiating event provides a valuable tool for infrastructure stakeholders to tailor the model for diverse application as demonstrated briefly by reference to the Cumbrian mainline in north-west England and potential application to tsunami related damage following the 2011 event in Japan.

## 4.7 Synopsis

I developed a multi-hazard risk model with cascading FPW for the Dawlish railway through retrieving and analysing major damage incidents in the period 1846–2014 with the aim of risk reduction. This approach allowed me to:

- Identify 29 damage events of significant engineering impact (i.e. line closure more than 12 h) on the Dawlish railway in the period 1846–2014 through archival research of historical and contemporary data.
- Based on the railway damage data, the three most frequent DM were identified which are:
    - I: landslide
    - II: direct ballast washout due to wave overtopping
    - III: failure of the upper sections of the wall and loss of infill material after foundation failure due to wave impact force which cascade to indirect ballast washout.
- For each of the 29 failure events, I have identified the common hazard involved, deconstructed the sequence of civil engineering failures and formulated a flowchart for each event, showing the interrelationship of multiple hazards and their potential to cascade.
- For the February 2014 railway damage incident in Dawlish, three FPW were identified:

1) the storm generated wave impact forces which damaged masonry elements in the wall structure cascading to failure of the upper sections of wall and ballast washout;
2) washout exacerbated by additional wave overtopping leading to flooding of the rails; displacing the ballast and uncovering the backfill material underneath;
3) intensive rainfall causing large landslides due to slope instability brought on by excess pore pressure in the shear faces of the sandstone cliffs above the railway line.

- I was then able to develop a risk model for the civil engineering assets associated with the railway network in Dawlish with the potential to provide stakeholders with a probability-based method of risk evaluation following further development. The proposed model has five cascading layers in the top-down order of:

  a) triggering event (storm);
  b) force generation (debris impact, wave impact, overtopping, excess pore pressure, wind impacts);
  c) common cause failure (foundation scour, masonry damage, rail flooding, slope instability);
  d) cascading failure (landslide, ballast washout, upper masonry seawall failure, loss of infill material), and
  e) network failure forcing service suspension.

- I have demonstrated the application of the developed risk model to other vulnerable coastal railway infrastructure. In the case of storm and surge damage I have used the example of the Cumbrian coast railway in the

UK where I identified DM II and III were activated with FPW 2,3 and 5 being involved in the cascading failure evident. In a further extension of its applicability, I have demonstrated the potential for the model to be used in other diverse hazard environments with differing initiating hazards. An example is given of the Tohoku (Japan) earthquake and tsunami of 2011 where I identified DM II - wave overtopping, FPW 2 and 3 leading to flooding of rails and ballast washout, along with DM I leading to landslide, DM III leading to toe scour and loss of infill material behind earth retaining walls and DM IV – wave debris force.

Chapter 5

# Numerical Modelling and Reconstruction of the Seawall Failure

## 5.1 Introduction

The progress of climate change and increasing sea levels has started to have wide ranging effects on critical engineering infrastructure (Shakou et al. [115]). The meteorological effects of increased atmospheric instability linked to warming seas mean we may be experiencing more frequent extreme storm events and more frequent series or chains of events as well as an increase in the force of these events, a phenomenon called storminess (Mölter et al. [81] and Feser et al. [33]).

Features of more extreme weather events in extratropical latitudes (30° - 60°, north and south of equator) include increased gusting winds, more frequent storm squalls, increased prolonged precipitation, rapid changes in atmospheric pressure and more frequent and significant storm surges (Dacre and Pinto [24]).

A recent example of these events impacting the UK with coincident significant damage to coastal infrastructure was the extratropical cyclonic storm chain of winter 2013/14 (Masselink et al. [74] and Adams and Heidarzadeh [3]). The cluster of storms had a profound effect on both coastal and inland infrastructure bringing widespread flooding events and large insurance claims (R.M.S. [105]).

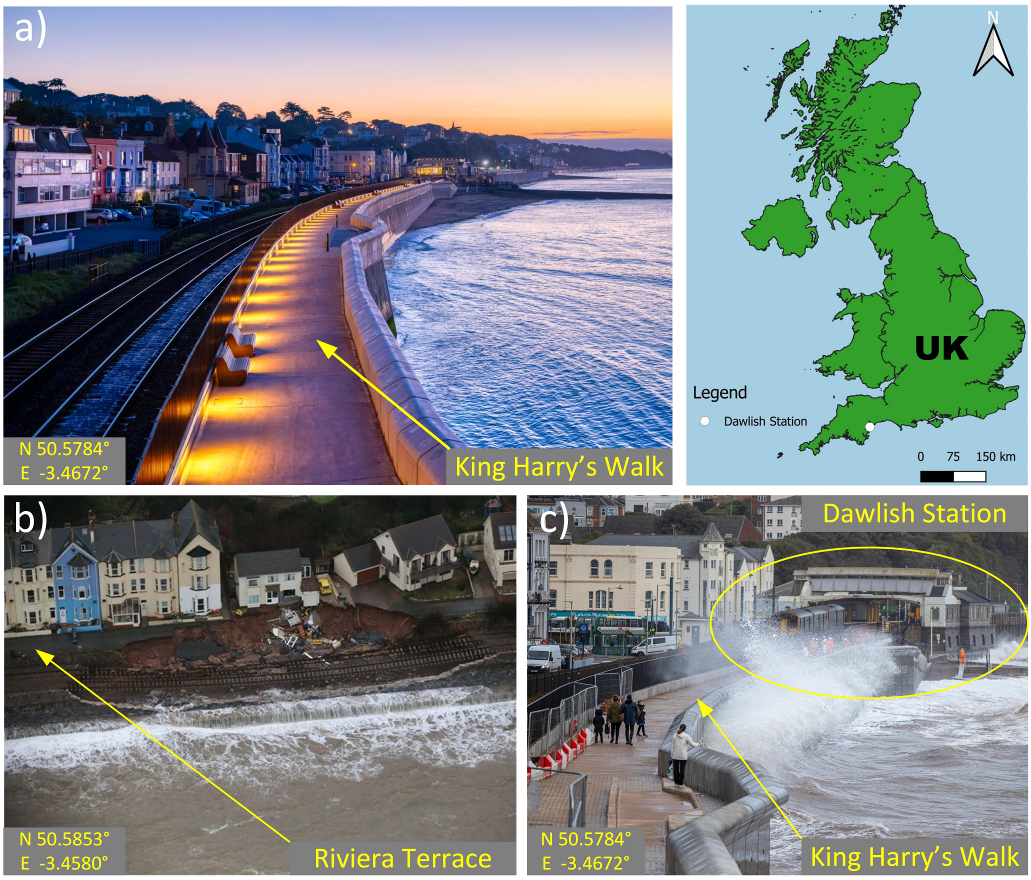



**Figure 5.1:** Location of Dawlish railway station. a) The completed section of the new seawall looking towards the train station along King Harry's Walk. b) An aerial view of the seawall damage sustained at Riviera Terrace in February 2014.c) Waves impacting the newly constructed seawall south of the station, now 2.5m taller with an integrated wave return. ©Network Rail.[92]

The extreme storms of February 2014 which had a catastrophic effect on the seawall of the south Devon stretch of the UK's southwest mainline caused a two-month closure of the line and significant disruption to the local and regional

**Table 5.1: The 20 scenarios considered for numerical simulations in this study.**

| Scenario | Water Depth (m) | Storm Surge (m) | Still Water Level $d_{eff}$ (m) | Wave Amplitude (m) | Maximum Overtopping Flowrate ($m^3/s/m$) | Maximum Force (kN) |
|---|---|---|---|---|---|---|
| 1 | 4.0 | 0.5 | 4.5 | 0.5 | 4.5 | 171 |
| 2 | 3.0 | 0.5 | 3.5 | 0.5 | 3.8 | 138 |
| 3 | 2.0 | 0.5 | 2.5 | 0.5 | n/a | 92 |
| 4 | 2.5 | 0.5 | 3.0 | 0.5 | n/a | 108 |
| 5 | 3.5 | 0.5 | 4.0 | 0.5 | 1.2 | 151 |
| 6 | 2.0 | 0.8 | 2.8 | 0.5 | n/a | 103 |
| 7 | 2.5 | 0.8 | 3.3 | 0.5 | 1.4 | 134 |
| 8 | 3.0 | 0.8 | 3.8 | 0.5 | 2.3 | 144 |
| 9 | 3.5 | 0.8 | 4.3 | 0.5 | 2.8 | 163 |
| 10 | 4.0 | 0.8 | 4.8 | 0.5 | 5.9 | 190 |
| 11 | 4.0 | 0.5 | 4.5 | 1.5 | 14.4 | 253 |
| 12 | 3.0 | 0.5 | 3.5 | 1.5 | 3.0 | 158 |
| 13 | 2.0 | 0.5 | 2.5 | 1.5 | 0.7 | 120 |
| 14 | 2.5 | 0.5 | 3.0 | 1.5 | 2.6 | 134 |
| 15 | 3.5 | 0.5 | 4.0 | 1.5 | 6.5 | 286 |
| 16 | 2.0 | 0.8 | 2.8 | 1.5 | 2.3 | 123 |
| 17 | 2.5 | 0.8 | 3.3 | 1.5 | 2.9 | 149 |
| 18 | 3.0 | 0.8 | 3.8 | 1.5 | 6.2 | 176 |
| 19 | 3.5 | 0.8 | 4.3 | 1.5 | 7.5 | 204 |
| 20 | 4.0 | 0.8 | 4.8 | 1.5 | 16.1 | 258 |

economy (Figure 5.1b) (Network Rail [87], Dawson, Shaw and Gehrels [26] and Adams and Heidarzadeh [3]). Restoration costs were £35m and economic effects to the southwest region of England were estimated up to £1.2bn (Peninsula Rail Taskforce [100]). Adams and Heidarzadeh [3] investigated the disparate cascading failure mechanisms which played a part in the failure of the railway through Dawlish and attempted to put these in context of the historical records of infrastructure damage on the line.

Subsequent severe storms in 2016 in the region have continued to cause damage and disruption to the line in the years since 2014 (Met Office [78]). Following the events of 2014, Network Rail who owns the network, has undertaken a resilience study and as a result has proposed a £400m refurbishment of the civil engineering assets that support the railway (Figure 5.1) [87].

The new seawall structure (Figure 5.1a,c), which is constructed of pre-cast concrete sections, encases the existing Brunel seawall (named after the project lead engineer, Sir Isambard Kingdom Brunel) has been improved with piled reinforced concrete foundations. It is now over 2 m taller to increase available crest freeboard and incorporates wave return features to minimise wave overtopping. The project aims to increase both the resilience of the assets to extreme weather events as well as maintaining or improving amenity value of the coastline for residents and visitors.

In this chapter, I return to the Brunel seawall and the damage it sustained during the 2014 storms which affected the assets on the evening of the 4th and daytime of the 5th of February and eventually resulted in a prolonged closure of the line.

The motivation for this research is to analyse and model the damage made to the seawall and explain the damage mechanisms in order to improve the resilience of many similar coastal structures in the UK and worldwide.

The innovation of this work is the multidisciplinary approach that I take comprising a combination of analysis of eyewitness accounts (social science), sea level and wave data analysis (physical science) as well as numerical modelling and engineering judgement (engineering sciences).

I investigate the contemporary wave climate and sea levels by interrogating the real time tide gauge and wave buoys installed along the southwest coast of the English Channel (Figure 5.1). I then model a typical masonry seawall (Figure 5.2), applying the computational fluid dynamics package FLOW3D-Hydro [34], to quantify the magnitude of impact forces the seawall would have experienced leading to its failure. I triangulate this information to determine the probable sequence of failures that led to the disaster in 2014.

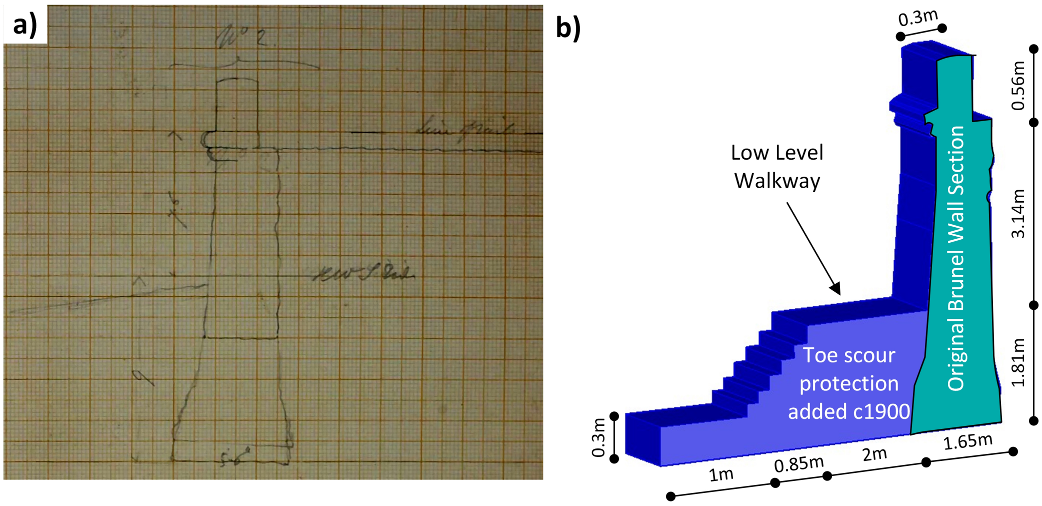



**Figure 5.2:** a) An original sketch of the Dawlish seawall made by the lead Engineer Mr Brunel around 1844–46 [14]. b) The 3D wall model created for the numerical simulations based on Brunel's sketch and subsequent additions of toe reinforcement for scour protection and low-level walkway. The original seawall section is shown in green, with later additions of toe scour protection shown in blue.

## 5.2 Eye Witness Account Analysis

Contemporary reporting of the 4th and 5th February 2014 storms by the main national news outlets in the UK (BBC, ITV and Channel 4) highlight the extreme nature of the events and the significant damage and disruption they were likely to have on the communities of the southwest of England. In interviews this was reinforced by Network Rail engineers who, even at this early stage were forecasting remedial engineering works to last for at least 6 weeks. One week later, following subsequent storms the cascading nature of the events was obvious. Multiple breaches of the seawall had taken place, with up to 35 separate landslide events and significant damage to parapet walls along the coastal route also were reported.

Residents of the area reported extreme effects of the storm, one likening it to an earthquake and reporting water ingress through doors windows and even through vertical chimneys (Table 3.2). This suggests extreme wave overtopping volumes and large wave impact forces. One resident described the structural effects as: "the house was jumping up and down on its footings".

Disaster management plans were quickly and effectively put into action by the local council, police service and National Rail. A major incident was declared and decisions regarding evacuation of the residents under threat were taken around 2100h on the night of 4th February when reports of initial damage to the seawall were received (Table 3.2). Local hotels were asked to provide short term refuge to residents while local leisure facilities were prepared to accept residents later that evening. Initial repair work to the railway line was hampered by successive high spring tides and storms in the following days although significant progress was still made when weather conditions permitted (Table 3.2).

## 5.3 Sea Level Observations and Spectral Analysis

The results of surge and wave analyses are presented in Figures 5.3 and 5.4. A surge height of up to 0.80 m was recorded in the examined tide gauge stations (Figure 5.3b-d). Two main episodes of high surge heights are identified: the first surge started on 3rd February 2014 at 0300 h (UTC) and lasted until 4th February 2014 at 0000 h; the second event occurred in the period 4th February 2014 1500 h to 5th February 2014 at 1700 h (Figure 5.3b-d). These data imply surge durations of 21 h and 26 h for the first and the second events, respectively. Based on the surge data in Figure 5.3, I note that the storm events of early February 2014 and

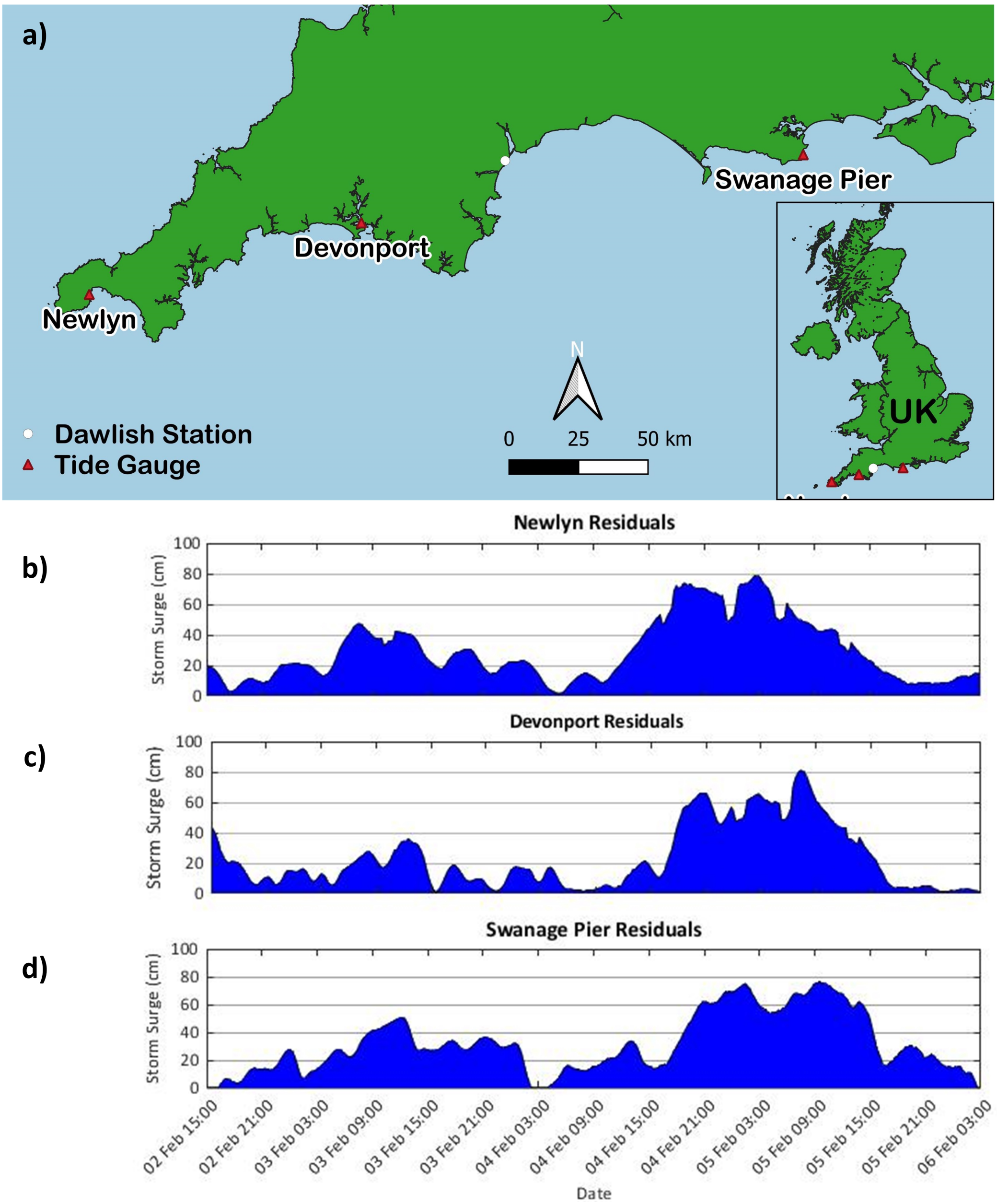



**Figure 5.3:** a) Area map showing the locations of tide gauges examined in this study. b), c), d) The surge signals calculated at different tide gauge stations.

the associated surges were relatively powerful, which impacted at least 230 km of the English south coast with large surge heights.

Based on wave buoy records, the maximum recorded amplitudes are at least 20.5 m in Dawlish and West Bay, 1.9 m in Tor Bay and 4.9 m in Chesil (Figure 5.4a-b). The buoys at Tor Bay and Chesil recorded dual peak period bands of 4 – 8 s and 8 – 12 s, whereas at Dawlish and West Bay registered triple-peak period bands at 4 – 8 s, 8 – 12 s, and 20 - 25 s (Figure 5.4c-d). It is important to note that the long-period waves at 20 – 25 s occur with short durations (approximately 2 min) while the waves at the other two bands of 4 – 8 s and 8 – 12 s appears to be present at all times during the storm event.

The wave component at the period band of 4 – 8 s can be most likely attributed to normal coastal waves while the one at 8 – 12 s, which is longer, is most likely the swell component of the storm. Regarding the third component of the waves with long period of 20 - 25 s, which occurs with short durations of 2 min, there are two hypotheses; it is either the result of a local (port and harbour) and regional (the Lyme Bay) oscillations (eg. Rabinovich [108], Heidarzadeh and Satake [46] and Wang et al. [133], or due to an abnormally long swell. To test the first hypothesis, I consider various water bodies such as Lyme Bay (approximate dimensions of 70 km × 20 km with an average water depth of 30 m; Figure 5.4), several local bays (approximate dimensions of 3.6 km × 0.6 km with an average water depth of 6 m) and harbours (approximate dimensions of 0.5 km × 0.5 km with an average water depth of 4 m). Their water depths are based on the online Marine navigation website[1]. According to Rabinovich [107], the oscillation modes of a semi-enclosed rectangle basin is given by the following equation:

$$T_{mn} = \frac{2}{\sqrt{gd}} \left[ \left( \frac{m}{2L} \right)^2 + \left( \frac{n}{W} \right)^2 \right]^{-\frac{1}{2}} \tag{5.1}$$

where, $T_{mn}$ is the oscillation period, $g$ is the gravitational acceleration, $d$ is water depth, $L$ is the length of the basin, $W$ is the width of the basin, $m = 1, 2, 3 \ldots$ and $n = 0, 1, 2, 3 \ldots$ ; $m$ and $n$ are the counters of the different modes. Applying Equation 5.1 to the aforementioned water bodies results in

[1] https://www.navionics.com/usa/

oscillation modes of at least 5 min, which is far longer than the observed period of 20 – 25 s. Therefore, I rule out the first hypothesis and infer that the long period of 20 – 25 s is most likely a long swell wave coming from distant sources. As discussed by Rabinovich [108] and Wang et al. [133], comparison between sea level spectra before and after the incident is a useful method to distinguish the spectrum of the weather event. A visual inspection of Figure 5.4 reveals that the forcing at the period band of 20 s - 25 s is non-existent before the incident.

## 5.4 Numerical Simulations of Wave Loading and Overtopping

Based on the results of sea level data analyses in the previous section, I use a dual-peak wave spectrum with peak periods of 10 s and 25 s for numerical simulations because such a wave would be comprised of the most energetic signals of the storm (Figure 5.4). For variations of water depth (2.0 m – 4.0 m), coastal wave amplitude (0.5 – 1.5 m) (Figure 5.5) and storm surge height (0.5 m – 0.8 m) (Figure 5.3), I developed 20 scenarios (Scn) which I used in numerical simulations (Table 5.1). Data during the incident indicated that water depth was up to the crest level of the seawall (approximately 4 m water depth); therefore, I varied water depth from 2 m to 4 m in the simulation scenarios. Regarding wave amplitudes, I referred to the variations at a nearby tide gauge station (West Bay) which showed wave amplitude up to 1.2 m (Figure 5.5). Therefore, wave amplitude was varied from 0.5 m to 1.5 m by considering a factor a safety of 25% for the maximum wave amplitude. As for the storm surge component, time series of storm surges calculated at three coastal stations adjacent to Dawlish showed that it was in the range of 0.5 m to 0.8 m (Figure 5.3). These 20 scenarios would help to study

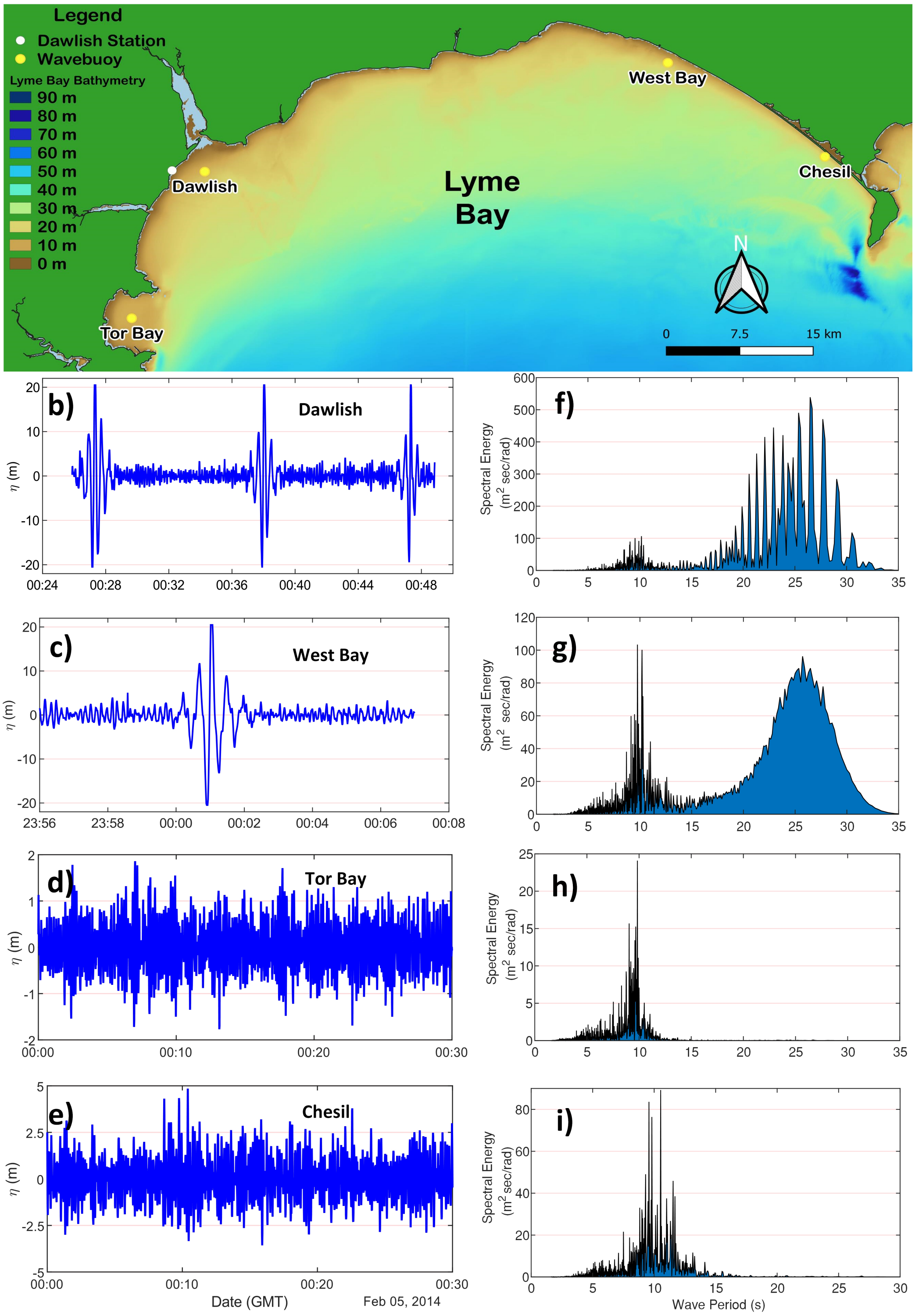



**Figure 5.4:** a) Area map showing the locations of wave buoys examined in this study. b), c), d), e) Sea level oscillations recorded at wave buoys at different locations. f), g), h), i) Corresponding spectra for each sea level record.

uncertainties associated with wave amplitudes and pressures.

