Assessment and Decision Frameworks for Seawall Structures

2013

Appendix A

Literature Review

SYDNEY COASTAL COUNCILS GROUP

Coastal Adaptation Decision Pathways Project **(CAP)**

The Sydney Coastal Councils Group (SCCG) is a voluntary Regional Organisation of Councils representing fifteen coastal and estuarine councils in the Sydney region. The Group promotes cooperation and coordination between Members to achieve the sustainable management of the urban coastal environment.

Project Management

Geoff Withycombe
Executive Officer
Sydney Coastal Councils Group

Douglas Lord
Director
Coastal Environment Pty Ltd

Professor Rodger Tomlinson
Director
Griffith Centre for Coastal Management
Griffith University

Project Co-ordination

Dr Ian Armstrong
Project Officer - Climate Change Adaptation
Sydney Coastal Councils Group
Ph: 02 9288.5802
ian@sydneycoastalcouncils.com.au

Australian Government
Department of Climate Change and Energy Efficiency

Funding has been provided by the Australian Government represented by the Department of Climate Change and Energy Efficiency. The Coastal Adaptation Decision Pathways project is an Australian Government Initiative.

Cover image: Coastal seawall. Provided by Douglas Lord

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Appendix A
Literature Review

Prepared for

Sydney Coastal Councils Group

Prepared by

Water Research Laboratory
University of New South Wales
110 King Street
Manly Vale NSW 2093

21 April 2013

Printed on Australian recycled paper.

SYDNEY COASTAL COUNCILS GROUP

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APPENDIX A PREFACE

This Appendix was prepared by the Water Research Laboratory (WRL) of the University of New South Wales for this Report titled *Assessment and Decision Frameworks for Seawall Structures*. The purpose of the information in this Appendix was to review available literature and to address specific questions relating to the issues surrounding minor seawall structures. The authors of the report were F. Flocard and M.J. Blacka. It has been published by WRL as Report WRL2012/04 *Seawall Assessment Literature Review* and was released in September 2012. It can also be viewed in that format.

The report has been included in its entirety within this report and is a true reflection of the original advice provided to the project by the Water Research Laboratory. No additions, edits or changes have been made to their final report, other than minor editorial and layout changes for consistency in appearance. References to sections, figures and tables are to those included within this Appendix.

As appropriate. information from this Appendix has been incorporated or referenced in the main report for this project.

EXECUTIVE SUMMARY

The Water Research Laboratory of the University of New South Wales was engaged by the Sydney Coastal Councils Group (SCCG) to compile a literature review providing a sound background and reference list of published information related to the assessment of existing seawalls and their adaptation to climate change.

Seawalls (and revetments) are generally parallel to the shore and can be classified as sloping-front or vertical-front structures. Sloping-front structures can be constructed as flexible rubble mound structures which are able to adjust to some toe and crest erosion or as rigid structures which have a fixed form and location. They can be built from either randomly placed armour (rock or concrete units), with pattern-placed concrete armour units, reinforced concrete, geotextile containers or gabion baskets. Vertical-front seawalls are usually composed of stone or concrete blocks, mass or reinforced concrete or steel sheet piles. Such vertical structures can either be built as tied-in, gravity or cantilever walls (see Figure 2). Vertical seawalls also typically act as retaining walls to material located behind.

Local governments are generally responsible for the maintenance of coastal protection infrastructure, such as seawalls which they construct on council-managed land, in order to ensure the protection of the community. These responsibilities create a number of challenges for the local governments in the context of climate change, as they have not only to consider historical climate variability but future climate change. National and state sea level rise planning guidelines have now been adopted in most regions nationally, with the aim of assisting local councils in coastal hazard assessments and planning for adaptation. A review of theses benchmarks is provided in Section 2.

Adaptation to climate change aims to reduce the risks associated with future changes in climate. However, it additionally seeks to harness beneficial opportunities that may arise under a changed future climate system. Adaptation is a mechanism to manage risks and adjust economic activity to reduce vulnerability. In regard to existing infrastructure, the recommended adaptation action by a Local Government Authority can be summarised as:

- monitor any changes to the condition in structures so that any modifications/