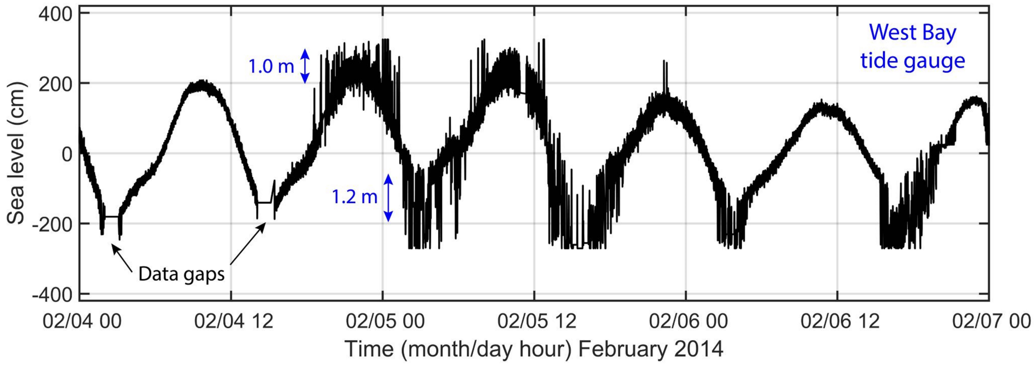



**Figure 5.5:** Oscillations of wave (high-frequency oscillations) and tide (low-frequency oscillations with 12-hour recurrence) at the West Bay tide gauge station.

Figure 5.6 shows snapshots of wave propagation and impacts on the seawall at different times. In order to detail the evolution of the pressures impacting on the seawall, and in particular the dramatic increases in pressure that were not foreseen, we have shown an isosurface for the incoming wave. The isosurface is a powerful graphical representation of all areas in the incoming wave with similar pressures. In effect, 5.6 represents a curated sample of instances from the wave timeseries. Typically due to linear hydrostatic pressure increase with increasing water depth, the figures show well defined demarcation between areas of increasing pressure (see 5.6 a,c and d) with highest pressure towards the seabed (red colour) and lowest pressure (in blue) shown at the water surface. However, unexpectedly in Figure 5.6b at time interval 61½ s, near the most vulnerable parapet wall section, we see a dramatic increase in pressure close to the water surface which is due to wave breaking energy impacting on the masonry elements.

### 5.4.1 Wave Amplitude Simulations

Large wave amplitudes can induce significant wave forcing on the structure and cause overtopping of the seawall, which could eventually cascade to other hazards

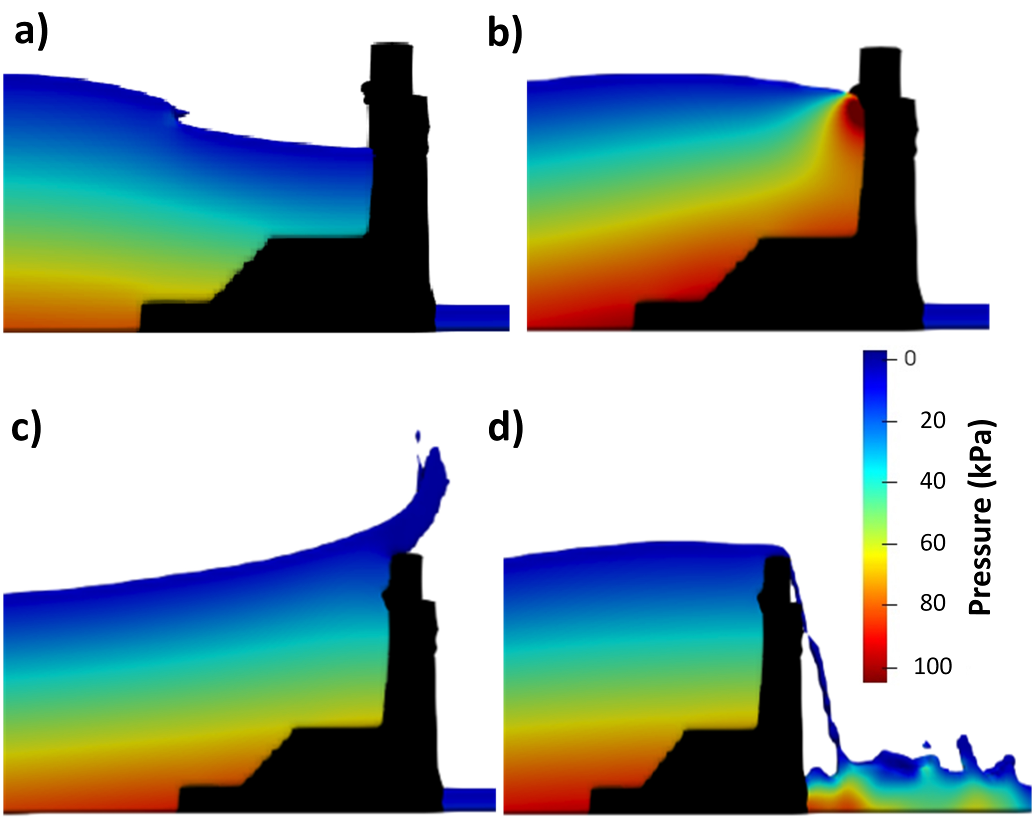



**Figure 5.6:** Wave pressure iso-surface due to Scn-15 (see Table 5.1 for details of this scenario). a) Breaking wave at t = 61 s. b) Maximum breaking pressure at parapet wall t = 61½ s. c) Wave overtopping wall crown at t = 62 s. d) Downward overtopping pressure on rail bed t = 63½ s.

such as erosion of the backfill and scour [3].

The first 10 scenarios of the modelling efforts are for the same incident wave amplitudes of 0.5 m, which occur at different water depths (2.0 – 4.0 m) and storm surge heights (0.5 – 0.8 m) (Table 5.1 and Figure 5.7). This is because I aim to study the impacts of still water level ($d_{eff}$ – the sum of mean sea level and surge height) on the time histories of wave amplitudes as the storm evolves.

As seen in Figure 5.7a, by decreasing still water level, wave amplitude increases. For example, for Scn-1 with effective depth of 4.5 m, the maximum amplitude of the first wave is 1.6 m, whereas it is 2.9 m for Scn-2 with effective depth of 3.5 m. However, due to intensive reflection and interference of the waves in front of the vertical seawall, such a relationship is barely seen for the second and the third wave peaks. It is important to note that the later peaks (second or third) produce the largest waves rather than the first wave.

Extraordinary wave amplifications are seen for Scn-2 ($\mathrm{d_{eff}}$ =3.5 m) and Scn-7 ($\mathrm{d_{eff}}$ =3.3 m), where the corresponding wave amplitudes are 4.5 m and 3.7 m, respectively. This may indicate that the still water level of $\mathrm{d_{eff}}$ = 3.3 – 3.5 m is possibly a critical water depth for this structure resulting in maximum wave amplitudes under similar storms.

In the second wave impact, the combined wave height (i.e., the wave amplitude plus the still water level), which is ultimately an indicator of wave overtopping, shows that the largest wave height is generated by Scn-2, -7 and -8 (Figure 5.7b) with still water levels of 3.5 m, 3.3 m, and 3.8 m and combined heights of 8.0 m, 7.0 m, and 6.9 m (Figure 5.7b). Since the height of seawall is 5.4 m, the combined wave heights for Scn-2, -7 and -8 are greater than the crest height of the seawall by 2.6 m, 1.6 m, and 1.5 m, respectively, which indicates wave overtopping.

For scenarios 11-20, with incident wave amplitudes of 1.5 m (Table 5.1), the largest wave amplitudes are produced by Scn-17 ($\mathrm{d_{eff}}$ =3.3 m), Scn-13 ($\mathrm{d_{eff}}$ =2.5 m) and Scn-12 ($\mathrm{d_{eff}}$ =3.5 m), which are 5.6 m, 5.1 m and 4.5 m. The maximum combined wave heights belong to Scn-11 ($\mathrm{d_{eff}}$ =4.5 m) and Scn-17 ($\mathrm{d_{eff}}$ =3.3 m), with combined wave heights of 9.0 m, and 8.9 m (Figure 5.8b), which are greater than the crest height of the seawall by 4.6 m and 3.5 m respectively.

the simulations for all 20 scenarios reveal that the first wave is not always the largest and wave interaction, reflection and interference play major roles in amplifying the waves in front of the seawall. This is primarily because the wall is fully vertical and therefore has a reflection coefficient of close to one (i.e.,

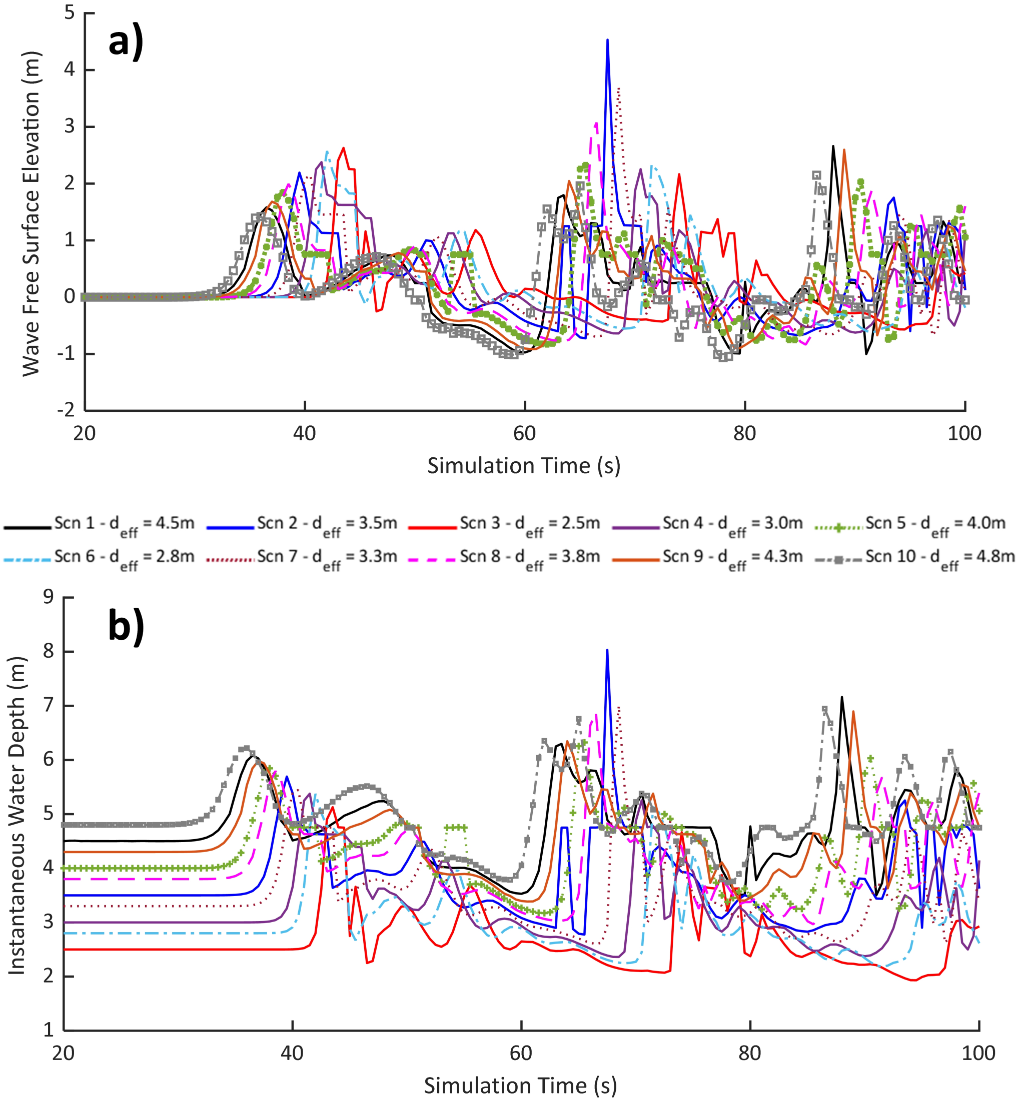



**Figure 5.7:** a) Time series of wave oscillations at the foot of the seawall (point "A" in Figure 3.6 for scenarios 1-10 with incident wave amplitude of 0.5 m. b) As in "a", but for instantaneous water depth (still water level plus wave amplitude).

full reflection). Simulations show that the combined wave height is up to 4.6 m higher than the crest height of the wall, implying that severe overtopping would be expected.

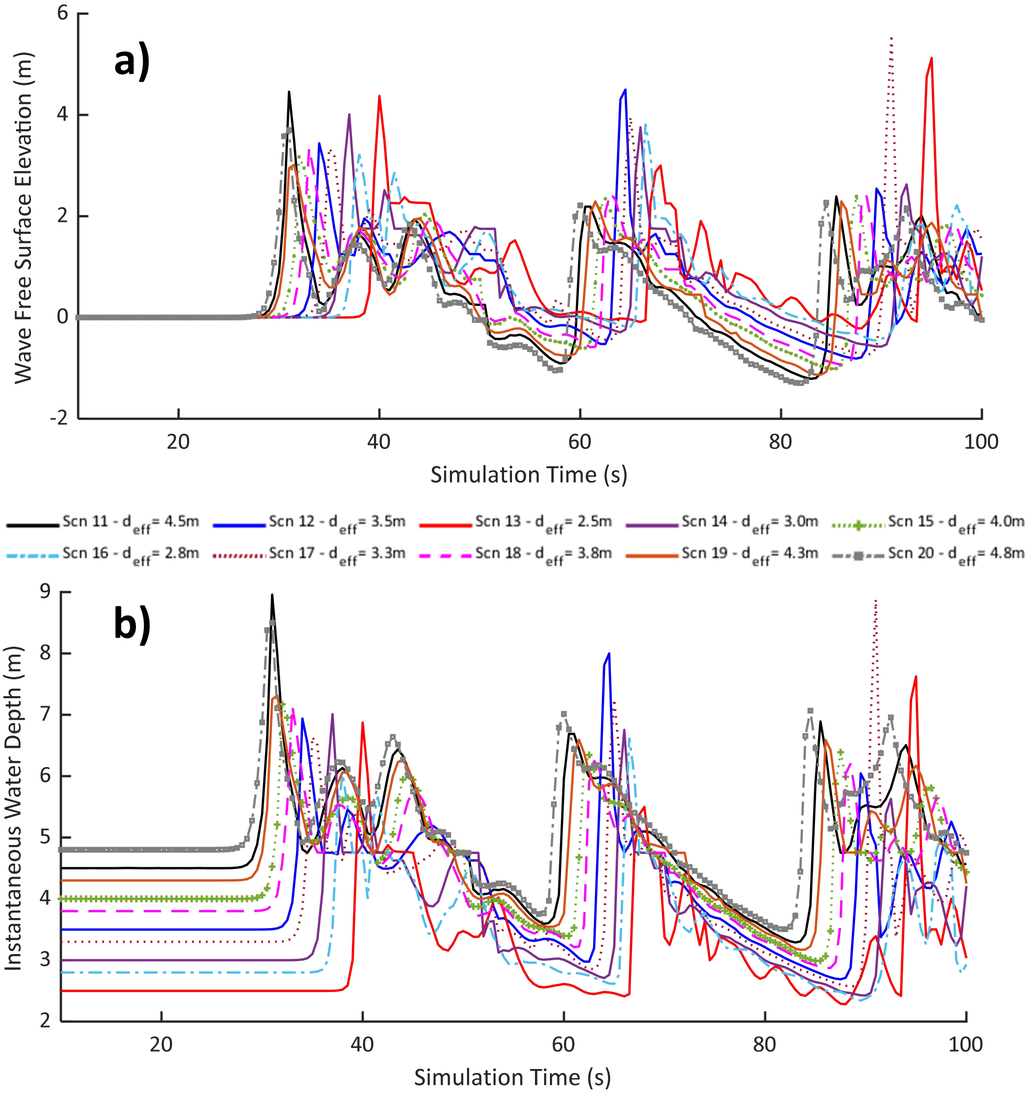



**Figure 5.8:** a) Time series of wave oscillations at the foot of the seawall (point "A" in Figure 3.6) for scenarios 11-20 with incident wave amplitude of 1.5 m. b) As in "a", but for instantaneous water depth (still water level plus wave amplitude).

### 5.4.2 Wave Loading Calculations

The pressure calculations for scenarios 1-10 are given in Figure 5.9 and those of scenarios 11-20 in Figure 5.10. The total pressure distribution in Figures 5.9-5.10 mostly follow a triangular shape with maximum pressure at the seafloor as expected from the Sainflou design equations [114]. These pressure plots comprise both static (due to mean sea level in front of the wall) and dynamic (combined

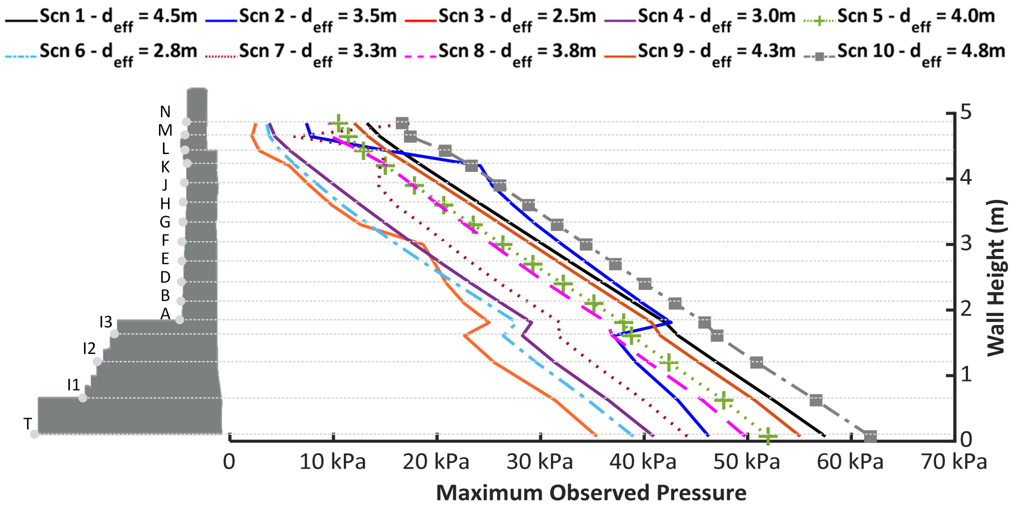



**Figure 5.9:** Distribution of maximum wave pressure along the height of the seawall from scenarios 1-10 with wave amplitude of 0.5 m.

effects of surge and wave) pressures.

For incident wave amplitudes of 0.5 m (Figure 5.9), the maximum wave pressure varies in the range of 35 – 63 kPa. At the sea surface, it is in the range of 4 – 20 kPa (Figure 5.9). For some scenarios (Scn-2 and 7), the pressure distribution deviates from a triangular shape and shows larger pressures at the top, which is attributed to the wave impacts and partial breaking at the sea surface. This adds an additional triangle-shaped pressure distribution at the sea surface elevation consistent with the design procedure developed by Goda [40] for braking waves. The maximum force on the seawall due to scenarios 1-10, which is calculated by integrating the maximum pressure distribution over the wave-facing surface of the seawall, is in the range of 92 – 190 kN (Table 5.1).

For scenarios 11-20, with incident wave amplitude of 1.5 m, wave pressures of 45 – 78 kPa, and 7 – 120 kPa, for the bottom and top of the wall, respectively were observed (Figure 5.10). Most of the plots show a triangular pressure distribution, except for Scn-11 and -15. A significant increase in wave impact pressure is seen for Scn-15 at the top of the structure, where a maximum pressure of approximately 120 kPa is produced while other scenarios give a pressure of 7 – 32 kPa for the sea surface. In other words, the pressure from Scn-15 is approximately four times larger than the other scenarios. Such a significant increase of the pressure at the top is most likely attributed to the breaking wave impact loads as detailed by Goda [40] and Cuomo et al. [23]. The wave simulation snapshots in Figure 5.6 show that the wave breaks before reaching the wall. The maximum force due to scenarios 11-20 is 120 – 286 kN.

The breaking wave impacts peaking at 286 kN in the simulations would suggest destabilisation of the upper masonry blocks, probably by grout malfunction. This significant impact force initiated the failure of the seawall which in turn caused extensive ballast erosion. Wave impact damage was proposed by Adams and Heidarzadeh [3] as one of the primary mechanisms in the 2014 Dawlish disaster. In the multi-hazard risk model proposed by these authors, damage mechanism III (failure pathway 5 in [3]) was characterised by wave impact force causing damage to the masonry elements, leading to failure of the upper sections of the seawall and loss of infill material. As blocks were removed, access to the track bed was increased for inbound waves allowing infill material from behind the seawall to be fluidised and subsequently removed by backwash. The loss of infill material critically compromised the stability of the seawall and directly led to structural failure. In parallel, significant wave overtopping (discussed in the next Section) led to ballast washout and cascaded, in combination with masonry damage, to catastrophic failure of the wall and suspension of the rails in mid-air (Figure 5.1), leaving the railway inoperable for two months.

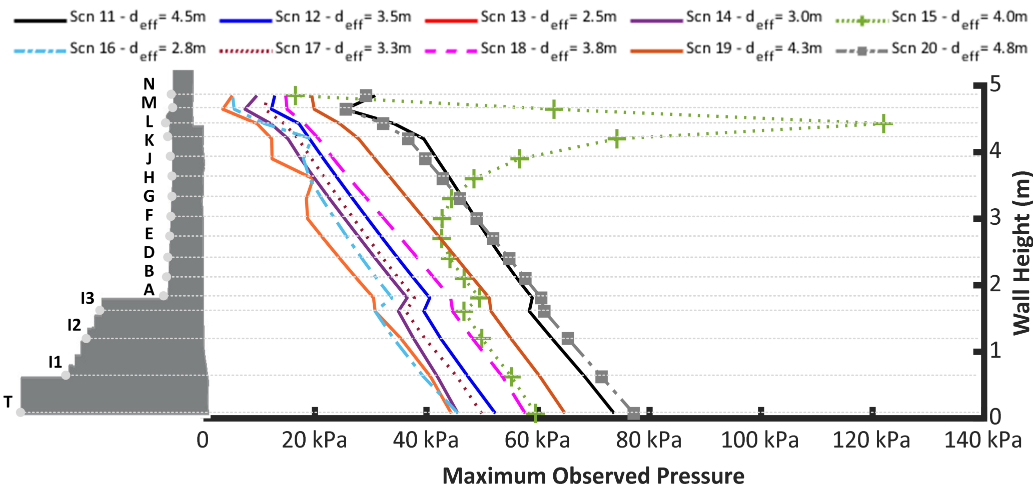



**Figure 5.10:** Distribution of maximum wave pressure along the height of the seawall from scenarios 11-20 with wave amplitude of 1.5 m.

## 5.4.3 Wave Overtopping

The two most important factors contributing to the 2014 Dawlish railway events were wave impact forces and overtopping. Figure 5.11 gives the instantaneous overtopping rates for different scenarios, which experienced overtopping. It can be seen that the overtopping rates range from 0.5 $\mathrm{m^3/s/m}$ to 16.1 $\mathrm{m^3/s/m}$ (Figure 5.11). Time histories of the wave overtopping rates show that the phenomenon occurs intermittently and each time lasts 1.0 – 7.0 s. It is clear that the longer the overtopping duration, the larger the volume of the water impacted on the structure. The largest wave overtopping rates of 16.1 $\mathrm{m^3/s/m}$ and 14.4 $\mathrm{m^3/s/m}$ belong to Scn-20 and -11, respectively. These two scenarios also give the largest combined wave heights (Figure 5.8).

The cumulative overtopping curves (Figures 5.12 and 5.13) show the total water volume overtopped the structure during the entire simulation time. This is an important hazard factor as it determines the level of soil saturation, water pore pressure in the soil and soil erosion (Van Der Meer et al. [130]). The maximum

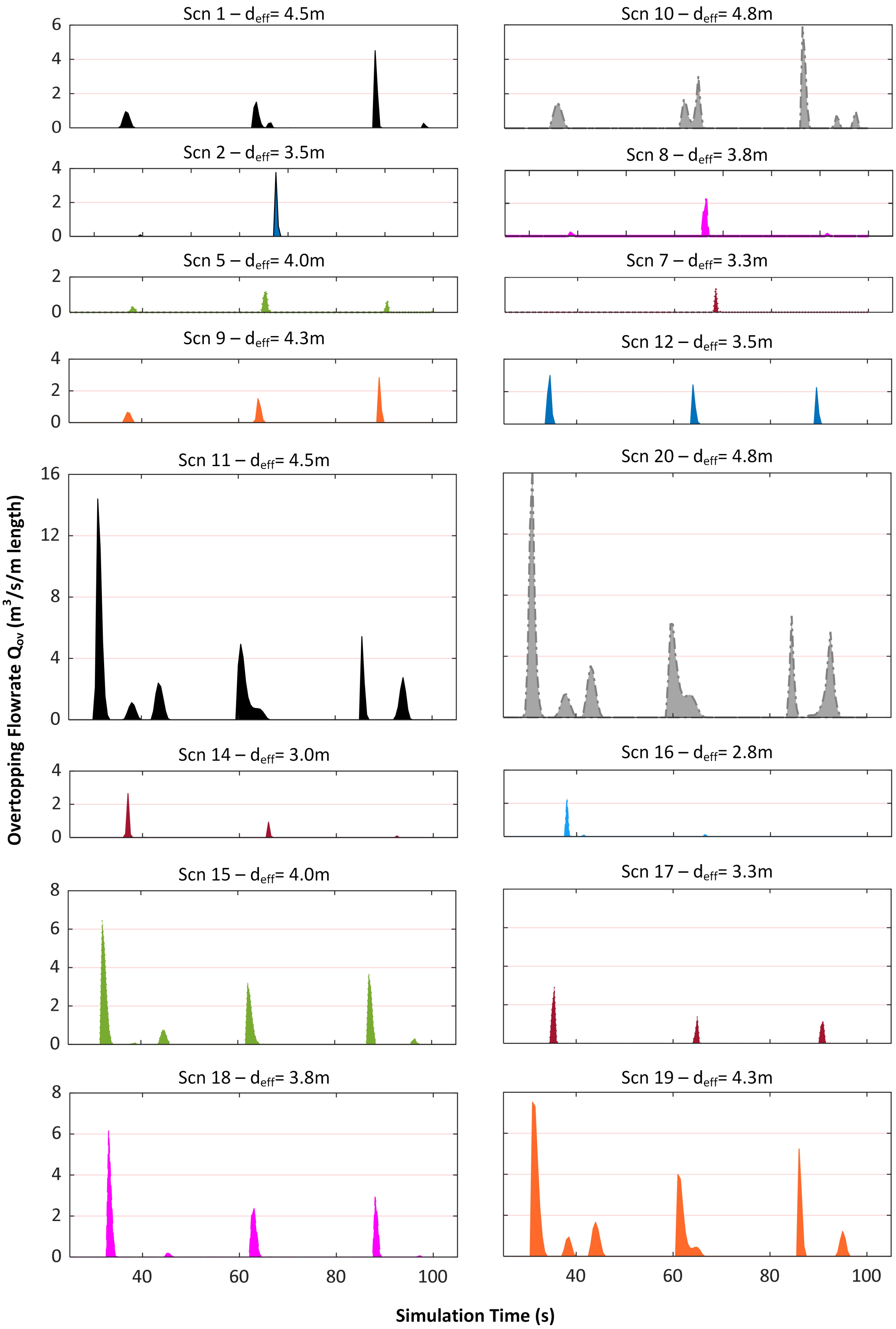



**Figure 5.11:** Wave overtopping rates for all scenarios with overtopping events.

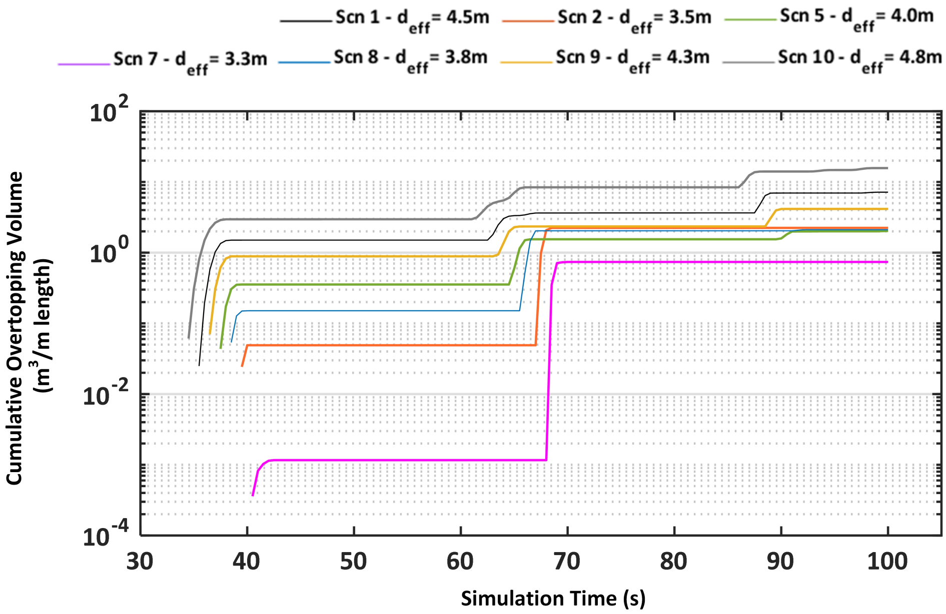



**Figure 5.12:** Cumulative wave overtopping volumes per metre length of wall from scenarios 1-10 with wave amplitude of 0.5 m. No overtopping was experienced in scenarios 3, 4 and 6.

volume belongs to Scn-20, which is 65.0 $\mathrm{m}^3/\mathrm{m}$ (cubic metres of water per meter length of wall). The overtopping volumes are 42.7 $\mathrm{m}^3/\mathrm{m}$ for Scn-11 and 28.8 $\mathrm{m}^3/\mathrm{m}$ for Scn-19. The overtopping volume is in the range of 0.7 – 65.0 $\mathrm{m}^3/\mathrm{m}$ for all scenarios.

For comparison, I compare the modelling results with those estimated using empirical equations. For the case of the Dawlish seawall, I apply the equation proposed by Van Der Meer et al. [130] to estimate wave overtopping rates, based on a set of decision criteria which are the influence of foreshore, vertical wall, possible breaking waves and low freeboard:

$$\frac{q}{\sqrt{g{H_m}^3}} = 0.0155 \left[\frac{H_m}{h_s}\right] \exp\left[-2.2\frac{R_c}{H_m}\right] \tag{5.2}$$

where, $q$ is mean overtopping rate per meter length of the seawall ($\mathrm{m}^3/\mathrm{s}/\mathrm{m}$), $g$ is acceleration due to gravity, $H_m$ is incident wave height at the toe of the

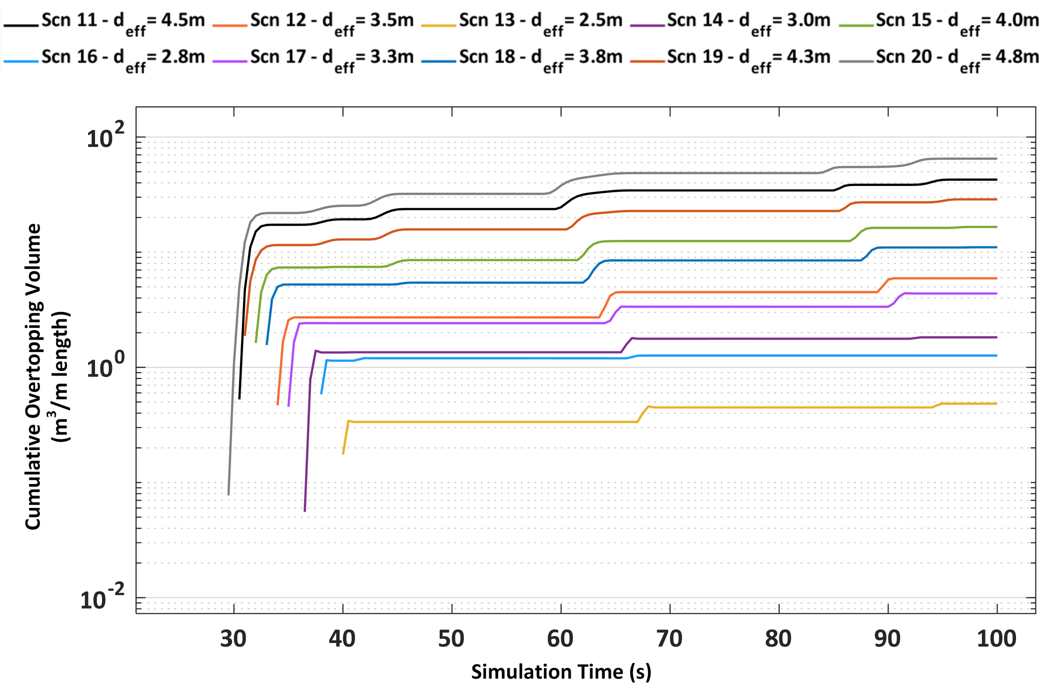



**Figure 5.13:** Cumulative wave overtopping volumes per metre length of wall from scenarios 11-20 with wave amplitude of 1.5 m.

structure, $R_c$ is the wall crest height above mean sea level, $h_s$ is the deep-water significant wave height, and $\exp(x)$ is the exponential function.

It is noted that Equation (5.2) is valid for 0.1 $< R_c/H_m <$ 1.35. For the case of Dawlish seawall and considering the scenarios with larger incident wave amplitude of 1.5 m ($h_s$= 1.5 m), the incident wave height at the toe of the structure is $H_m$ = 2.2 - 5 m, the wall crest height above mean sea level is $R_c$ = 0.6 – 2.9 m. As a result, Equation (5.2) gives mean overtopping rates up to approximately 2.9 $\mathrm{m^3/s/m}$. A visual inspection of simulated overtopping rates in Figure 5.11 for Scn 11-20, shows that the mean value of the simulated overtopping rates are close to estimates using Equation (5.2).

## 5.5 Synopsis

I applied a combination of eyewitness account analysis, sea level data analysis and numerical modelling in combination with my engineering judgement to explain the damage to the Dawlish railway seawall in February 2014. The main findings are:

- Eyewitness data analysis showed that the extreme nature of the event was well forecasted in the hours prior to the storm impact, however the magnitude of the risks to the structures were not well understood. Multiple hazards were activated simultaneously, and the effects cascaded to amplify the damage. Disaster management was effective, exemplified by the establishment of an emergency rendezvous point and temporary evacuation centre during the storm indicating a high level of hazard awareness and preparedness.
- Based on sea level data analysis, I identified triple-peak period bands at 4 – 8 s, 8 – 12 s, and 20 – 25 s in the sea level data. Storm surge heights and the wave oscillations were up to 0.8 m and 1.5 m, respectively.

- Based on the numerical simulations of 20 scenarios with different still water levels, incident wave amplitudes, surge heights and peak periods, I found that the wave oscillations at the foot of the seawall results in multiple wave interactions and interference. Consequently, large wave amplitudes, up to 4.6 m higher than the height of seawall, were generated and overtopped the wall. Extreme impulsive wave impact forces of up to 286 kN were generated by the waves interacting with the seawall.
- I measured maximum wave overtopping rates of 0.5 – 16.1 $\mathrm{m}^3/\mathrm{s}/\mathrm{m}$ for my scenarios. The cumulative overtopping water volumes per meter length of the wall were 0.7 – 65.0 $\mathrm{m}^3/\mathrm{m}$.

Analysis of all the evidence combined with my engineering judgement suggests that the most likely initiating cause of the failure was impulsive wave impact forces destabilising one or more grouted joints between adjacent masonry blocks in the wall. Maximum observed pressures of 286 kN in my simulations are four times greater in magnitude than background pressures leading to block removal and initiating failure. Therefore, the sequence of cascading events was:

1. Impulsive wave impact force causing damage to masonry
2. Failure of the upper sections of the seawall
3. Loss of infill resulting in a reduction of structural strength in the landward direction
4. Ballast washout as wave overtopping and inbound wave activity increased
5. Progressive structural failure following successive tides.

From a risk mitigation point of view, the stability of the seawall in the face of future energetic cyclonic storm events and sea level rise will become a critical factor in protecting the rail network. Mitigation efforts will involve significant infrastructure investment to strengthen the civil engineering assets combined with improved hazard warning systems consisting of meteorological forecasting and real-time wave observations and instrumentation. These efforts must take into account the amenity value of coastal railway infrastructure to local communities and the significant number of tourists who visit every year. In this regard, public awareness and active engagement in the planning and execution of the project will be crucial in order to secure local stakeholder support for the significant infrastructure project that will be required for future resilience.

Chapter 6

# Conclusions and Further Work

## 6.1 Overview of Thesis

The thesis has presented the work undertaken to formulate a multi-hazard risk model for critical coastal rail infrastructure incorporating aspects of separate damage mechanisms (DM) leading to cascading failure pathways (FPW). I have achieved this by a combination of historical and contemporary archival research. I have detailed and analysed eye witness accounts of real time damage to an historic masonry seawall originally built by I.K. Brunel in 1845. Having developed the multi-hazard risk model, I then proved it's ability to be used in real life events on the South Devon Railway (SDR).

Since the model was developed for coastal rail infrastructure generally, I then progressed to look at other vulnerable coastal rail alignments in the UK to ensure the model had applicability beyond the main line in Devon. In this regard I highlighted two diverse areas in the UK - one in South Wales and the other in Northwest England. I successfully applied the risk model for a similar initiating hazard on a rail alignment in Cumbria. I demonstrated that common DM and FPW were present in both places and both led to service suspension of a strategically important rail link. The application of the model was further extended to encompass a different initiating hazard - that of a tsunami following an earthquake in Japan. Common DM and FPW were discovered acting on the Japanese coastal rail network following the events of the Tohoku tsunami of 2011. The multi-hazard risk model developed in this study has also been applied to other diverse hazards worldwide, such as to flood-related dam failures in the UK [45], and complex cascading risk interactions within human, software and organizational systems [99].

Finally, I used a numerical model of the seawall to simulate the magnitude of wave forces that acted on the seawall during the events of 4th and 5th February 2014. My results pointed to a likely cause of the failure of the vertical masonry seawall, and I used eye witness accounts and engineering judgement in combination with the results of my numerical modelling to hypothesise the chain of events which evenutally led to collpase of the wall, 56 days of service suspension and up to £1.2 bn of losses to the Southwest of England.

Chapter 2 presented a critical review of the literature related to the genesis and synthesis of cascading risk models for civil engineering infrastructure and their connection with DRR efforts. The history of the development of cascading disasters was discussed and how these interact with multi-hazard scenarios to form complex disaster events. I reviewed the necessary steps in sea level data analysis techniques and the development of computational fluid dynamics for use in numerical modelling of wave/structure interactions. At the end of the chapter, I summarised the research needs:

- Formation of a cascading multi-hazard risk model for coastal rail infrastructure
- Development of a source of tide gauge data

- Processing of real time wave climate data
- Numerical simulation of failure events

Based on these research needs I formulated a set of research questions and approach in Section 2.5 which highlighted the development and application of the multi-hazard risk model to explain observed damage events on a coastal railway in Devon and then to extend its use to explain the most likely cause of failure using analysis and numerical simulation.

Chapter 3 outlined the sources of data used throughout the study and provided information on the methodology I adapted to process this data in order to generate the outputs.

The development of the cascading multi-hazard risk model was presented in Chapter 4 along with analysis of the most important damage mechanisms (DM), the model application in South Devon for two selected events and consequently model application in other geographical and hazard contexts.

Chapter 5 saw me return to the vertical masonry seawall in Dawlish and the efforts to numerically model the structure and the wave interactions. The purpose of this work was to identify the magnitude of forces that the wall sustained during the storm and from the results to suggest a likely cause of failure.

## 6.2 Main Conclusions

The results of my work are discussed at the end of each chapter, however the main conclusions of the study can be summarised as follows:

1. Current state-of-the-art data and methods were collated, compared and expanded for the formation of a multi-hazard risk model for critical coastal infrastructure.

2. A mechanism for disaggregating damage data reporting was developed and used in conjunction with failure tree analysis for application to civil engineering infrastructure.

3. Novel use of raw, quality controlled data from tide gauges and wave buoys allowed me to develop an understanding of sea state conditions during a major storm.

4. I develop and describe a process for validating wave-structure interactions for a vertical masonry seawall during a storm.

5. A multi-hazard cascading risk model is developed for the Dawlish railway incorporating DM and cascading FPW.

6. Using the model I identified the most frequent DM from historical railway damage data and highlighted the most important FPW that were activated in 2014.

7. Extension of the model applicability was demonstrated for a similar hazard on a different railway line in England.

8. Use of the model for diverse activating hazards was demonstrated by using the case of the Tohoku earthquake and tsunami event. I identified commonalities in DM and FPW in both Japan and UK.

9. Eyewitness data analysis suggested the 2014 event was extreme in nature, was forecasted well and demonstrated the cascading effects amplifying the damage suffered. Disaster management response was effective.

10. A triple band sea state was identified with abnormally long wave periods of 20-25 s. Storm surge heights and wave oscillations were up to 0.8 m and 1.5 m respectively.

11. Numerical simulations demonstrated significant wave interactions and interference in front of the seawall. Consequently, wave amplitudes of up to 4.6 m higher than the height of the seawall were generated. This caused extensive wave overtopping to occur.

12. The most likely sequence of cascading events which led to failure of the seawall was identified as:

    - Impulsive wave impact force causing damage to masonry
    - Failure of upper sections of the seawall
    - Loss of infill material leading to reduction of structural strength in the landward direction
    - Ballast washout as wave overtopping and inbound wave activity increased
    - Progressive structural failure following successive high tides

## 6.3 Limitations and Future Work

This thesis focuses on the development of a multi-hazard risk model for the Dawlish railway in Devon, UK. As such the model is aimed at understanding the wave-structure interaction of a coastal vertical masonry seawall carrying a railway alignment. In the UK, there are many cases of vertical seawalls which are subject to storm damage, with some of these carrying coastal railways, roads or pedestrian promenades. With minor changes to the potential DM and FPW the model could be used for other types of coastal defence structure.

As part of this work I have successfully used the model in alternative railway settings in the UK and have suggested its use for alternative types of initiating hazard event (eg tsunami following earthquake in Japan).

The methodology undertaken to develop the model is a result of a rich and long seam of historical information, both in terms of weather events and in the subsequent engineering interventions undertaken since the inception of the railway line by Brunel in 1845. As such it is unique in its high cost of maintenance. This approach is a limitation for other assets, where they are not as old or where differing local conventions were used in construction.

Work is currently underway to document a series of disaster events using the risk model where I believe common types of damage have historically occurred. As I have detailed earlier, future work on understanding and applying the cascading risk model on other critical infrastructure types such as transport infrastructure (e.g. roads, airports, motorways and dams) as well as alternative initiating hazards (e.g. coastal flooding, earthquake, tsunami and hurricanes) is recommended to be extended by other researchers. Other recommended future work includes extending the application of the historical database to a probabilistic hazard analysis taking into account future SLR in the UK and also to integrate the present work with a full Bayesian Network analysis potentially integrating the approach of multi-criteria decision analysis [69].

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Appendix A

# Contemporary Reports of Damage

The British Newspaper Archive at the BL provides a comprehensive record of regional and national press from the 1700s onward and currently consists of over 55 million pages of press. In addition, the Newsroom at the British library also gives access to national publications such as The Times, The Telegraph and The Guardian. As part of this research I collected and analysed newspaper articles mentioning Dawlish, the sea wall, storms, disruption and railway. The results of this research and some comments on the articles are included in this appendix.

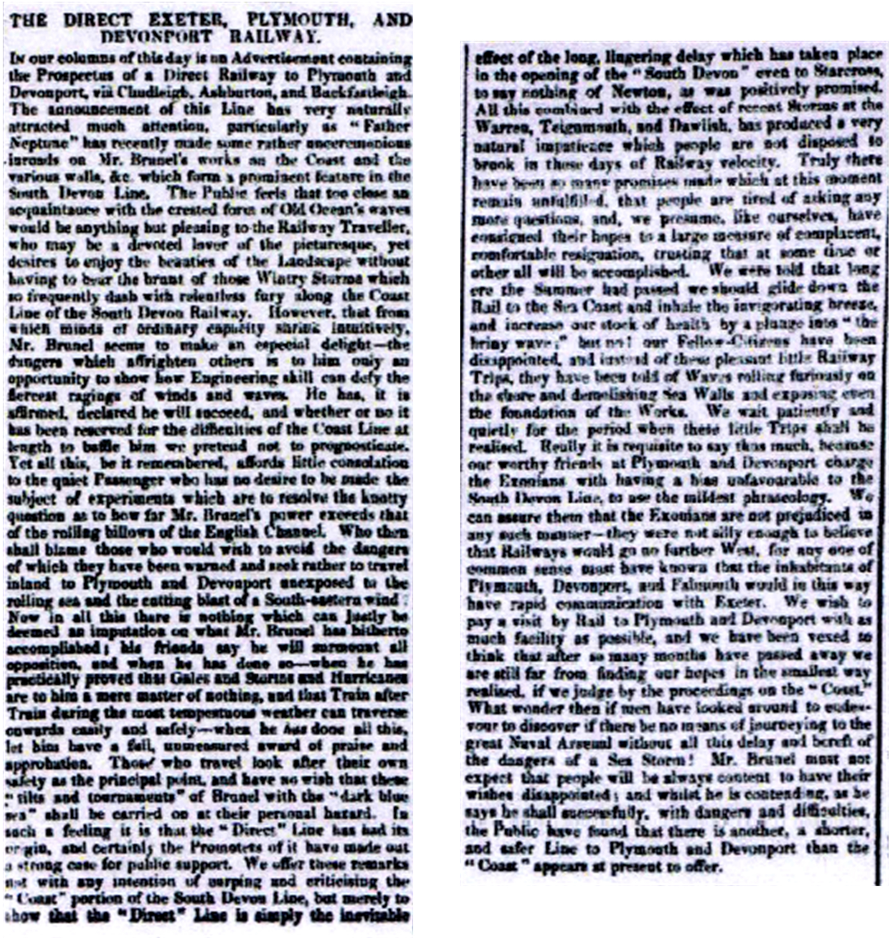
The articles are presented chronologically and note is made here that not all events have been included in my records of seawall damage in Table 3.1, for the same reasons as mentioned earlier. My focus was on damage that resulted in a (cross-referenced) incident that caused either a complete closure of the line or single line working for at least 12 consecutive hours. As noted, my table of incidents are therefore conservative when viewed from the perspective of storm damage to the railway. The articles following do, however, provide considerable evidence to support my conclusions on the likely damage mechanisms (DM) given independent opinion on reports of wave heights, sea state and damage to the infrastructure.

## Exeter Flying Post

### Wednesday 1st October 1845

Weather was playing an important part in the discourse over railway development in South Devon even before the coastal railway was opened. There seems considerable concern and opinion that an internal routeing of railway would ultimately be more resilient to storm and flooding damage. Mr Brunel is portrayed in this article as being overly confident of his engineering prowess and his almost blind belief in being able to tame the weather and the sea. This demonstrates his (probably necessary) belief in engineering capabilities as a pioneering engineer.

Mention is also made of the public's need for personal safety and how this might influence their usage of the South Devon Line in the future, despite Mr Brunel's contention that all trains will be safe. Reference is also made of missed construction deadlines and promises not kept in terms of the railway development.



THE DIRECT EXETER, PLYMOUTH, AND DEVONPORT RAILWAY.

In our columns of this day is an Advertisement containing the Prospectus of a Direct Railway to Plymouth and Devonport, via Chudleigh, Ashburton, and Buckfastleigh. The announcement of this Line has very naturally attracted much attention, particularly as "Father Neptune" has recently made some rather unceremonious inroads on Mr. Brunel's works on the Coast and the various walls, &c. which form a prominent feature in the South Devon Line. The Public feels that too close an acquaintance with the crested form of Old Ocean's waves would be anything but pleasing to the Railway Traveller, who may be a devoted lover of the picturesque, yet desires to enjoy the beauties of the Landscape without having to bear the brunt of those Wintry Storms which so frequently dash with relentless fury along the Coast Line of the South Devon Railway. However, that from which minds of ordinary capacity shrink intuitively, Mr. Brunel seems to make an especial delight—the dangers which affrighten others is to him only an opportunity to show how Engineering skill can defy the fiercest ragings of winds and waves. He has, it is affirmed, declared he will succeed, and whether or no it has been reserved for the difficulties of the Coast Line at length to baffle him we pretend not to prognosticate. Yet all this, be it remembered, affords little consolation to the quiet Passenger who has no desire to be made the subject of experiments which are to resolve the knotty question as to how far Mr. Brunel's power exceeds that of the rolling billows of the English Channel. Who then shall blame those who would wish to avoid the dangers of which they have been warned and seek rather to travel inland to Plymouth and Devonport unexposed to the rolling sea and the cutting blast of a South-eastern wind? Now in all this there is nothing which can justly be deemed an imputation on what Mr. Brunel has hitherto accomplished; his friends say he will surmount all opposition, and when he has done so—when he has practically proved that Gales and Storms and Hurricanes are to him a mere matter of nothing, and that Train after Train during the most tempestuous weather can traverse onwards easily and safely—when he *has* done all this, let him have a full, unmeasured award of praise and approbation. Those who travel look after their own safety as the principal point, and have no wish that these "tilts and tournaments" of Brunel with the "dark blue sea" shall be carried on at their personal hazard. In such a feeling it is that the "Direct" Line has had its origin, and certainly the Promoters of it have made out a strong case for public support. We offer these remarks not with any intention of carping and criticising the "Coast" portion of the South Devon Line, but merely to show that the "Direct" Line is simply the inevitable effect of the long, lingering delay which has taken place in the opening of the "South Devon" even to Starcross, to say nothing of Newton, as was positively promised. All this combined with the effect of recent Storms at the Warren, Teignmouth, and Dawlish, has produced a very natural impatience which people are not disposed to brook in these days of Railway velocity. Truly there have been so many promises made which at this moment remain unfulfilled, that people are tired of asking any more questions, and, we presume, like ourselves, have consigned their hopes to a large measure of complacent, comfortable resignation, trusting that at some time or other all will be accomplished. We were told that long ere the Summer had passed we should glide down the Rail to the Sea Coast and inhale the invigorating breeze, and increase our stock of health by a plunge into "the briny wave;" but no! our Fellow-Citizens have been disappointed, and instead of these pleasant little Railway Trips, they have been told of Waves rolling furiously on the shore and demolishing Sea Walls and exposing even the foundation of the Works. We wait patiently and quietly for the period when these little Trips shall be realised. Really it is requisite to say thus much, because our worthy friends at Plymouth and Devonport charge the Exonians with having a bias unfavourable to the South Devon Line, to use the mildest phraseology. We can assure them that the Exonians are not prejudiced in any such manner—they were not silly enough to believe that Railways would go no further West, for any one of common sense must have known that the inhabitants of Plymouth, Devonport, and Falmouth would in this way have rapid communication with Exeter. We wish to pay a visit by Rail to Plymouth and Devonport with as much facility as possible, and we have been vexed to think that after so many months have passed away we are still far from finding our hopes in the smallest way realised, if we judge by the proceedings on the "Coast." What wonder then if men have looked around to endeavour to discover if there be no means of journeying to the great Naval Arsenal without all this delay and bereft of the dangers of a Sea Storm! Mr. Brunel must not expect that people will be always content to have their wishes disappointed; and whilst he is contending, as he says he shall successfully, with dangers and difficulties, the Public have found that there is another, a shorter, and safer Line to Plymouth and Devonport than the "Coast" appears at present to offer.

**Figure A.1:** Newspaper Excerpt from 1845

### Bristol Mercury

### Railway Intelligence - from Exeter Gazette

### Saturday 14th November 1846

Seven combined seawall and coping breaches, consisting of approximately 83m, 105m, 27m, 63m, 71m, 71m and 27m lengths. One breach of coping stones only - 33m long. Total rebuilding is required as confirmed by Mr. Brunel. 150 men working on the wall with an additional 32 stone masons.

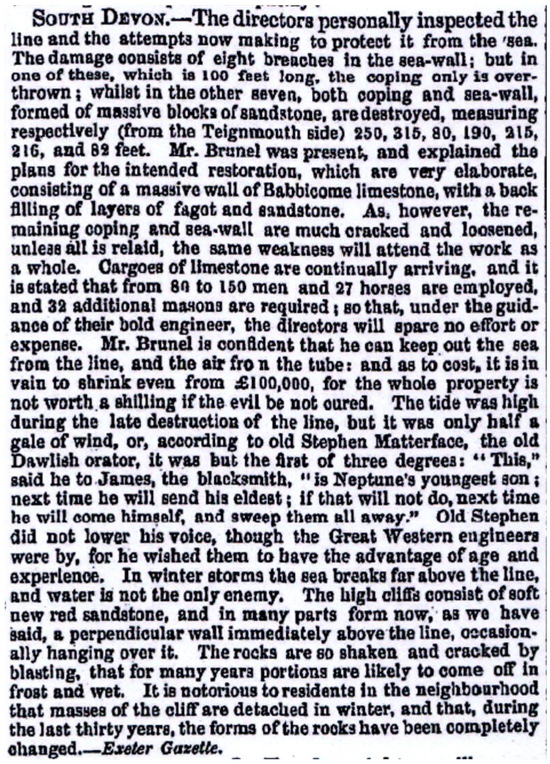
Local orator warns the Directors that although the tide was high, the wind was not. He predicted on-going problems for the wall due to weather related incidents.

"In winter the waves break far above the line ..."

Confirmation of overtopping known as a potential problem from the beginning.

"The rocks are so shaken and cracked by blasting that for many years portions are likely to come off in frost and wet."

Landslides are predicted as a result of local geology, engineering intervention and weathering processes.



SOUTH DEVON.—The directors personally inspected the line and the attempts now making to protect it from the sea. The damage consists of eight breaches in the sea-wall; but in one of these, which is 100 feet long, the coping only is overthrown; whilst in the other seven, both coping and sea-wall, formed of massive blocks of sandstone, are destroyed, measuring respectively (from the Teignmouth side) 250, 315, 80, 190, 215, 216, and 82 feet. Mr. Brunel was present, and explained the plans for the intended restoration, which are very elaborate, consisting of a massive wall of Babbicome limestone, with a back filling of layers of fagot and sandstone. As, however, the remaining coping and sea-wall are much cracked and loosened, unless all is relaid, the same weakness will attend the work as a whole. Cargoes of limestone are continually arriving, and it is stated that from 80 to 150 men and 27 horses are employed, and 32 additional masons are required; so that, under the guidance of their bold engineer, the directors will spare no effort or expense. Mr. Brunel is confident that he can keep out the sea from the line, and the air from the tube: and as to cost, it is in vain to shrink even from £100,000, for the whole property is not worth a shilling if the evil be not cured. The tide was high during the late destruction of the line, but it was only half a gale of wind, or, according to old Stephen Matterface, the old Dawlish orator, it was but the first of three degrees: "This," said he to James, the blacksmith, "is Neptune's youngest son; next time he will send his eldest; if that will not do, next time he will come himself, and sweep them all away." Old Stephen did not lower his voice, though the Great Western engineers were by, for he wished them to have the advantage of age and experience. In winter storms the sea breaks far above the line, and water is not the only enemy. The high cliffs consist of soft new red sandstone, and in many parts form now, as we have said, a perpendicular wall immediately above the line, occasionally hanging over it. The rocks are so shaken and cracked by blasting, that for many years portions are likely to come off in frost and wet. It is notorious to residents in the neighbourhood that masses of the cliff are detached in winter, and that, during the last thirty years, the forms of the rocks have been completely changed.—*Exeter Gazette.*

**Figure A.2:** Newspaper Excerpt from 1846

### Exeter Flying Post

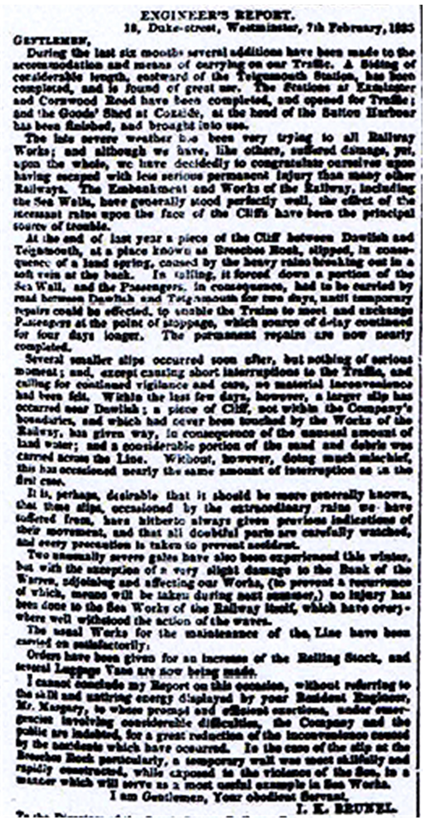
### Saturday 1st January 1853

Reporting of the likely 1st event mentioned in Brunel's report to the SDR annual general meeting (ref A.4). By all accounts from multiple sources this storm event was powerful and geographically significant.

As well as the South West of England damage, casualties and structural damage in London was also reported at the same time.

A most *tremendous fall of cliff* took place on Wednesday on the South Devon Railway between Dawlish and Teignmouth. On the formation of the line it was found necessary to cut a tunnel through the rocks known as "The Parson and Clerk." A portion of Langstone-cliff was thus cut off, and its base being undermined by the action of the water, great fears were entertained for its safety. The recent heavy rain and hurricanes increased the danger, and men were stationed at various points to give notice immediately anything occurred. The necessity of the adoption of such a course was first experienced on Sunday, when a portion of the cliff fell down near Holcombe tunnel. The 8.2 a.m. down train had just left the Dawlish station when it ocurred, but by the promptness with which the man on the look-out gave notice of the accident it was stopped in time, or there would have been a fearful crash. A large body of men were soon obtained, and the line was cleared in time for the 12.7 up train. On Thursday morning, however, there was a terrific fall of cliff; at about half-past one o'clock several tons of Langstone cliff fell with a tremendous crash, covering the line for some distance, and rendering all traffic impossible. The passengers by all the trains were obliged to be conveyed from Dawlish to Teignmouth, and *vice versâ*, in cabs, omnibuses, and every other description of vehicle which the company could obtain. The telegraphic wires were also broken, and all communication with the stations below was thus, for the time, prevented. Large gangs of men were speedily put to work to clear the line of the *débris*. Mr. Brunel, the engineer, with several of the directors, went to the spot and superintended the removal of the fallen mass. Fortunately, no life was lost, nor have we heard of a single accident to the person. It is supposed that the storm on Sunday night hastened the demolition of the cliff, as it visited this neighbourhood with great severity, stones weighing half a cwt. each being carried up into Teignmouth by the force of the waves.

**Figure A.3:** Newspaper Excerpt from 1853



ENGINEER'S REPORT.

18, Duke-street, Westminster, 7th February, 1853

GENTLEMEN,

During the last six months several additions have been made to the accommodation and means of carrying on our Traffic. A Siding of considerable length, eastward of the Teignmouth Station, has been completed, and is found of great use. The Stations at Exminster and Cornwood Road have been completed, and opened for Traffic; and the Goods' Shed at Coxside, at the head of the Sutton Harbour has been finished, and brought into use.

The late severe weather has been very trying to all Railway Works; and although we have, like others, suffered damage, yet, upon the whole, we have decidedly to congratulate ourselves upon having escaped with less serious permanent injury than many other Railways. The Embankment and Works of the Railway, including the Sea Walls, have generally stood perfectly well, the effect of the incessant rains upon the face of the Cliffs have been the principal source of trouble.

At the end of last year a piece of the Cliff between Dawlish and Teignmouth, at a place known as Breeches Rock, slipped, in consequence of a land spring, caused by the heavy rains breaking out in a soft vein at the back. In falling, it forced down a portion of the Sea Wall, and the Passengers, in consequence, had to be carried by road between Dawlish and Teignmouth for two days, until temporary repairs could be effected, to enable the Trains to meet and exchange Passengers at the point of stoppage, which source of delay continued for four days longer. The permanent repairs are now nearly completed.

Several smaller slips occurred soon after, but nothing of serious moment; and, except causing short interruptions to the Traffic, and calling for continued vigilance and care, no material inconvenience had been felt. Within the last few days, however, a larger slip has occurred near Dawlish; a piece of Cliff, not within the Company's boundaries, and which had never been touched by the Works of the Railway, has given way, in consequence of the unusual amount of land water; and a considerable portion of the sand and debris was carried across the Line. Without, however, doing much mischief, this has occasioned nearly the same amount of interruption as in the first case.

It is, perhaps, desirable that it should be more generally known, that these slips, occasioned by the extraordinary rains we have suffered from, have hitherto always given previous indications of their movement, and that all doubtful parts are carefully watched, and every precaution is taken to prevent accident.

Two unusually severe gales have also been experienced this winter, but with the exception of a very slight damage to the Bank of the Warren, adjoining and affecting our Works, (to prevent a recurrence of which, means will be taken during next summer,) no injury has been done to the Sea Works of the Railway itself, which have everywhere well withstood the action of the waves.

The usual Works for the maintenance of the Line have been carried on satisfactorily.

Orders have been given for an increase of the Rolling Stock, and several Luggage Vans are now being made.

I cannot conclude my Report on this occasion, without referring to the skill and untiring energy displayed by your Resident Engineer, Mr. Margary, to whose prompt and efficient exertions, under emergencies involving considerable difficulties, the Company and the public are indebted, for a great reduction of the inconvenience caused by the accidents which have occurred. In the case of the slip at the Breeches Rock particularly, a temporary wall was most skilfully and rapidly constructed, while exposed to the violence of the Sea, in a manner which will serve as a most useful example in Sea Works.

I am Gentlemen, Your obedient Servant,

I. K. BRUNEL.

**Figure A.4:** Brunel Engineers' Report 1853

## The Western Courier

## SDR Annual General Meeting

## Engineer's Report

## Wednesday 23rd February 1853

Brunel suggests that the railway structures are coping well with the weather, but the cliffs are suffering from high amounts of rainfall leading to landslides.

At the end of 1852, Breeches Rock failed in landslide leading to 6 days of disruption to the service, and damage to the seawall. Permanent repairs are nearly completed (2 months later). Smaller slips followed but of little consequence.

Recently, a larger slip has occurred on land not owned by the railway, however material was carried onto the rails and needed to be removed. This disrupted service for 6 days similar to the first event at Breeches Rock.

Two abnormally severe gales are reported, however no damage to the railway or seawall is reported apart from some embankment damage near Dawlish Warren.

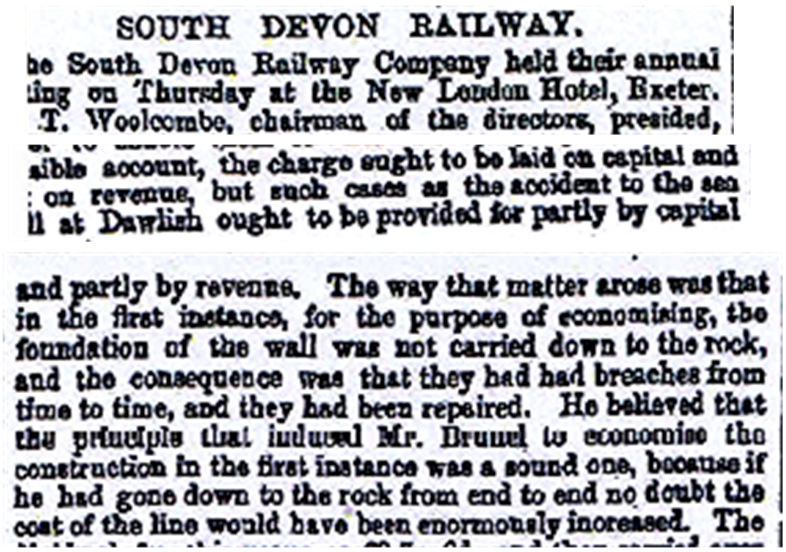
Brunel specifically thanks Mr Margery, the resident engineer, for his diligent work.

### Exeter Flying Post

### (post 1871)

At some point in the 1870's a SDR annual general meeting reported a serious engineering problem with the sea wall on the railway. This report came a significant time after the death of Mr Brunel (1859).

The report below shows that Mr Brunel had knowingly built the seawall, without adequate provisions for foundations to the bedrock. This was apparently done in order to economise on costs and represents a significant finding of my research. It would appear that the engineering judgement of Mr Brunel had been compromised in favour of costs and that this may have significantly contributed to the damage record of the seawall since its inception in 1846.



SOUTH DEVON RAILWAY.

he South Devon Railway Company held their annual ting on Thursday at the New London Hotel, Exeter. .T. Woolcombe, chairman of the directors, presided,

sible account, the charge ought to be laid on capital and on revenue, but such cases as the accident to the sea ll at Dawlish ought to be provided for partly by capital

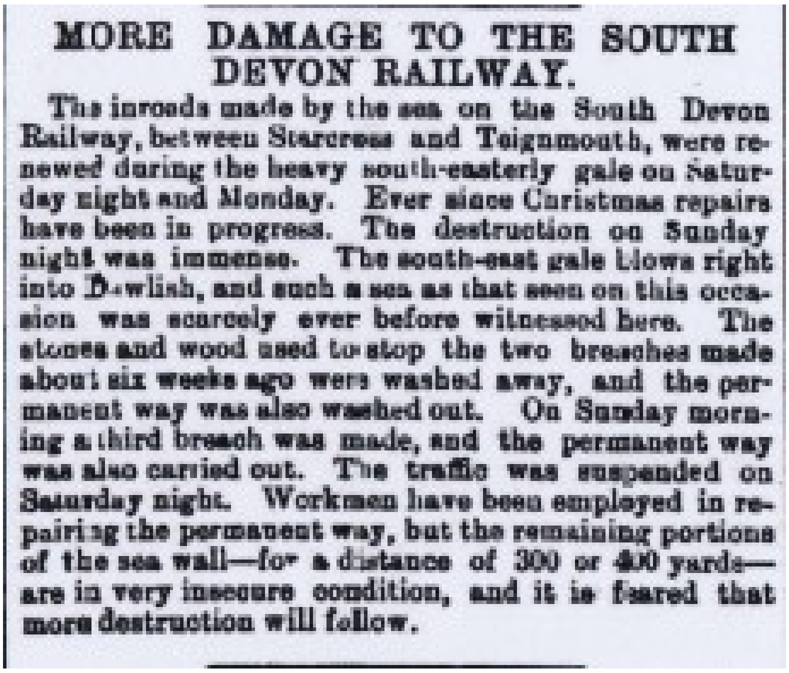
and partly by revenue. The way that matter arose was that in the first instance, for the purpose of economising, the foundation of the wall was not carried down to the rock, and the consequence was that they had had breaches from time to time, and they had been repaired. He believed that the principle that induced Mr. Brunel to economise the construction in the first instance was a sound one, because if he had gone down to the rock from end to end no doubt the cost of the line would have been enormously increased. The

**Figure A.5:** Newspaper Excerpt post 1871

## Blackburn Standard

### Wednesday 5th February 1873

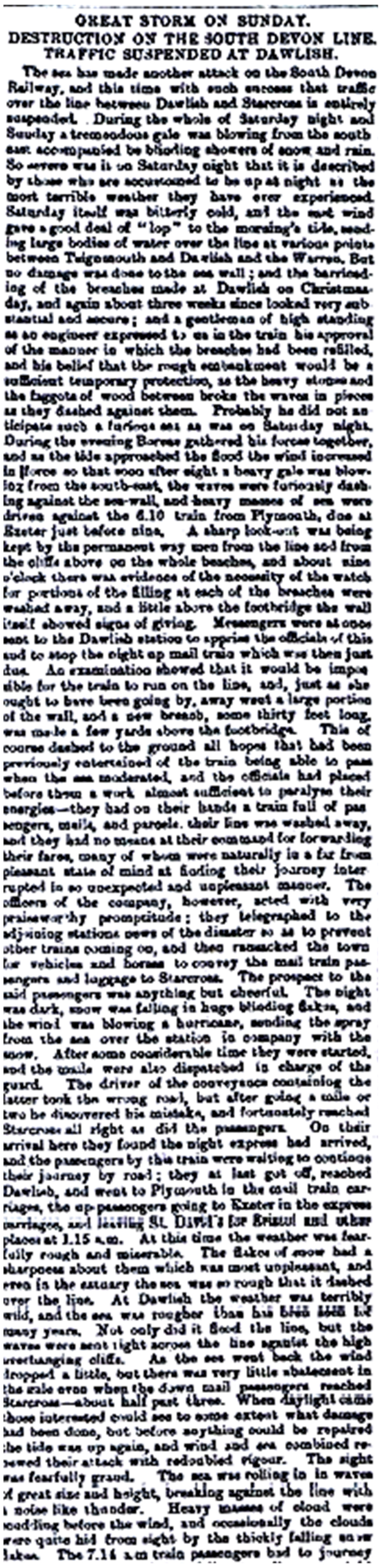
Multiple breaches in seawall and ballast wash out caused by south easterly winds stretching approx 400 metres. Service suspended.



MORE DAMAGE TO THE SOUTH DEVON RAILWAY.

The inroads made by the sea on the South Devon Railway, between Starcross and Teignmouth, were renewed during the heavy south-easterly gale on Saturday night and Monday. Ever since Christmas repairs have been in progress. The destruction on Sunday night was immense. The south-east gale blows right into Dawlish, and such a sea as that seen on this occasion was scarcely ever before witnessed here. The stones and wood used to stop the two breaches made about six weeks ago were washed away, and the permanent way was also washed out. On Sunday morning a third breach was made, and the permanent way was also carried out. The traffic was suspended on Saturday night. Workmen have been employed in repairing the permanent way, but the remaining portions of the sea wall—for a distance of 300 or 400 yards—are in very insecure condition, and it is feared that more destruction will follow.

**Figure A.6:** Newspaper Excerpt from 1873



GREAT STORM ON SUNDAY.
DESTRUCTION ON THE SOUTH DEVON LINE.
TRAFFIC SUSPENDED AT DAWLISH.

The sea has made another attack on the South Devon Railway, and this time with such success that traffic over the line between Dawlish and Starcross is entirely suspended. During the whole of Saturday night and Sunday a tremendous gale was blowing from the south east accompanied by blinding showers of snow and rain. So severe was it on Saturday night that it is described by those who are accustomed to be up at night as the most terrible weather they have ever experienced. Saturday itself was bitterly cold, and the east wind gave a good deal of "lop" to the morning's tide, sending large bodies of water over the line at various points between Teignmouth and Dawlish and the Warren. But no damage was done to the sea wall; and the barricading of the breaches made at Dawlish on Christmas-day, and again about three weeks since looked very substantial and secure; and a gentleman of high standing as an engineer expressed to us in the train his approval of the manner in which the breaches had been refilled, and his belief that the rough embankment would be a sufficient temporary protection, as the heavy stones and the faggots of wood between broke the waves in pieces as they dashed against them. Probably he did not anticipate such a furious sea as was on Saturday night. During the evening Boreas gathered his forces together, and as the tide approached the flood the wind increased in force so that soon after eight a heavy gale was blowing from the south-east, the waves were furiously dashing against the sea-wall, and heavy masses of sea were driven against the 6.10 train from Plymouth, due at Exeter just before nine. A sharp look-out was being kept by the permanent way men from the line and from the cliffs above on the whole beaches, and about nine o'clock there was evidence of the necessity of the watch for portions of the filling at each of the breaches were washed away, and a little above the footbridge the wall itself showed signs of giving. Messengers were at once sent to the Dawlish station to apprise the officials of this and to stop the eight up mail train which was then just due. An examination showed that it would be impossible for the train to run on the line, and, just as she ought to have been going by, away went a large portion of the wall, and a new breach, some thirty feet long, was made a few yards above the footbridge. This of course dashed to the ground all hopes that had been previously entertained of the train being able to pass when the sea moderated, and the officials had placed before them a work almost sufficient to paralyse their energies—they had on their hands a train full of passengers, mails, and parcels. their line was washed away, and they had no means at their command for forwarding their fares, many of whom were naturally in a far from pleasant state of mind at finding their journey interrupted in so unexpected and unpleasant manner. The officers of the company, however, acted with very praiseworthy promptitude; they telegraphed to the adjoining stations news of the disaster so as to prevent other trains coming on, and then ransacked the town for vehicles and horses to convey the mail train passengers and luggage to Starcross. The prospect to the said passengers was anything but cheerful. The night was dark, snow was falling in huge blinding flakes, and the wind was blowing a hurricane, sending the spray from the sea over the station in company with the snow. After some considerable time they were started, and the mails were also dispatched in charge of the guard. The driver of the conveyance containing the latter took the wrong road, but after going a mile or two he discovered his mistake, and fortunately reached Starcross all right as did the passengers. On their arrival here they found the night express had arrived, and the passengers by this train were waiting to continue their journey by road; they at last got off, reached Dawlish, and went to Plymouth in the mail train carriages, the up-passengers going to Exeter in the express carriages, and leaving St. David's for Bristol and other places at 1.15 a.m. At this time the weather was fearfully rough and miserable. The flakes of snow had a sharpness about them which was most unpleasant, and even in the estuary the sea was so rough that it dashed over the line. At Dawlish the weather was terribly wild, and the sea was rougher than has been seen for many years. Not only did it flood the line, but the waves were sent right across the line against the high overhanging cliffs. As the sea went back the wind dropped a little, but there was very little abatement in the gale even when the down mail passengers reached Starcross—about half past three. When daylight came those interested could see to some extent what damage had been done, but before anything could be repaired the tide was up again, and wind and sea combined renewed their attack with redoubled vigour. The sight was fearfully grand. The sea was rolling in in waves of great size and height, breaking against the line with a noise like thunder. Heavy masses of cloud were scudding before the wind, and occasionally the clouds were quite hid from sight by the thickly falling snow flakes. The 7.14 a.m train passengers had to journey

**Figure A.7:** North Devon Journal 1873 (1/2)

**The North Devon Journal**

**Thursday 6th February 1873**

(1 of 2)

South-easterly gales lasting Saturday night into Sunday morning - significant storm event.

Reported as worst storm experienced by eye-witnesses.

Significant wave overtopping the line on Saturday.

No seawall damage - repairs seem secure. Engineers expressed confidence in temporary embankment.

Later that same evening - strong south easterly storm caused multiple breaches in the wall and threatened damage to a footbridge.

Rail impassable, mail trains suspended on the line. Passengers had to be ferried by other means to their destinations.

Worst weather seen at Dawlish for many years. Significant wind and snow storms.

New breach in wall approximately 30m long.

flakes. The 7.14 a.m train passengers had to journey in the [illegible] as did their fellow travellers over night and the early up-train arrivals had also to go by road from Dawlish to Starcross. The force of the wind kept the tide at the flood much longer than it would have remained under ordinary circumstances, and of course it was so much longer before any attempt could be made to ascertain the full amount of the damage or repair it. When the tide did go back sufficiently the full amount of the damage was seen. There are now three breaches in the wall. The first is about sixty yards long and was made on Christmas-day. That has been barricaded with heavy limestones with layers of faggots between, and the breach was thus filled up pretty substantially. But before this was thoroughly finished there came the gale and forty-foot breach of January 11th. This was filled in the same way as was the other breach. Above this the wall had been shaken very considerably, and a little higher up than the foot-bridge which crosses the line half-way between Dawlish and the Warren a slight fissure was made a few days since. The tides of Saturday night and Sunday morning washed away about a dozen yards of the material used for barricading the the first breach and pieces of the wall on either side of the breach were also knocked down. At the second breach every vestige of the stone thrown out and all the faggots were washed clean away, and with it went the material forming the original permanent way of the line. The rails remain hanging in mid-air; but the foundation of the line was on a level with the beach. The third breach—the new one—is about thirty yards long, and here, too, all the permanent way—the [illegible] supporting the rails—was washed out and brought on the same level as the beach. The wall between each breach and also above the higher breach is cracked in all directions, and in so shaky a condition that there is no doubt it will fall if it is not washed down. The greatest anxiety was evinced concerning the new foot bridge, for as it is an exceedingly heavy mass of masonry fears were entertained that it would come down. The masonry however still stands firm, though the wall on either side is in a most dilapidated condition. Faggots strew the beach in all directions. The amount of damage now done is very serious indeed, so serious that under the most favourable circumstances the line cannot be possibly be restored to its former condition for several months. Almost all that has been done since Christmas has been washed away, and the heavy outlay already incurred therefore goes for nothing.

A large number of men were at work on Sunday afternoon endeavouring to refill the breaches against the evening tide, so as to offer some resistance to the sea. The passengers are conveyed between the Dawlish and Starcross as promptly as possible, but it is miserable riding, particularly in one vehicle [illegible] the seats of which were wet and the curtains around were broken, so that the journey to Starcross was about as miserable as any can well conceive. Further vehicles and horses arrived from various towns by Sunday afternoon's trains to meet Monday's heavier traffic.

Many of the marshes between St. Thomas and Starcross were flooded on Sunday afternoon, and a great portion of Powderham Park was under water. The snow, which was eight or ten inches deep in Exeter, did not lie on the ground in any considerable quantity between Exminster and Dawlish, and there were more showers of rain than snow. Between Starcross and the Warren the new second line of rails is laid down, but in several places the rains have caused the new embankment to slip away. The sea dashed over the stone embankment thrown out by the railway company opposite Mount Pleasant, and some of the earthwork on which the tramway is laid washed away.

Monday.—Most vigorous efforts were made through Sunday night and Monday in partially filling up the breaches, some 160 men being employed. The sea was beautifully calm, and the weather was fine, so that the operations were proceeded with without the slightest interruption. Towards nightfall, on Monday evening, huge bonfires were lit, which, with the light afforded by the moon, enabled additional relays of men to be put on. The same process was followed as on former occasions, by throwing in faggots of wood, stones, and earth, the object at first being to fill up to the inner line of rail, so as to admit, if possible, of the up mail train being passed over. The arrangements of the Company, for the traffic between Dawlish and Starcross, generally gave satisfaction—several omnibuses, breaks, and cabs being used for passengers, and waggons for luggage. On Monday night the up mail train passed safely over the damaged portion of the line.

**Figure A.8:** North Devon Journal 1873 (2/2)

## The North Devon Journal

## Thursday 6th February 1873

(2 of 2)

There are now 3 breaches in the wall: First, 60m long made on Christmas Day; Second, 40m breach on 11th January; Third, 30m long.

Rails hanging in mid air (c.f. Feb 2014)

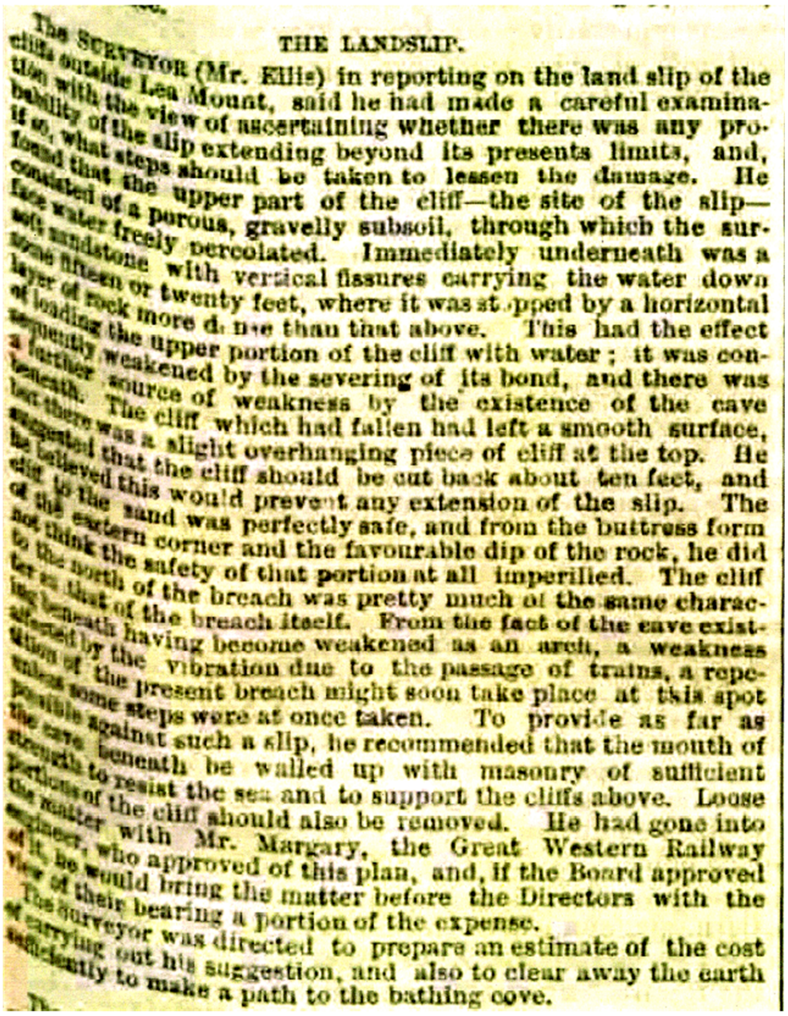
Seawall washed to beach level in several places and cracked and damaged in all directions - near collapse condition by successive tides.

Reported such serious damage to require several months service suspension.

### Exeter & Plymouth Gazette

### Saturday 6th March 1880

An overhanging cliff is reported to have caused a landslip near the railway and blocking access to a local beach. A comprehensive review of the mechanism of landslip is given detailing geotechnical details of faulting and fissures in the strata. Vibration of passing trains are mentioned as potential for activating further landslips and as such the railway company should make a contribution to the costs of cutting back the overhanging cliffs and reinforcing a cave underneath the breach with masonry to improve strength.

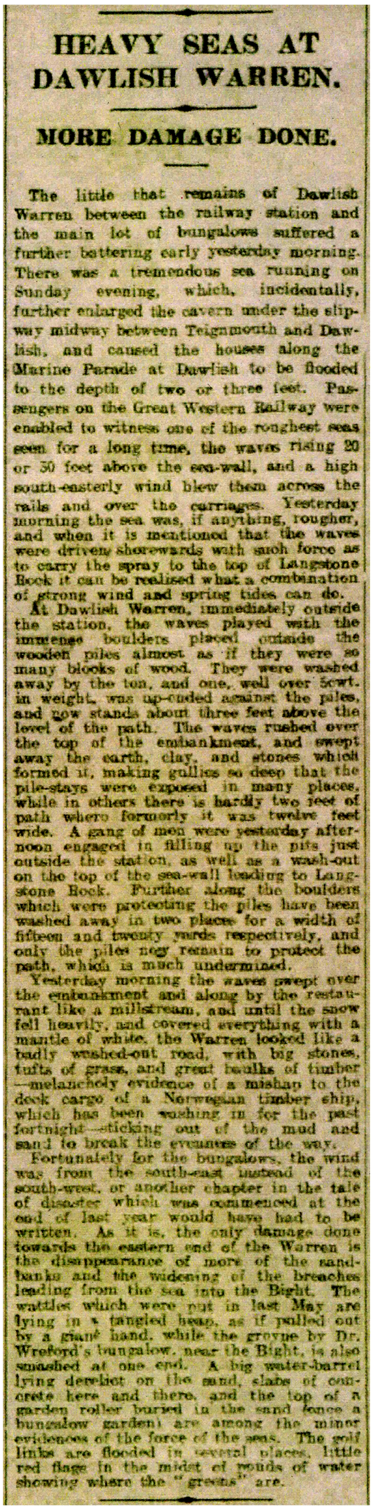


THE LANDSLIP.

The SURVEYOR (Mr. Ellis) in reporting on the land slip of the cliffs outside Lea Mount, said he had made a careful examination with the view of ascertaining whether there was any probability of the slip extending beyond its presents limits, and, if so, what steps should be taken to lessen the damage. He found that the upper part of the cliff—the site of the slip—consisted of a porous, gravelly subsoil, through which the surface water freely percolated. Immediately underneath was a soft sandstone with vertical fissures carrying the water down some fifteen or twenty feet, where it was stopped by a horizontal layer of rock more dense than that above. This had the effect of loading the upper portion of the cliff with water; it was consequently weakened by the severing of its bond, and there was a further source of weakness by the existence of the cave beneath. The cliff which had fallen had left a smooth surface, but there was a slight overhanging piece of cliff at the top. He suggested that the cliff should be cut back about ten feet, and he believed this would prevent any extension of the slip. The cliff to the sand was perfectly safe, and from the buttress form of the eastern corner and the favourable dip of the rock, he did not think the safety of that portion at all imperilled. The cliff to the north of the breach was pretty much of the same character as that of the breach itself. From the fact of the cave existing beneath having become weakened as an arch, a weakness affected by the vibration due to the passage of trains, a repetition of the present breach might soon take place at this spot unless some steps were at once taken. To provide as far as possible against such a slip, he recommended that the mouth of the cave beneath be walled up with masonry of sufficient strength to resist the sea and to support the cliffs above. Loose portions of the cliff should also be removed. He had gone into the matter with Mr. Margary, the Great Western Railway engineer, who approved of this plan, and, if the Board approved of it, he would bring the matter before the Directors with the view of their bearing a portion of the expense.

The Surveyor was directed to prepare an estimate of the cost of carrying out his suggestion, and also to clear away the earth sufficiently to make a path to the bathing cove.

**Figure A.9:** Newspaper Excerpt from 1880



HEAVY SEAS AT DAWLISH WARREN.

MORE DAMAGE DONE.

The little that remains of Dawlish Warren between the railway station and the main lot of bungalows suffered a further battering early yesterday morning. There was a tremendous sea running on Sunday evening, which, incidentally, further enlarged the cavern under the slipway midway between Teignmouth and Dawlish, and caused the houses along the Marine Parade at Dawlish to be flooded to the depth of two or three feet. Passengers on the Great Western Railway were enabled to witness one of the roughest seas seen for a long time, the waves rising 20 or 30 feet above the sea-wall, and a high south-easterly wind blew them across the rails and over the carriages. Yesterday morning the sea was, if anything, rougher, and when it is mentioned that the waves were driven shorewards with such force as to carry the spray to the top of Langstone Rock it can be realised what a combination of strong wind and spring tides can do.

At Dawlish Warren, immediately outside the station, the waves played with the immense boulders placed outside the wooden piles almost as if they were so many blocks of wood. They were washed away by the ton, and one, well over 5cwt. in weight, was up-ended against the piles, and now stands about three feet above the level of the path. The waves rushed over the top of the embankment, and swept away the earth, clay, and stones which formed it, making gullies so deep that the pile-stays were exposed in many places, while in others there is hardly two feet of path where formerly it was twelve feet wide. A gang of men were yesterday afternoon engaged in filling up the pits just outside the station, as well as a wash-out on the top of the sea-wall leading to Langstone Rock. Further along the boulders which were protecting the piles have been washed away in two places for a width of fifteen and twenty yards respectively, and only the piles now remain to protect the path, which is much undermined.

Yesterday morning the waves swept over the embankment and along by the restaurant like a millstream, and until the snow fell heavily, and covered everything with a mantle of white, the Warren looked like a badly washed-out road, with big stones, tufts of grass, and great baulks of timber —melancholy evidence of a mishap to the deck cargo of a Norwegian timber ship, which has been washing in for the past fortnight—sticking out of the mud and sand to break the evenness of the way.

Fortunately for the bungalows, the wind was from the south-east instead of the south-west, or another chapter in the tale of disaster which was commenced at the end of last year would have had to be written. As it is, the only damage done towards the eastern end of the Warren is the disappearance of more of the sandbanks and the widening of the breaches leading from the sea into the Bight. The wattles which were put in last May are lying in a tangled heap, as if pulled out by a giant hand, while the groyne by Dr. Wreford's bungalow, near the Bight, is also smashed at one end. A big water-barrel lying derelict on the sand, slabs of concrete here and there, and the top of a garden roller buried in the sand (once a bungalow garden) are among the minor evidences of the force of the seas. The golf links are flooded in several places, little red flags in the midst of ponds of water showing where the "greens" are.

**Figure A.10:** Newspaper Excerpt from 1912

**Exeter & Plymouth Gazette**

**Tuesday 6th February 1912**

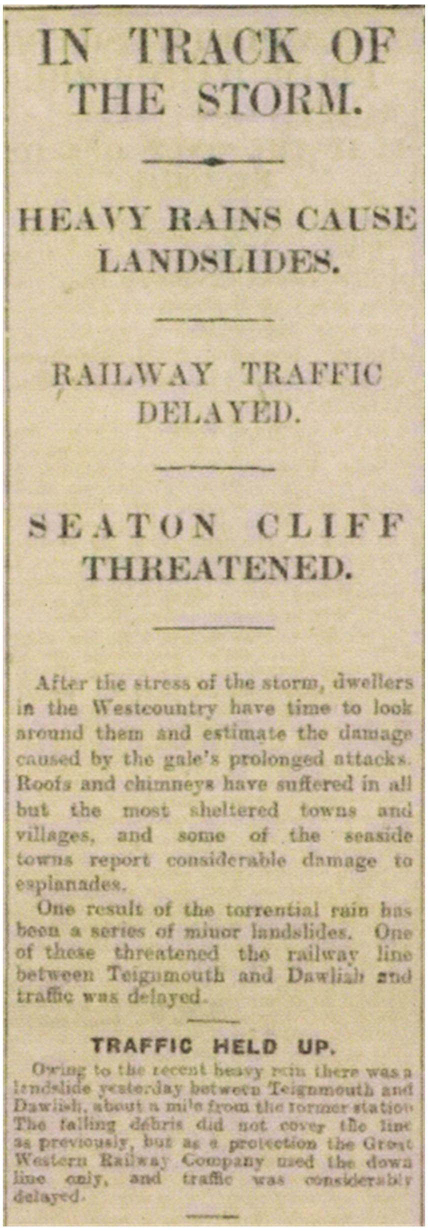
Houses along marine parade are flooded up to 1m with sea water.

Waves rising up to 10m above the sea wall.

South easterly wind direction, high spring tides (cf. 2014 event).

Rock armour material of up to 26 tonnes being moved easily by the sea conditions - the waves moving the block 1m above the promenade.

Flooding of rails and caverns appearing - gangs of men involved in replacing washed out materials near Dawlish station.



IN TRACK OF THE STORM.

HEAVY RAINS CAUSE LANDSLIDES.

RAILWAY TRAFFIC DELAYED.

SEATON CLIFF THREATENED.

After the stress of the storm, dwellers in the Westcountry have time to look around them and estimate the damage caused by the gale's prolonged attacks. Roofs and chimneys have suffered in all but the most sheltered towns and villages, and some of the seaside towns report considerable damage to esplanades.

One result of the torrential rain has been a series of minor landslides. One of these threatened the railway line between Teignmouth and Dawlish and traffic was delayed.

TRAFFIC HELD UP.

Owing to the recent heavy rain there was a landslide yesterday between Teignmouth and Dawlish, about a mile from the former station. The falling débris did not cover the line as previously, but as a protection the Great Western Railway Company used the down line only, and traffic was considerably delayed.

**Figure A.11:** Newspaper Excerpt from 1925

## The Western Morning News

## Tuesday 6th January 1925

Extensive heavy rains lead to landslides on the railway between Dawlish and Teignmouth.

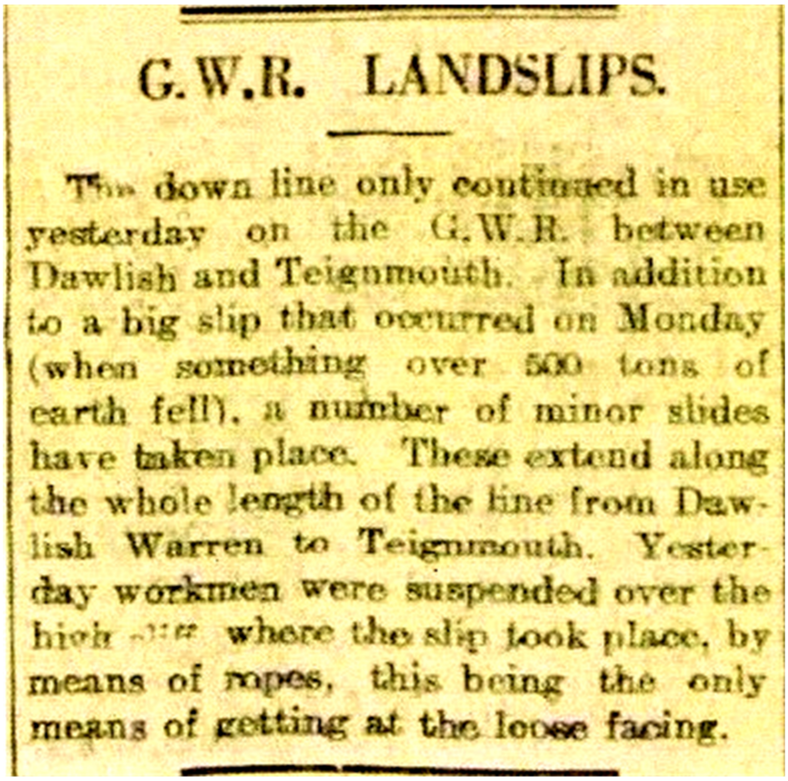
Single line working instigated by GWR.

### Exeter & Plymouth Gazette

### Thursday 8th January 1925

Single-line working in operation - major landslip on Monday was estimated over 500 tons, with additional landslips along the whole section of railway between Dawlish and Teignmouth.

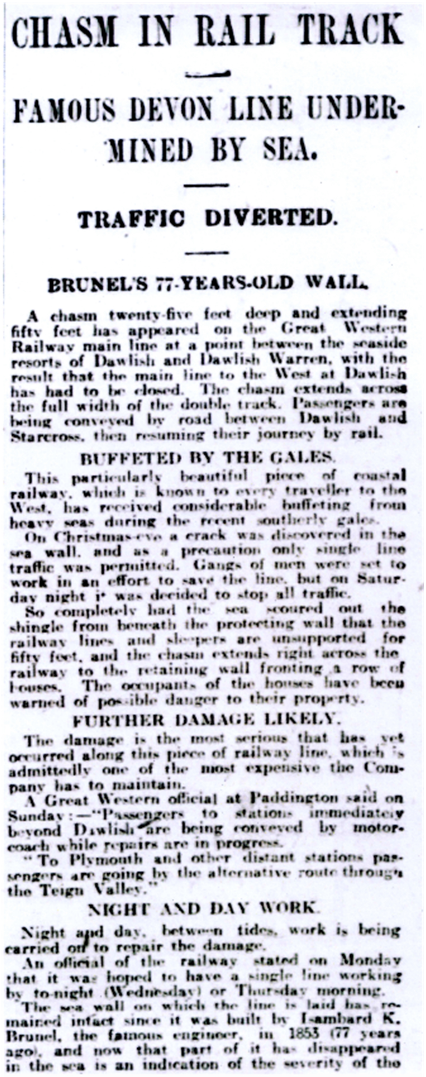
Workers are suspended trying to consolidate the loose material on the cliff edge.



G.W.R. LANDSLIPS.

The down line only continued in use yesterday on the G.W.R. between Dawlish and Teignmouth. In addition to a big slip that occurred on Monday (when something over 500 tons of earth fell), a number of minor slides have taken place. These extend along the whole length of the line from Dawlish Warren to Teignmouth. Yesterday workmen were suspended over the high cliff where the slip took place, by means of ropes, this being the only means of getting at the loose facing.

**Figure A.12:** Newspaper Excerpt from 1925



CHASM IN RAIL TRACK

FAMOUS DEVON LINE UNDER-MINED BY SEA.

TRAFFIC DIVERTED.

BRUNEL'S 77-YEARS-OLD WALL.

A chasm twenty-five feet deep and extending fifty feet has appeared on the Great Western Railway main line at a point between the seaside resorts of Dawlish and Dawlish Warren, with the result that the main line to the West at Dawlish has had to be closed. The chasm extends across the full width of the double track. Passengers are being conveyed by road between Dawlish and Starcross, then resuming their journey by rail.

BUFFETED BY THE GALES.

This particularly beautiful piece of coastal railway, which is known to every traveller to the West, has received considerable buffeting from heavy seas during the recent southerly gales.

On Christmas-eve a crack was discovered in the sea wall, and as a precaution only single line traffic was permitted. Gangs of men were set to work in an effort to save the line, but on Saturday night it was decided to stop all traffic.

So completely had the sea scoured out the shingle from beneath the protecting wall that the railway lines and sleepers are unsupported for fifty feet, and the chasm extends right across the railway to the retaining wall fronting a row of houses. The occupants of the houses have been warned of possible danger to their property.

FURTHER DAMAGE LIKELY.

The damage is the most serious that has yet occurred along this piece of railway line, which is admittedly one of the most expensive the Company has to maintain.

A Great Western official at Paddington said on Sunday:—"Passengers to stations immediately beyond Dawlish are being conveyed by motor-coach while repairs are in progress.

"To Plymouth and other distant stations passengers are going by the alternative route through the Teign Valley."

NIGHT AND DAY WORK.

Night and day, between tides, work is being carried on to repair the damage.

An official of the railway stated on Monday that it was hoped to have a single line working by to-night (Wednesday) or Thursday morning.

The sea wall on which the line is laid has remained intact since it was built by Isambard K. Brunel, the famous engineer, in 1853 (77 years ago), and now that part of it has disappeared in the sea is an indication of the severity of the

**Figure A.13:** Newspaper Excerpt from 1930

**The Western Courier**

**Monday 6th January 1930**

This report erroneously claims that the Brunel wall has remained intact for 77 years. This claim was repeated during reporting of the 2014 breach. The 1930 breach is very similar to, if not as serious or widespread as the breach in 2014 - but was approximately in exactly the same position. There are considerable similarities in the details of the damage between both events.

Single line working is mentioned after complete failure of the seawall over successive high tides.

### Exeter & Plymouth Gazette

### Monday 19th January 1931

Landslide outside of Dawlish causes suspension and single line working of the railway.

The event lasts some days and disruption is reported to both passenger and freight trains.

# FALL OF CLIFF.

## *Railway Lines Blocked near Dawlish.*

## SINGLE-LINE WORKING.

A heavy fall of cliff temporarily blocked the Great Western Railway lines between Hole Head tunnel and Spray Point, Teignmouth, on Saturday.

The landslip, which was partially checked by a wall, occurred just after the 7.36 a.m. train from Teignmouth to Exeter had passed, and blocked both lines. The driver of the Bristol down goods train, due at Teignmouth at 7.45, noticed the obstruction and proceeded cautiously, notifying the stationmaster at Teignmouth of the occurrence. A gang of men were soon engaged in clearing the earth and boulders, some of which weighed about half a ton. Other boulders frequently fell, and made the work very dangerous. Traffic was disorganised throughout South Devon, but one train was diverted later to the Teign Valley line, and an emergency 'bus service was put in operation between Dawlish and Teignmouth. After an hour's hard work on the obstruction, the down road was cleared, and single-line working was established between Dawlish and Teignmouth. At 10 o'clock the 9.14 train for London passed at a slow rate on the down line. The northern mail was delayed for about 10 minutes at Exeter pending inquiries.

It is anticipated that single-line working will be continued for a few days, as a precautionary measure for, while the present fall is not great, the possibility of a further fall is a contingency which cannot be ignored. The heavy frosts of the past week, coupled with the vibration of the trains, are held responsible for the fall, which came from the top of the cliff. The under part is in an unsafe condition, and the loose portions are being removed.

**Figure A.14:** Newspaper Excerpt from 1931

# Travel chaos as 70mph gales batter Britain

By A J McIlroy

TORRENTIAL rain and winds gusting to more than 70mph pounded parts of Britain yesterday making driving hazardous and disrupting rail services.

Worst affected were the West Country and South Wales, suffering their third day of storms. These were moving into eastern parts last night and the London Weather Centre said the week ahead would be "extremely wet and windy".

Relentless winds and high tides hampered attempts by Railtrack engineers to reopen rail services to the South West yesterday after the network west of Exeter was cut off on Saturday by waves breaching sea walls near Dawlish and Teignmouth in Devon.

South Wales and West Railways, which operates the regional services, expects to continue emergency buses for part of today.

A Railtrack spokesman said: "We have had engineers out since Sunday morning working on the breaches. The high tides mean we cannot get at the wall to carry out repairs."

There was flooding in Devon, where drivers were warned to take extreme care. Sidmouth seafront was closed as waves crashed over the esplanade at high tide.

Passengers on the King Harry ferry on the River Fal in Cornwall were stranded for almost three hours when its chain jammed 20 yards from shore.

The water companies welcomed the rain but said much more was needed before drought restrictions could be lifted. South West Water, one of the companies operating restrictions, said Roadford Reservoir, near Launceston, Cornwall, the region's biggest, was still only 27 per cent full.

Sea birds were being cared for by the RSPCA yesterday after they were covered in oil debris from the sea bed believed to have been churned up by the gales. Worst affected was the St Austell Bay area of Cornwall.

Heavy snowfalls on the east coast of America disrupted flights from Britain. Passengers hoping to fly to New York, Washington, Philadelphia and Newark were stranded as record snowfalls closed the airports yesterday.

British Airways cancelled all four Concorde flights between Heathrow and New York's JFK airport.

American Airlines cancelled all its six flights from Heathrow to JFK and an evening flight to Boston. United Airlines cancelled its two flights to JFK, two to Washington and one to Newark.

The Royal Navy rescued the five-man crew of a Romanian cargo ship yesterday after ordering them to leap into heavy seas 300 miles south west of Cape Finisterre on the Spanish coast.

A helicopter from HMS Northumberland found the 4,000-ton Covasna pitching too violently in 30ft waves to winch up the seamen. Instead, they dropped survival suits and picked up the men from the water.

About 400 tourists returning to Britain from Spain were diverted to Le Havre in France yesterday after gales forced the cancellation of the P&O ferry service from Bilbao to Portsmouth.

**Figure A.15:** Newspaper Excerpt from 1996

### The Daily Telegraph

### Tuesday 9th January 1996

Services suspended along the SDR due to storms and high tides making repair work impossible. Waves have breached the seawall with replacement bus services needed to ferry passengers across the region.

Note the considerable wave overtopping also apparent at Sidmouth, 20 km to NE of Dawlish.

Appendix B

# Consolidated Damage Record

Use was made of the information gathered by Dawson, Shaw and Gehrels [26] and Rogers and O'Breasail [112] which was obtained via personal communication with Dr. David Dawson, Lecturer in Transport Management & Resilience at University of Leeds in order to cross-reference the original material obtained in Appendix A. The information presented in Table B.1 has been compiled as part of a resilience study of the climate change effects and future SLR on transport infrastructure in the South West of England.

The data of damage to the railway in Table B.1 is arranged primarily in chronological order and includes important information on the exact position of the destruction events with some information on interventions taken to repair the damage.

In the UK, the national rail network is surveyed linearly in Gunter chains (a unit of measure equal to 66 feet or approximately 20.12m), with 80 chains to 1 mile, from the headquarters or terminus of the original train company. For the Great Western mainline, this station is Paddington in London. The definition of the chain is contained in the UK Weights and Measure Act 1985 and can be found at: https://www.legislation.gov.uk/ukpga/1985/72/schedule/1/part/VI.

Every engineering asset on the line will be referenced according to its chainage to aid surveying and asset management. Consequently, the seawall at Dawlish runs from Langstone Rock in the east (204.70 miles or 204 miles 70 chains) to Sprey Point in the west (208.16 miles, 208 miles 16 chains). The location of major assets of interest in this study are given below:

- Rockstone Footbridge, 205.42 miles
- Sea Lawn Terrace, site of 2014 breach, 205.51 miles
- Dawlish Station, 206 miles
- King Harry's Walk, Marine Parade, 206.15 miles
- Smuggler's Lane, 207.47 miles

**Table B.1:** Consolidated Damage Record

| Chainage Position (from) | Chainage Position (to) | Year | Damage Details |
|---|---|---|---|
| 208.35 | | 1859 | A washaway of the line occurred. The breach in the wall was repaired in limestone and apparently at the same time an apron in limestone was built to protect the footings. |
| 205.15 | | 1863 | Coping washed off. |
| 205.42 | | 1867 | Footbridge also washed away. |
| 205.40 | | 1867 | Two chains of the retaining wall washed away. |
| 205.71 | | 1868 | A washout occurred. |
| 205.41 | 205.50 | 1869 | A length of wall washed away. |
| 205.39 | 205.42 | 1872 | Sections of main wall and parapet walls were washed away. |
| 205.60 | | 1873 | Wall washed away. |
| 205.00 | 206.00 | 1879 | Coping knocked off. |
| 206.60 | | 1885 | High tide and rough sea came over line at Dawlish Station, East Cliff. Damage to slipway. |
| 205.00 | | 1893 | Breakwater wall and planking damaged at Langstone point. |
| 204.60 | | 1895 | The sea washed beach away at Langstone causing the sand between the seawall and parapet to run out. Seawall at Langstone damaged, coping and piling damaged. |
| 204.70 | | 1899 | At Langstone, a hole was washed out in the seawall. |
| 204.60 | | 1903 | Hole in wall between Langstone and the Warren. |
| 205.76 | | 1904 | Walls of crib undermined, the western most groyne further damaged, eastern most groyne also damaged. Beach bare east of station. |
| 205.77 | | 1904 | Heavy gales, great damage to slipway under Coastguard's house. |
| 204.59 | | 1911 | Large hole in footpath on seawall near Langstone. |
| 204.64 | | 1911 | A length of wall was washed away and rebuilt. |
| 206.60 | | 1914 | Heavy seas lifted platform deck at Dawlish station and washed it on to beach. |
| 205.26 | 205.36 | 1915 | 100 linear feet of coping loosened. |
| 205.32 | 205.40 | 1916 | 40 linear feet of coping loosened. |
| 207.74 | 208.50 | 1916 | Seawall path damaged by storm 27/10/1916. Some places 9" to 1' deep. |
| 208.14 | | 1916 | Breakwater at Spray Point badly damaged and rebuilt. |

| Chainage Position (from) | Chainage Position (to) | Year | Damage Details |
|---|---|---|---|
| 208.20 | 208.30 | 1916 | Footings of wall damaged. |
| 205.44 | | 1917 | A hole 45' long appeared between the seawall and parapet wall, the ground sank 7'. |
| 207.15 | | 1917 | Large cavity of 20' deep and 36' long. The cavity was filled with dry rock. |
| 205.60 | | 1928 | The seawall was damaged in three places. Wall rebuilt and granite faced. |
| 205.60 | | 1930 | Wall and ballast washed away leaving tracks hanging. |
| 206.26 | 206.33 | 1941 | Ballast replaced under down Main Line. |
| 207.40 | | 1943 | Stone tipped to protect seawall following damage to protective works. |
| 207.48 | 208.15 | 1944 | Repairs carried out to apron of seawall after damage by heavy gales and high tides. |
| 205.70 | | 1947 | Repairs carried out to face wall and slipway, damaged by gales. |
| 206.60 | | 1974 | 13c length of platform deck (Dawlish station) lifted by storm February. |
| 207.10 | 207.17 | 1984 | A series of depressions formed in at the portal in the down cess at the back of the seawall as a result of storms. |
| 207.50 | 207.78 | 1986 | Concrete spraying due to severe undermining. |
| 206.76 | | 1987 | Massive void of 6ft. |
| 206.25 | 206.30 | 1988 | Concrete spraying to repair undermining of foundation |
| 207.14 | 207.18 | 1988 | Voiding at back of seawall. |
| 205.51 | | 1990 | Steps damaged. Repairs in masonry & cone. |
| 205.75 | | 1990 | Damage to ramps. |
| 205.76 | | 1990 | Damage to ramp. Repaired in spray concrete. |
| 207.46 | | 1990 | Cracks and fractured joints. |
| 206.50 | | 1994 | Storm damage to lower wall. Repaired in masonry. |
| 205.45 | | 1996 | Toe damaged, void beneath wall. |
| 205.29 | | 1996 | Void beneath walkway. |
| 205.38 | 205.51 | 1996 | Failure of sprayed concrete resulting in undermining of the wall, loss of fill and collapse of the walkway and boundary wall. |
| 206.73 | | 1996 | Severe damage to end of breakwater. |
| 207.14 | | 1996 | Depression and collapse of cabin. Hole plugged in face of wall. |
| 207.15 | | 1996 | Voiding. |
| 207.46 | | 1996 | Cracks and fractured joints. |
| 207.76 | 208.00 | 1996 | Copings dislodged by wave action. Replaced in concrete. |
| 208.14 | | 1996 | Breakwater demolished. |
| 208.17 | 208.22 | 1996 | Hole in face of Spray Point. |
| 208.27 | | 1996 | Substantial damage to face of west ramp. |
| 208.20 | | 1996 | Hole in face of wall with loss of fill. |
| 208.14 | 208.80 | 1996 | Severe damage to face and surface of ramp. Repaired in masonry/concrete. |
| 207.46 | | 1997 | Cracks and fractured joints. |
| 206.73 | | 1998 | Severe damage to end of breakwater. |
| 206.25 | | 2001 | Undermining of sprayed concrete. |

| Chainage Position (from) | Chainage Position (to) | Year | Damage Details |
|---|---|---|---|
| 208.14 | 208.80 | 2001 | Severe damage to face and surface of ramp. Repaired in masonry/concrete. |
| 206.24 | | 2002 | Undermining of sprayed concrete. |
| 204.74 | | 2004 | Substantial length of coping washed away. |
| 205.51 | | 2004 | Damage to top of steps. |
| 205.30 | | 2004 | Copings washed away. Replaced to new design. |
| 206.16 | | 2004 | End of breakwater damaged. |
| 206.18 | 206.31 | 2004 | Damage to track support gabions. |
| 206.73 | | 2004 | Severe damage to end of breakwater. |
| 207.17 | | 2004 | Damage to top of sprayed concrete. |
| 207.45 | | 2004 | A large section of the steps washed away, with loss of wall extending back to the track formation. |
| 207.46 | | 2004 | Wall and steps breached, repaired in stone/mass concrete. |
| 207.48 | | 2004 | Loss of coping also occurred with a substantial section of wall beneath being washed away. |
| 207.50 | | 2004 | Top 50% of wall destroyed including copings and walkway. Replaced to new design after storm. |
| 207.75 | 207.77 | 2004 | Copings washed away, replaced to new design. |
| 208.13 | | 2004 | Face of ramp and toe damaged. |
| 208.15 | | 2004 | Damage to breakwater. |
| 208.27 | | 2004 | Ramp face damaged over 10m. |
| 208.54 | | 2004 | 20m of copings washed away. |

# Appendix C

# Dominant Failure Matrix

Information and archival research were used to create an overarching dominant failure matrix taking into account all possible routes to systems failure as detailed in the research accounts. The results of this matrix operation are presented in the following pages as Table C.1: a comprehensive compilation of all failure forces mentioned in the historical accounts and substantiated with other technical references (such as Network Rail), Table C.2: an exhaustive treatment of the possible failure mechanisms following the force initiation and Table C.3: the resultant possible causes of network suspension on the line as a result of preceding force and mechanism combinations.

This damage matrix was used to create the event tree analysis flowcharts for each major incident on the line since its inception in 1845. Each one is presented in Appendix D.

**Table C.1: The major dominant failure force events experienced on the Dawlish line since construction.**

| Date (d/m/y) | Wave Impact | Wave Overtopping | Wave Debris Impact | Wind Impact Damage | Flooding Impervious Surfaces | Saturation Pervious Materials |
|---|---|---|---|---|---|---|
| 05/10/1846 | y | y | | | | |
| 20/11/1846 | y | y | | | | |
| 26/12/1852 | | | | | | y |
| 28/12/1852 | | | | | | y |
| 04/02/1853 | | | | | | y |
| 13/02/1853 | | | | | | y |
| 16/02/1855 | y | y | | | | |
| 25/10/1859 | y | y | | | | |
| 08/01/1867 | | y | | | | |
| 31/01/1869 | y | y | | | | |
| 25/12/1872 | y | y | | | | |
| 30/12/1872 | y | y | | | | |
| 11/01/1873 | y | y | | | | |
| 01/02/1873 | y | y | | | | |
| 01/12/1874 | | | | | | y |
| 01/12/1875 | | | | | | y |
| 03/02/1916 | y | y | | | | |
| 12/03/1923 | y | y | | | | |
| 24/12/1929 | y | y | | | | |
| 04/01/1930 | y | y | | | | |
| 10/02/1936 | y | y | | | | |
| 01/03/1962 | | y | | | | |
| 01/02/1974 | y | y | | y | | |
| 26/02/1986 | y | y | | | | |
| 01/01/1996 | y | y | | | | |
| 01/12/2000 | y | | | | | y |
| 19/11/2002 | | | y | | | |
| 07/01/2004 | y | y | | y | | |
| 27/10/2004 | y | y | | y | | |
| 22/09/2006 | y | y | | | | |
| 14/12/2012 | | y | | | | y |
| 05/02/2014 | y | y | | | | y |
| Number of Occurrences | 22 | 24 | 1 | 3 | 0 | 9 |
| % Occurrence | 0.69 | 0.75 | 0.03 | 0.09 | 0.00 | 0.28 |
| Annual Probability of Occurrence | 0.131 | 0.143 | 0.006 | 0.018 | 0.000 | 0.054 |

**Table C.2: The dominant failure mechanisms experienced on the Dawlish line since construction**

| Date (d/m/y) | Foundations Undermined | Damage to Masonry and Mortar Joints | Flooding of Rails & Track Bed | Coping and Parapet Destroyed | Increased Cliff Erosion | Electrical Short Circuit | Flooding Station | Flooding Rails | Cliff Slope Instability | Loss of Infill Seawall Collapse | Upper Section Seawall Failure | Ballast/Infill Washout |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 05/10/1846 | y | y | y | | | | | | | y | y | y |
| 20/11/1846 | y | y | y | | | | | | | y | y | y |
| 26/12/1852 | | | | | | | | | y | | | |
| 28/12/1852 | | | | | | | | | y | | | |
| 04/02/1853 | | | | | | | | | y | | | |
| 13/02/1853 | | | | | | | | | y | | | |
| 16/02/1855 | y | | y | | | | | | | y | | y |
| 25/10/1859 | | y | y | y | | | | | | | y | y |
| 08/01/1867 | | | | y | | | | | | | | |
| 31/01/1869 | y | y | y | | | | | | | y | y | y |
| 25/12/1872 | y | y | y | | | | | | | y | y | y |
| 30/12/1872 | y | y | y | | | | | | | y | y | y |
| 11/01/1873 | y | | y | y | | | | | | y | | y |
| 01/02/1873 | y | | y | y | | | | | | y | | y |
| 01/12/1874 | | | | | | | | | y | | | |
| 01/12/1875 | | | | | | | | | y | | | |
| 03/02/1916 | y | | y | y | | | | | | y | | y |
| 12/03/1923 | y | | y | y | | | | | | y | | y |
| 24/12/1929 | y | | y | | | | | | | | | y |
| 04/01/1930 | y | | y | | | | | | | | | y |
| 10/02/1936 | y | | | y | | | | | | y | | y |
| 01/03/1962 | | | y | y | | | | | | | | y |
| 01/02/1974 | | y | y | y | | | | | | | | y |
| 26/02/1986 | y | | y | y | | | | | | | | y |
| 01/01/1996 | y | y | y | y | | | | | | | y | y |
| 01/12/2000 | | y | | | | | | | y | | y | |
| 19/11/2002 | | | | | | | | | | | | |
| 07/01/2004 | | y | | y | | | | | | | y | y |
| 27/10/2004 | | y | | y | | | | | | | y | y |
| 22/09/2006 | y | | | y | | | | | | | | y |
| 14/12/2012 | | | y | | | | | | y | | | y |
| 05/02/2014 | y | | y | | | | | | y | y | | y |
| Number of Occurences | 17 | 11 | 19 | 14 | 0 | 0 | 0 | 0 | 9 | 12 | 10 | 23 |
| % Occurrence | 0.53 | 0.34 | 0.59 | 0.44 | 0.00 | 0.00 | 0.00 | 0.00 | 0.28 | 0.38 | 0.31 | 0.72 |
| Annual Probability of Occurrence | 0.101 | 0.065 | 0.113 | 0.083 | 0.000 | 0.000 | 0.000 | 0.000 | 0.054 | 0.071 | 0.060 | 0.137 |

**Table C.3: The dominant system failures experienced on the Dawlish line since construction**

| Date (d/m/y) | Track Bed Failure | Rail Blocked | Rockfall | Signal Failure | Points Failure | Locomotive Failure | Station Closure | Service Cancellation | Landslide |
|---|---|---|---|---|---|---|---|---|---|
| 05/10/1846 | y | | | | | | | | |
| 20/11/1846 | y | | | | | | | | |
| 26/12/1852 | | y | | | | | | | y |
| 28/12/1852 | | y | | | | | | | y |
| 04/02/1853 | | y | | | | | | | y |
| 13/02/1853 | | y | | | | | | | y |
| 16/02/1855 | y | | | | | | | | |
| 25/10/1859 | y | y | | | | | | | |
| 08/01/1867 | | y | | | | | | | |
| 31/01/1869 | y | | | | | | | | |
| 25/12/1872 | y | | | | | | | | |
| 30/12/1872 | y | | | | | | | | |
| 11/01/1873 | y | | | | | | | | |
| 01/02/1873 | y | | | | | | | | |
| 01/12/1874 | | y | | | | | | | y |
| 01/12/1875 | | y | | | | | | | y |
| 03/02/1916 | y | | | | | | | | |
| 12/03/1923 | y | | | | | | | | |
| 24/12/1929 | y | | | | | | | | |
| 04/01/1930 | y | | | | | | | | |
| 10/02/1936 | y | | | | | | | | |
| 01/03/1962 | y | | | | | | | | |
| 01/02/1974 | | | | | | | y | | |
| 26/02/1986 | y | | | | | | | | |
| 01/01/1996 | y | y | | | | | | | |
| 01/12/2000 | | y | | | | | | | y |
| 19/11/2002 | | | | | | | y | | |
| 07/01/2004 | y | | | y | | | | | |
| 27/10/2004 | y | | | y | | | | | |
| 22/09/2006 | y | | | | | | | | |
| 14/12/2012 | y | y | | | | | | | y |
| 05/02/2014 | y | y | | | | | | | y |
| Number of Occurrences | 22 | 12 | 0 | 2 | 0 | 0 | 2 | 0 | 9 |
| % Occurrence | 0.69 | 0.38 | 0.00 | 0.06 | 0.00 | 0.00 | 0.06 | 0.00 | 0.28 |
| Annual Probability of Occurrence | 0.131 | 0.071 | 0.000 | 0.012 | 0.000 | 0.000 | 0.012 | 0.000 | 0.054 |

Appendix D

# Failure Tree Analysis

As detailed in Section 3.4 I have produced an event tree analysis flowchart for each major event in Table 3.1. These flowcharts were used to conglomerate the information into a overarching multi-hazard cascading risk model presented in Chapter 4. For information, the flowchart for each individual event from Table 3.1 is detailed in the pages following.

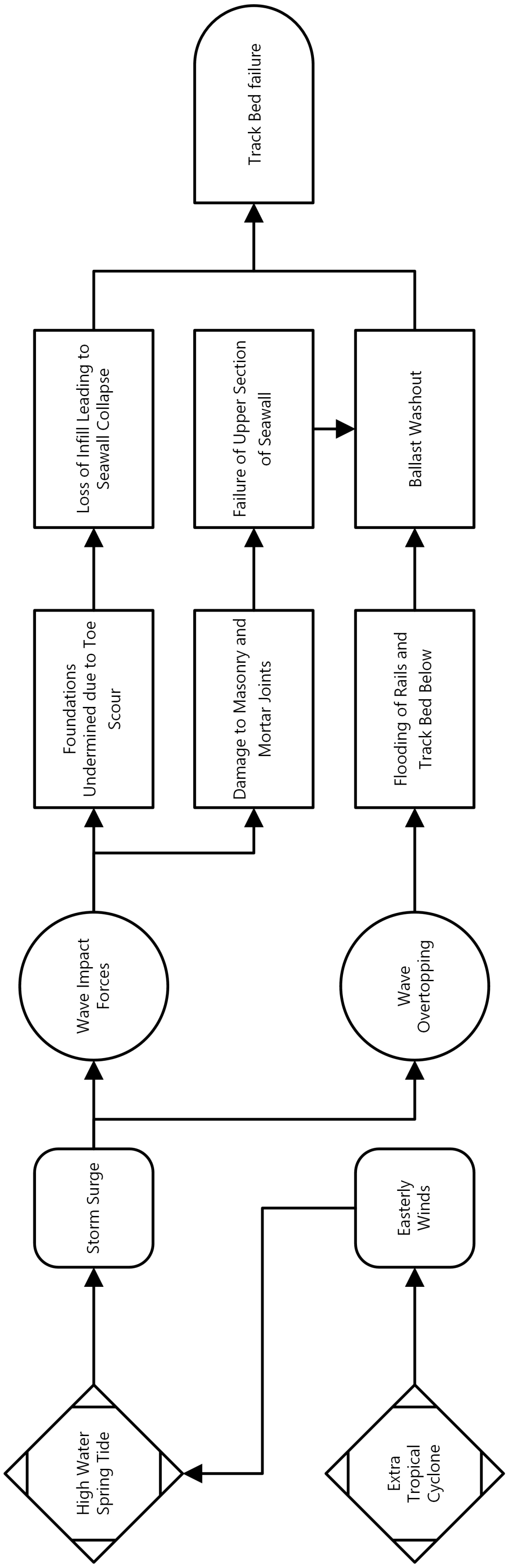



**Figure D.1:** 1846 Damage Chart

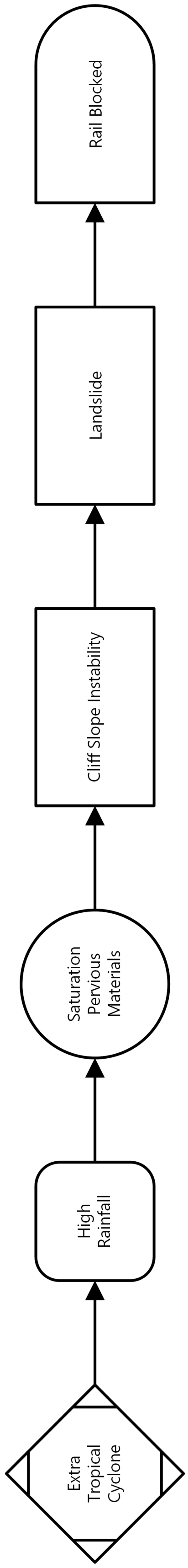



**Figure D.2:** 1852 Damage Chart

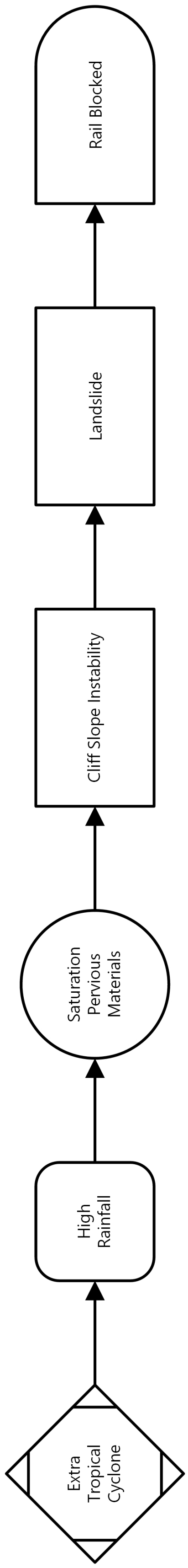



**Figure D.3:** 1853 Damage Chart

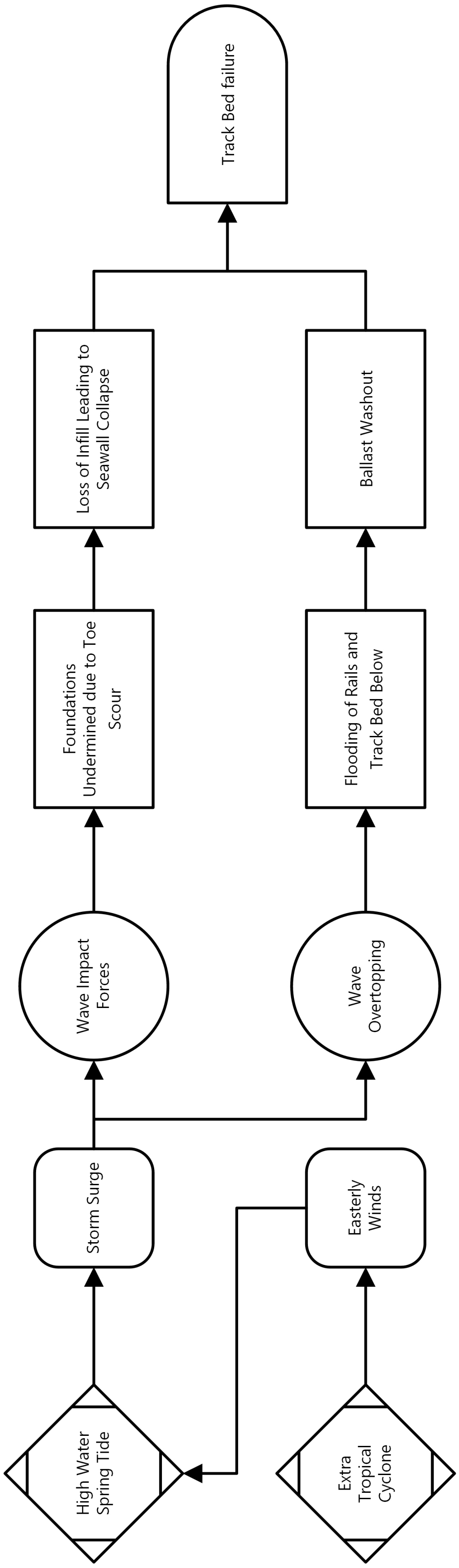



**Figure D.4:** 1855 Damage Chart

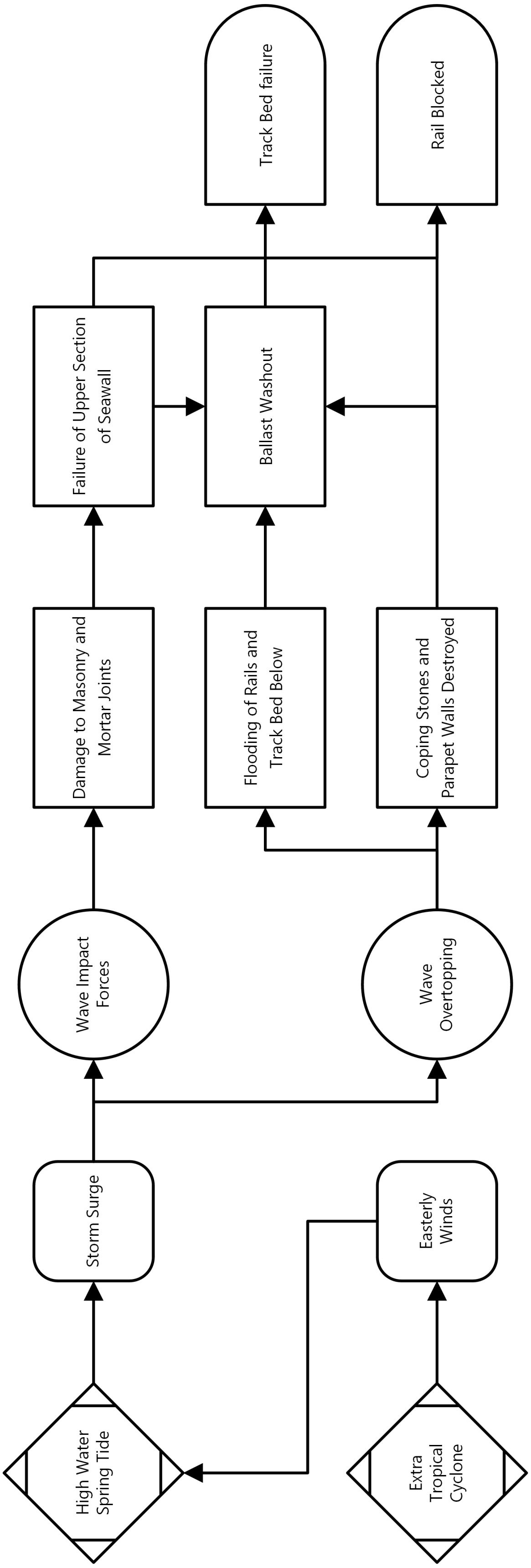



**Figure D.5:** 1859 Damage Chart

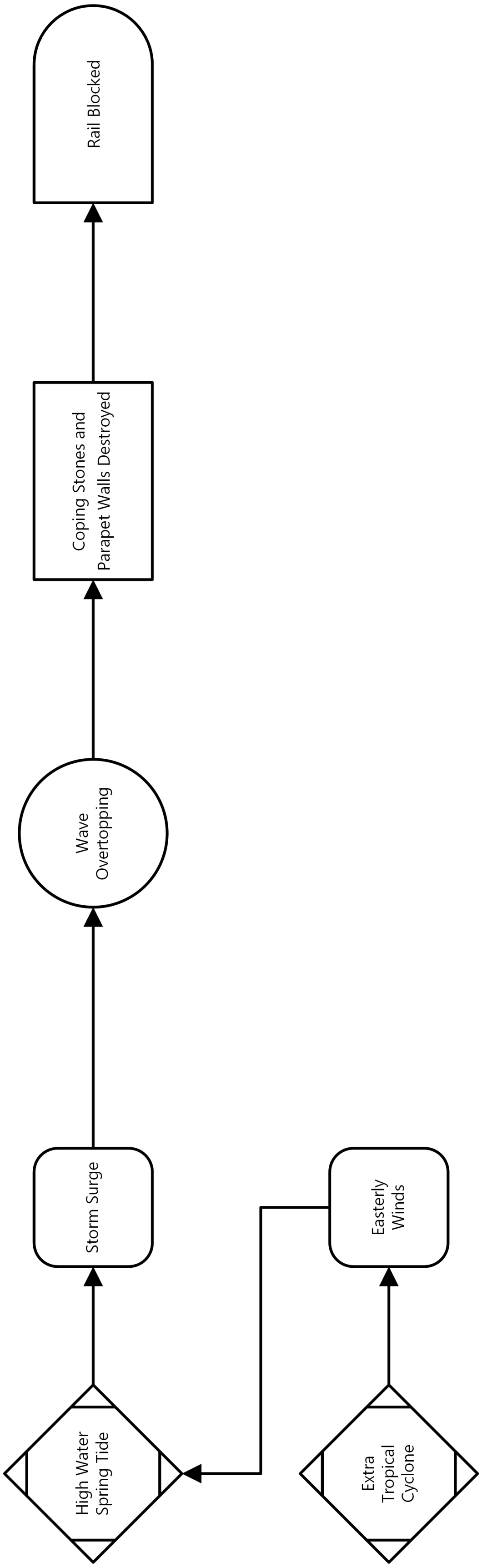



**Figure D.6:** 1867 Damage Chart

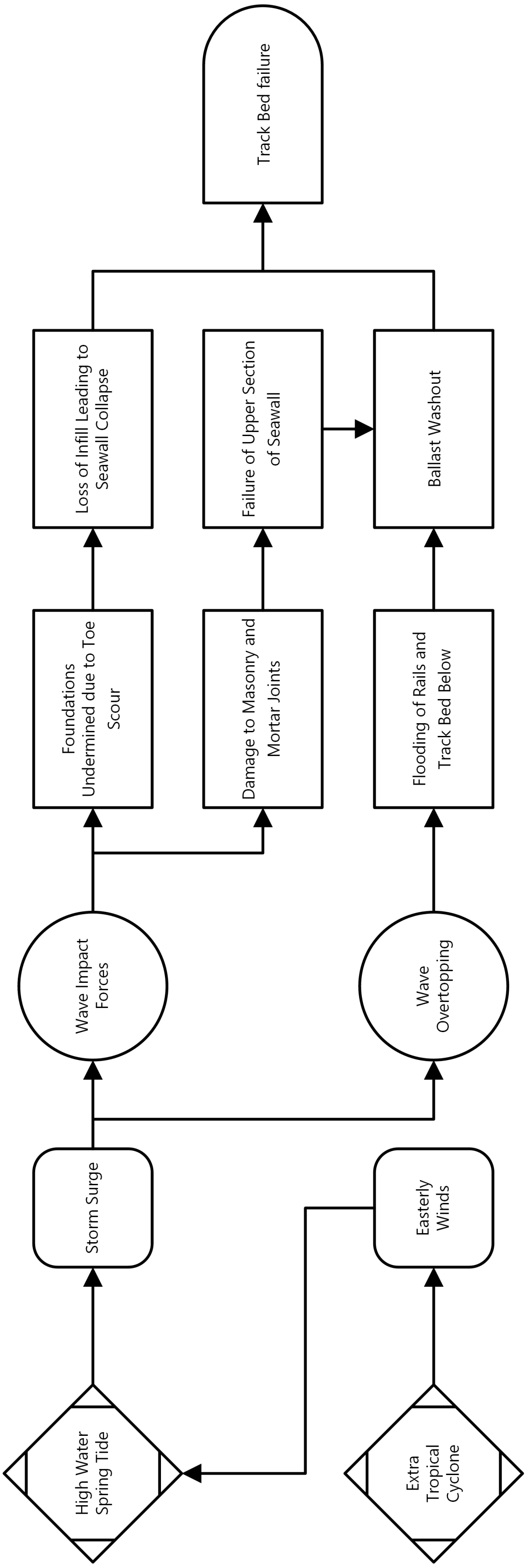



**Figure D.7:** 1869 Damage Chart

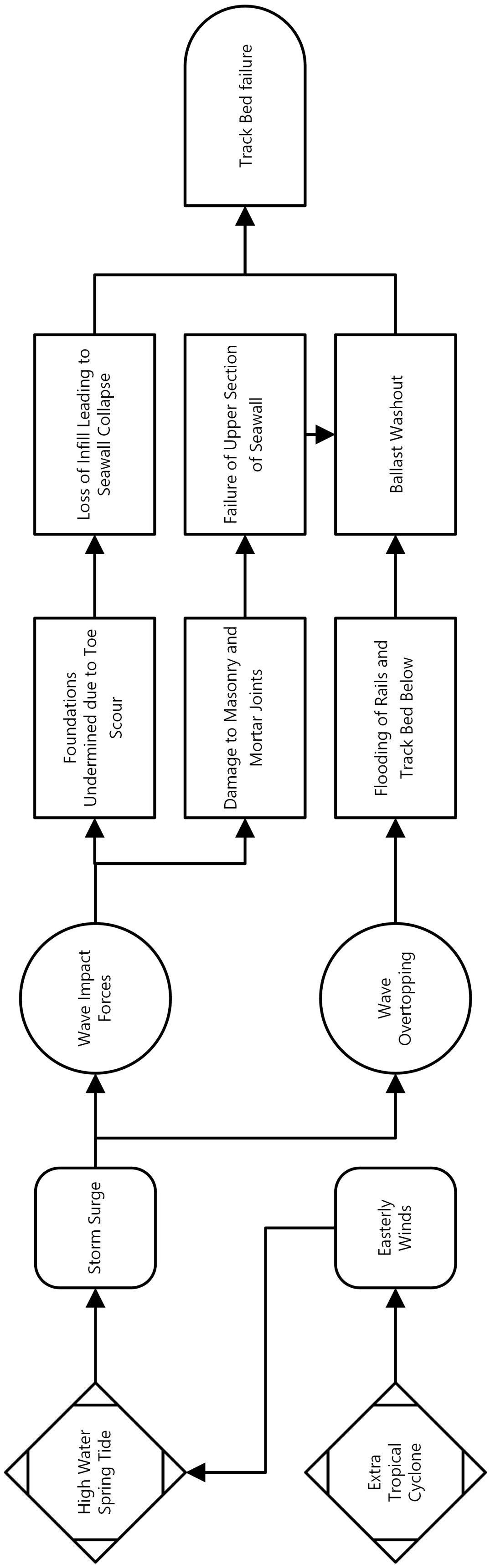



**Figure D.8:** 1872 Damage Chart

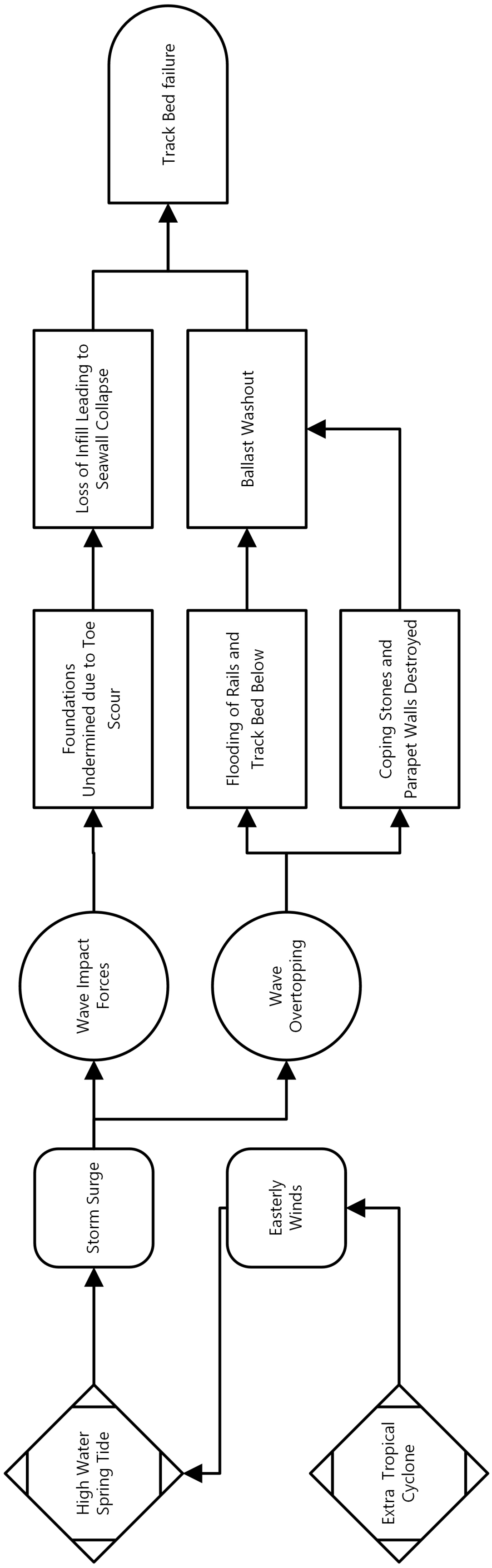



**Figure D.9:** 1873 Damage Chart

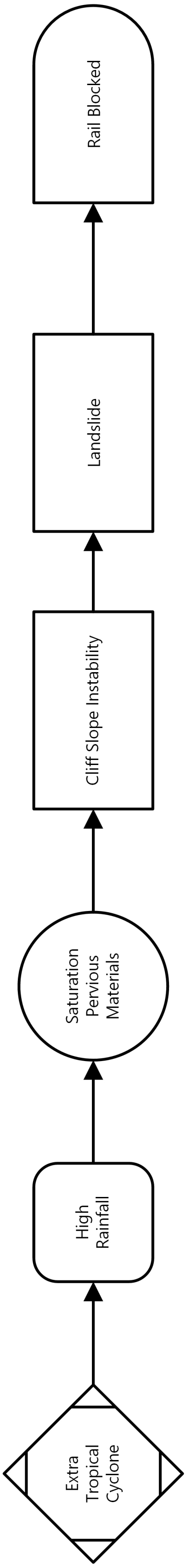



**Figure D.10:** 1874 Damage Chart

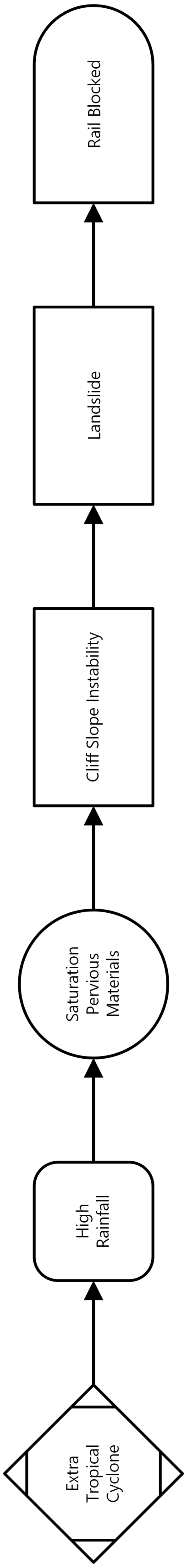



**Figure D.11:** 1875 Damage Chart

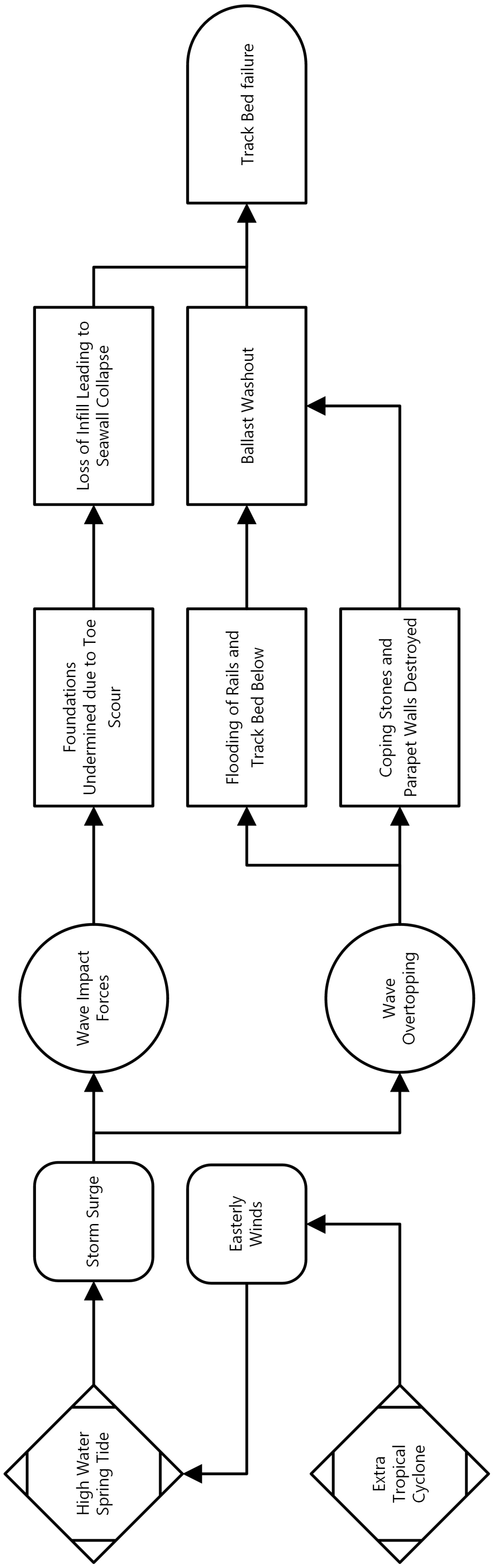



**Figure D.12:** 1916 Damage Chart

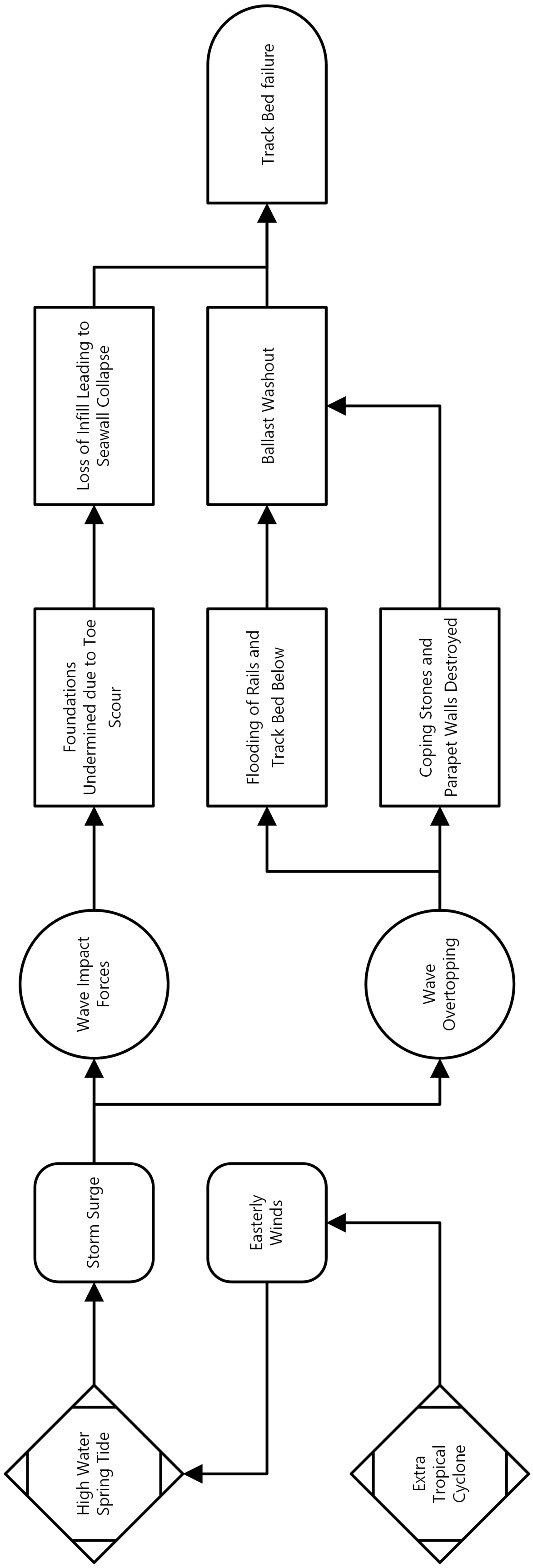



**Figure D.13:** 1923 Damage Chart

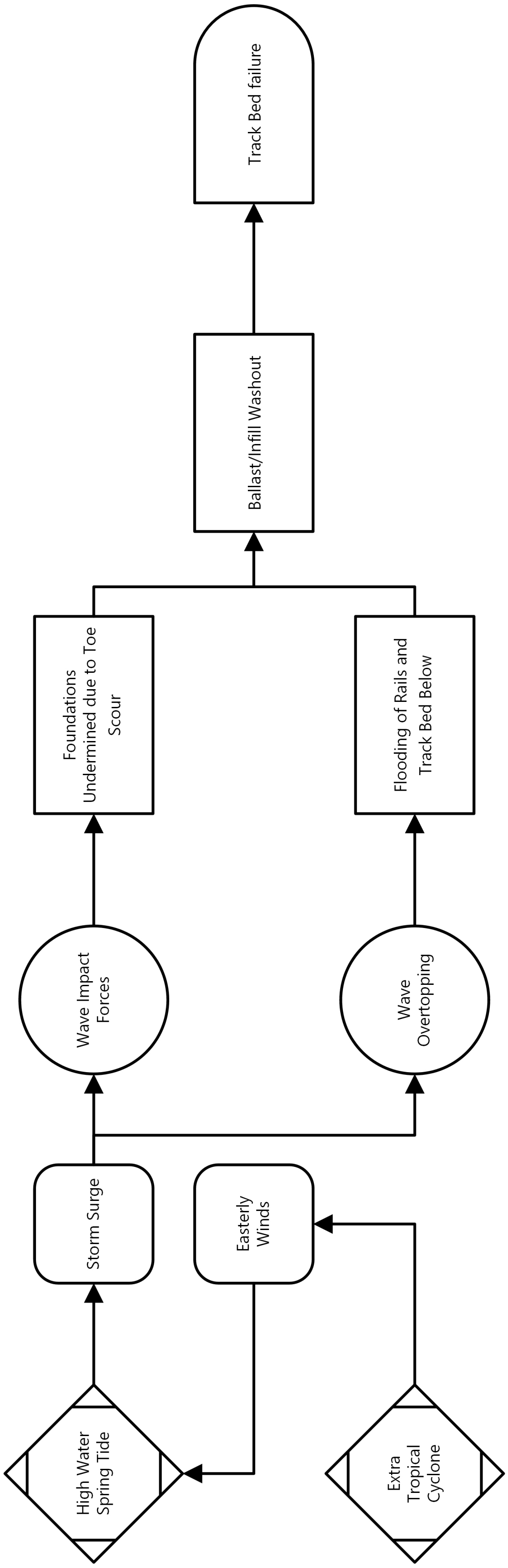



**Figure D.14:** 1930 Damage Chart

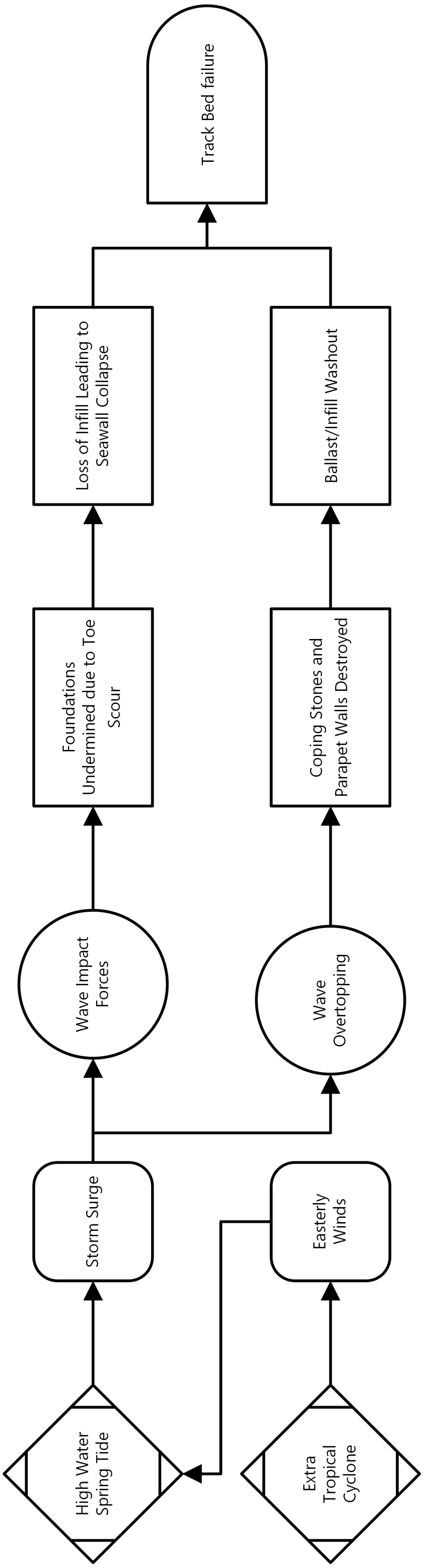



**Figure D.15:** 1936 Damage Chart

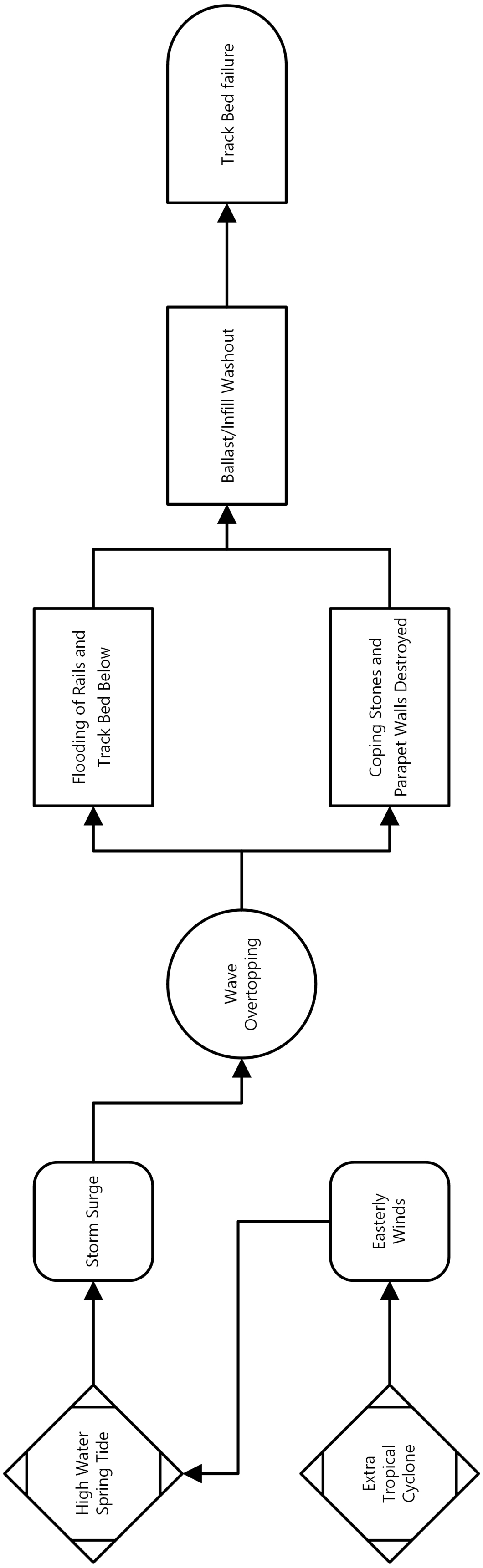



**Figure D.16:** 1962 Damage Chart

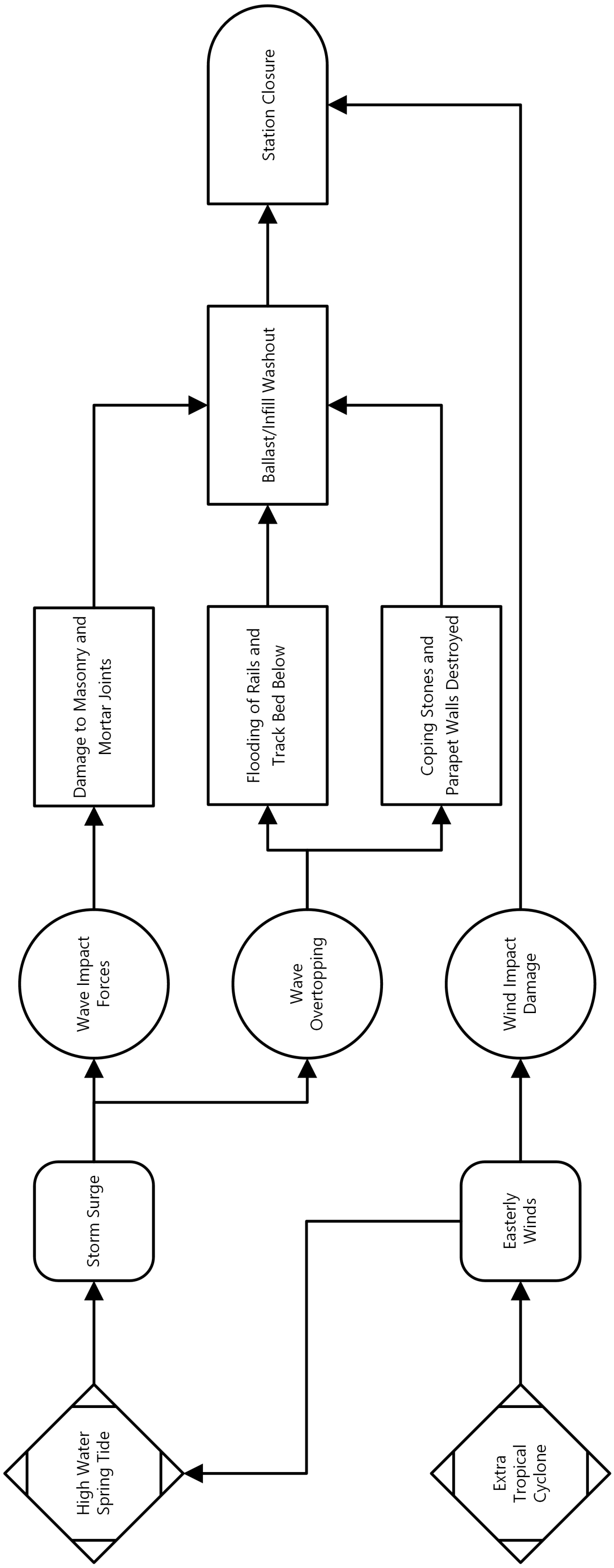



**Figure D.17:** 1974 Damage Chart

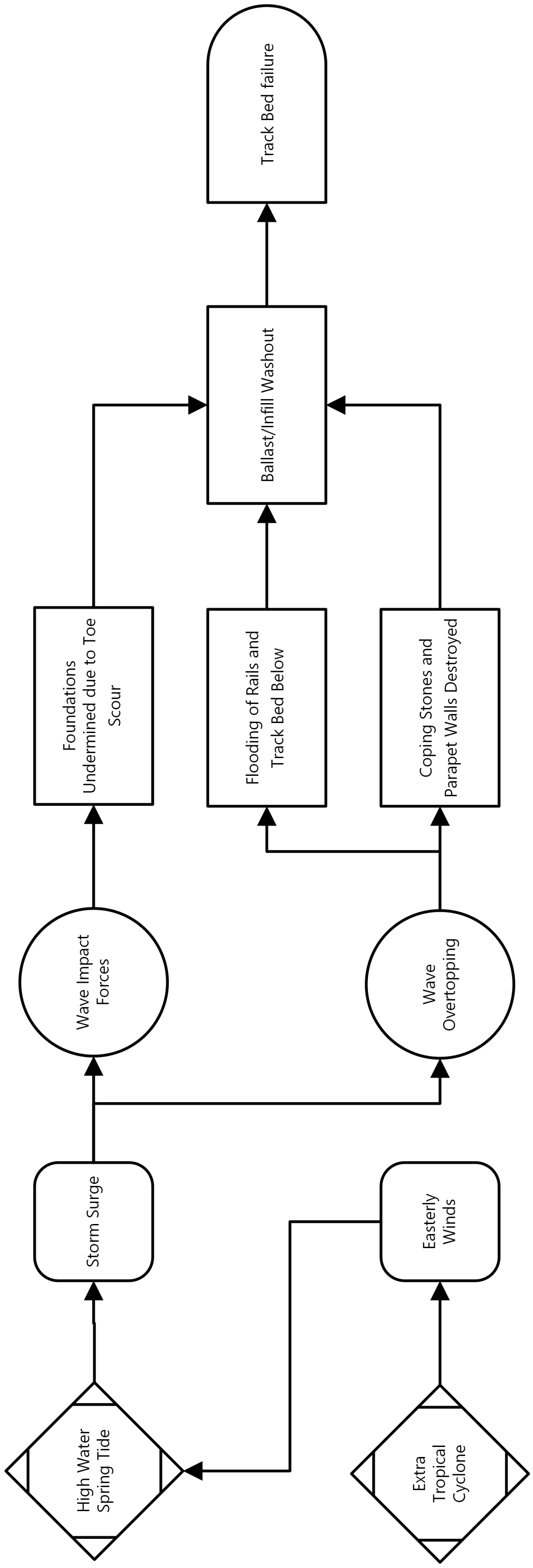



**Figure D.18:** 1986 Damage Chart

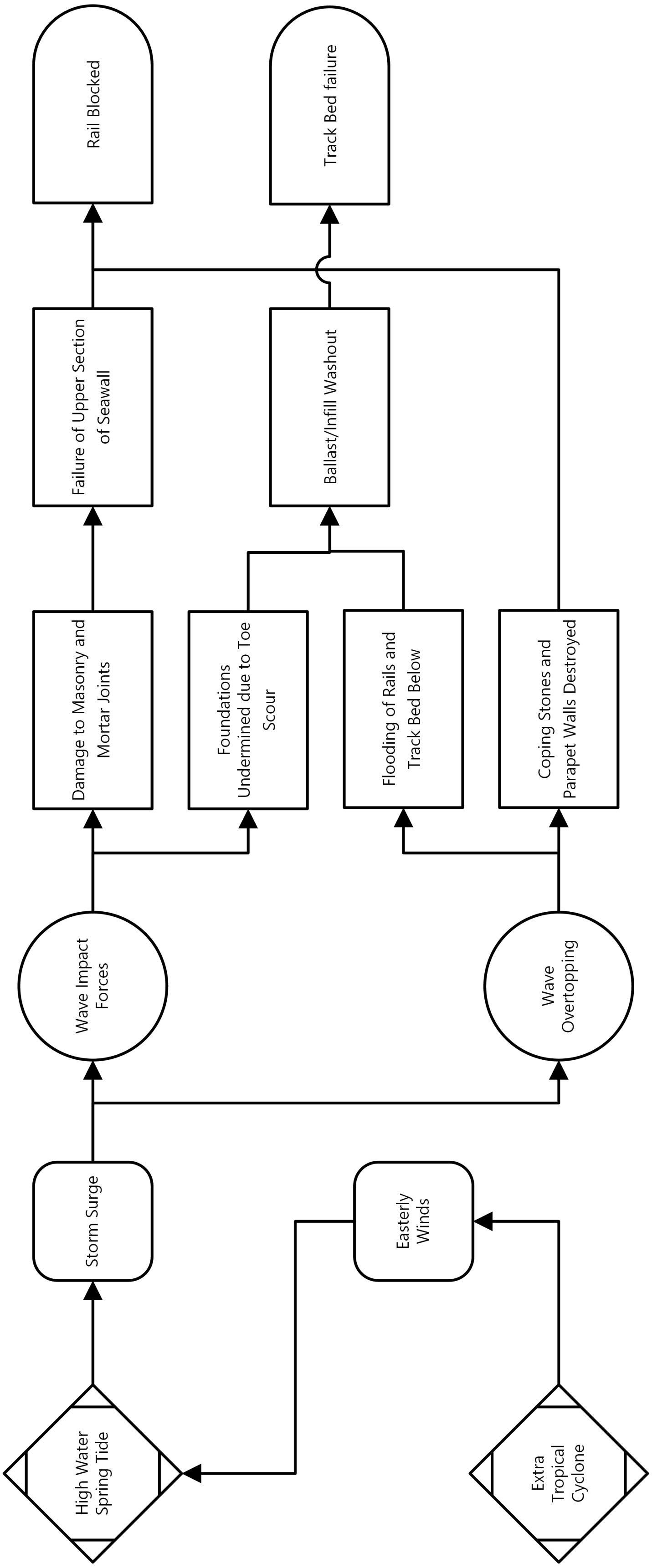



**Figure D.19:** 1996 Damage Chart

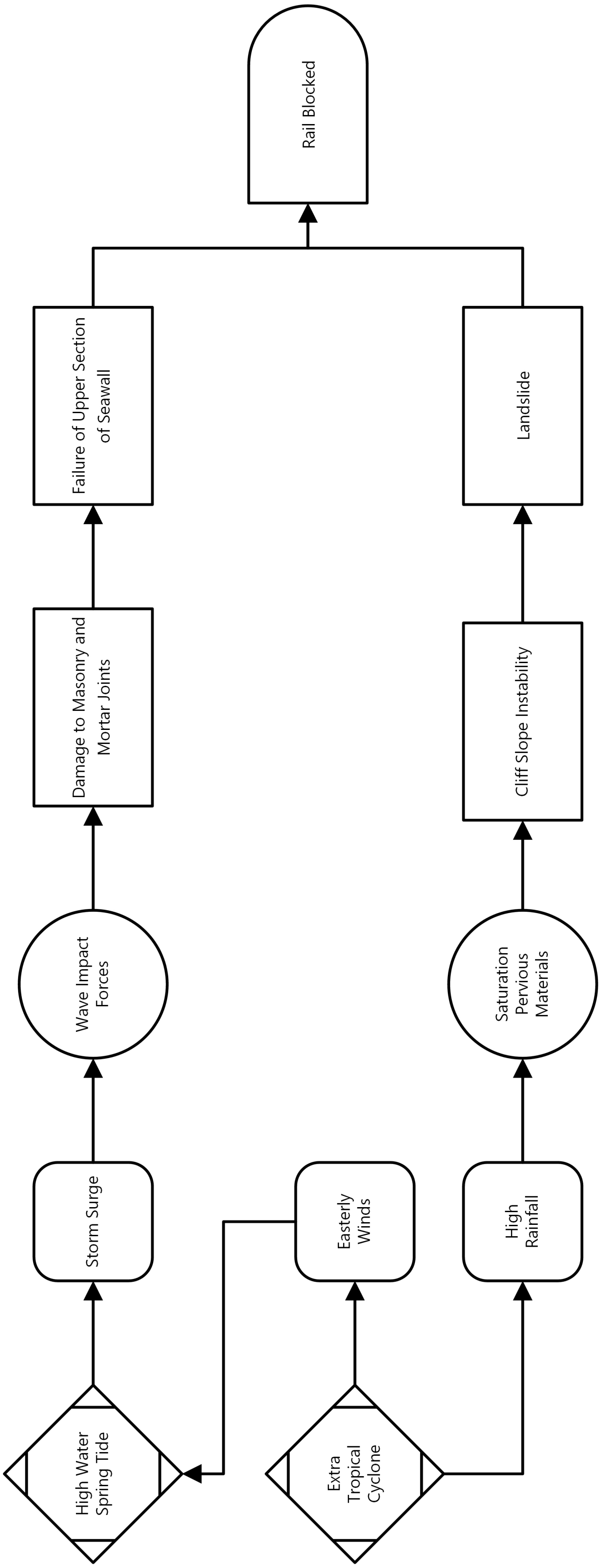



**Figure D.20:** 2000 Damage Chart

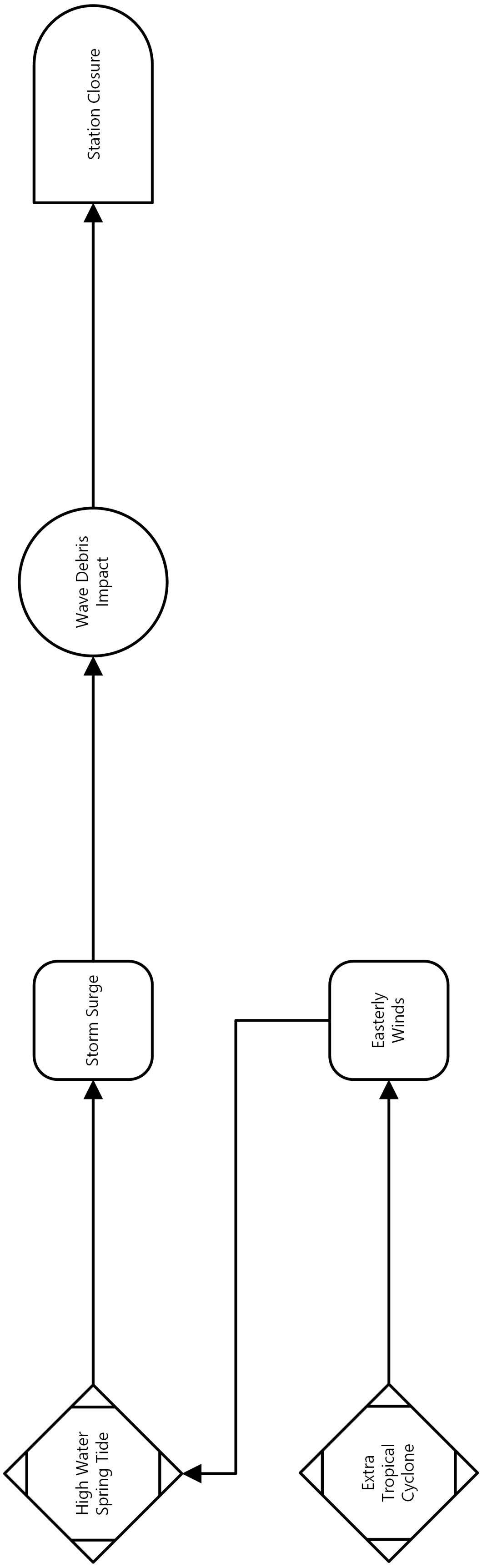



**Figure D.21:** 2002 Damage Chart

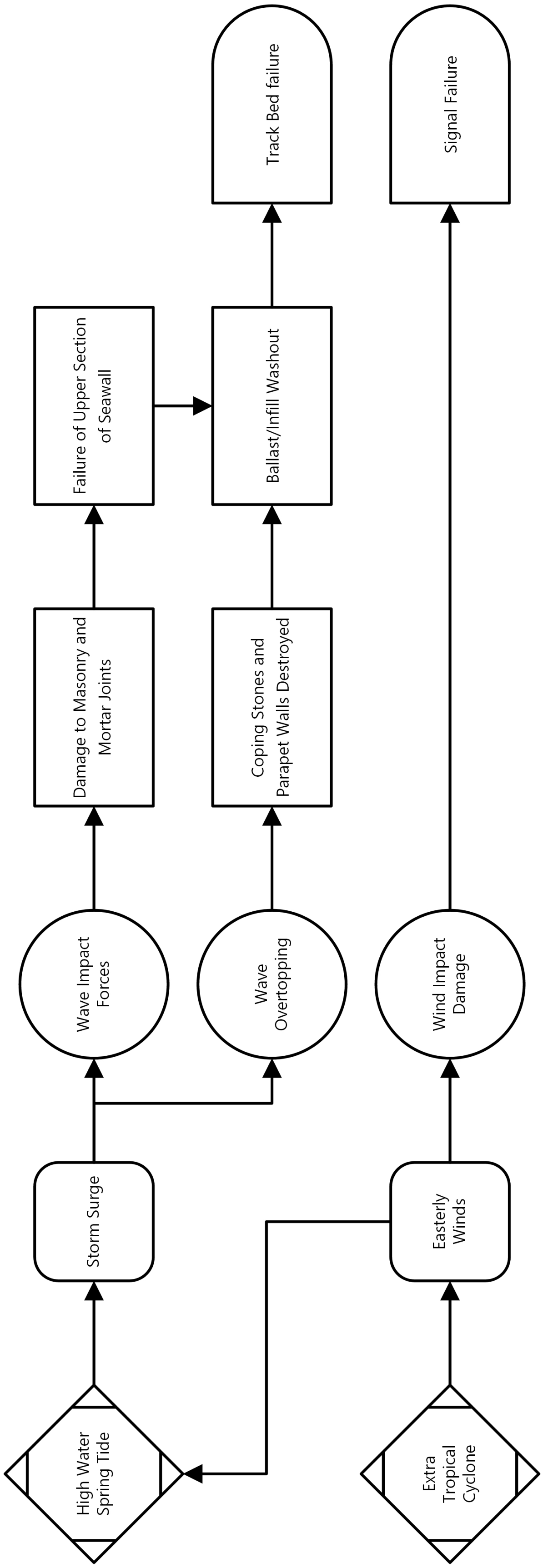



**Figure D.22:** 2004 Damage Chart

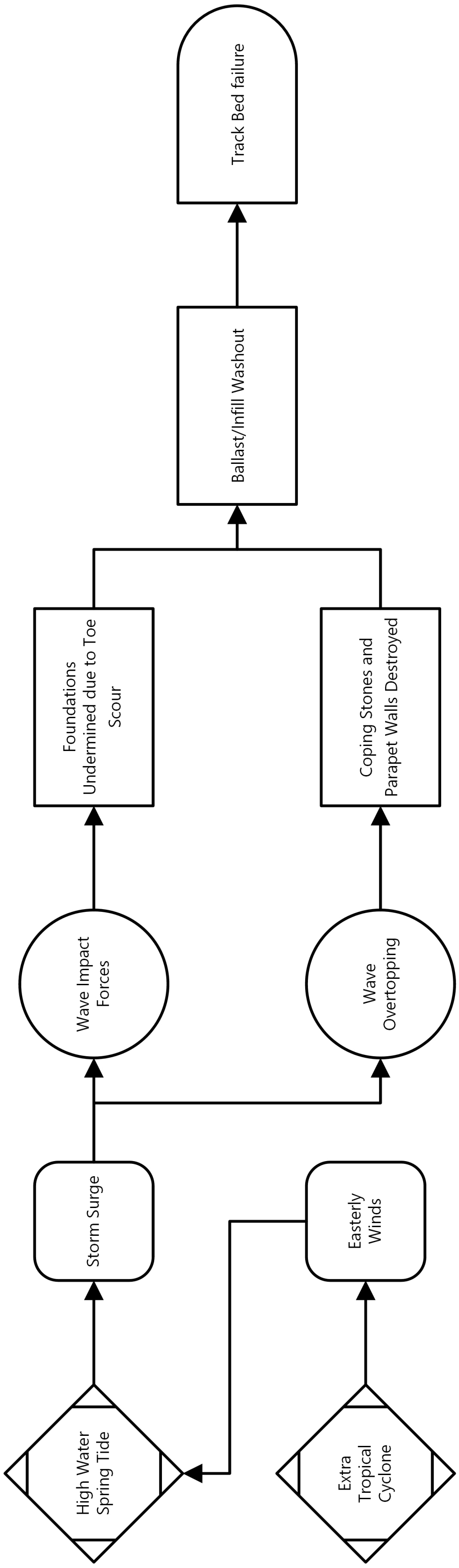



**Figure D.23:** 2006 Damage Chart

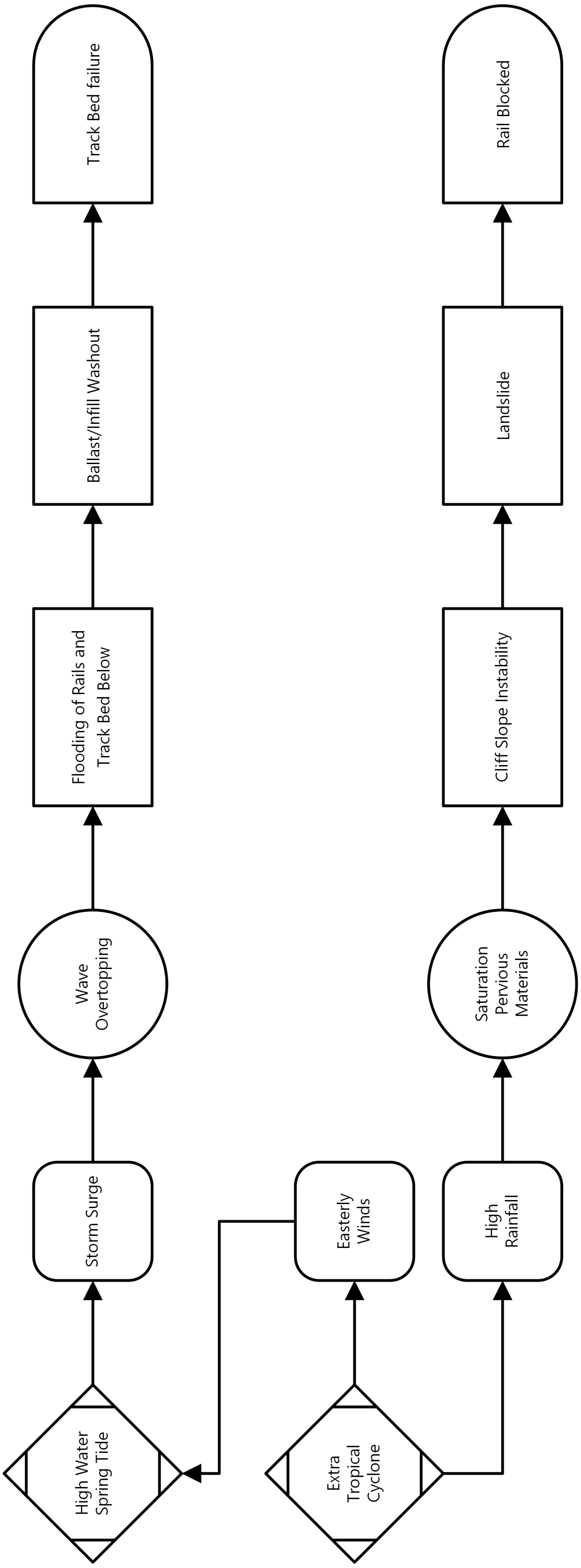



**Figure D.24:** 2012 Damage Chart

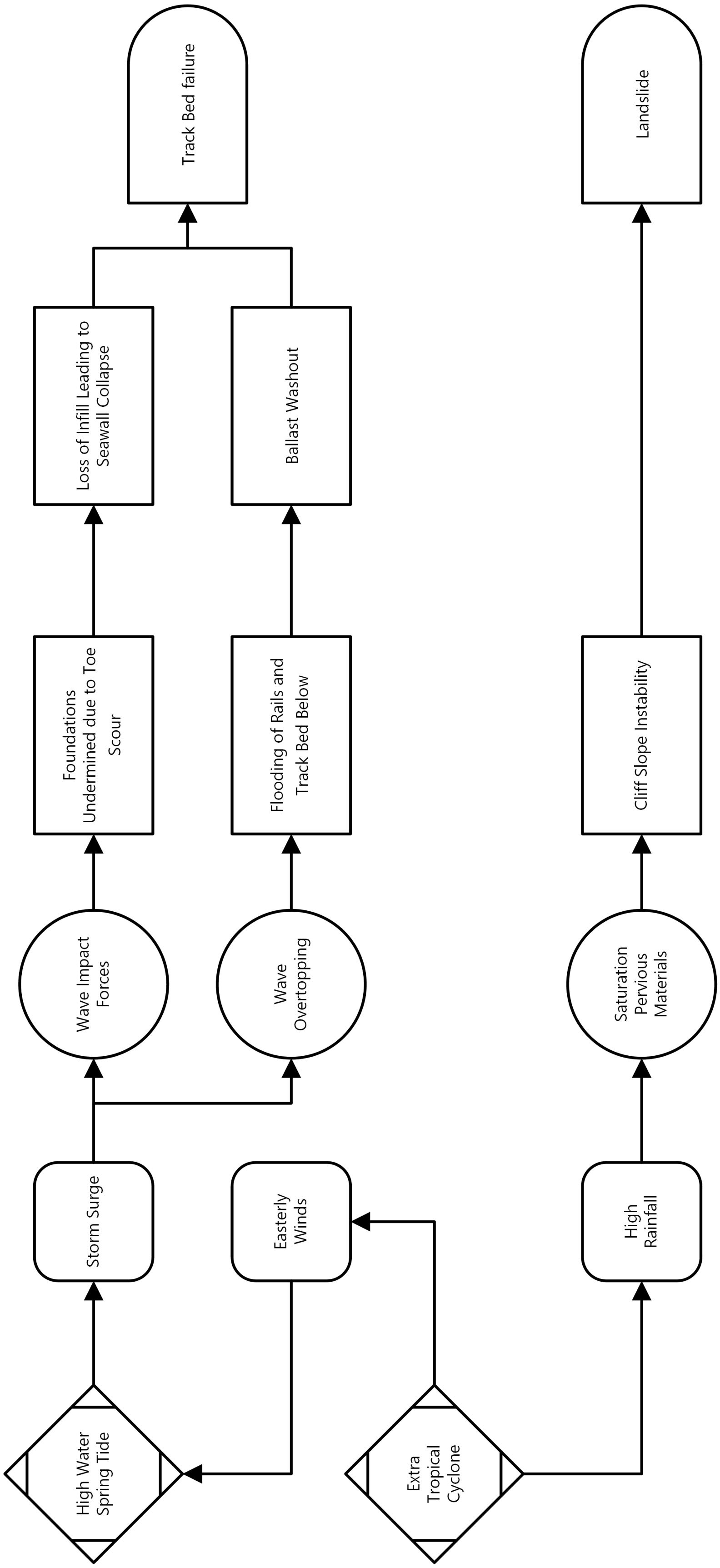



**Figure D.25:** 2014 Damage Chart

## Colophon

This thesis is based on a template developed by Matthew Townson and Andrew Reeves. It was typeset with LaTeX $2_\varepsilon$. It was created using the *memoir* package, maintained by Lars Madsen, with the *madsen* chapter style. The font used is Latin Modern, derived from fonts designed by Donald E. Kunith.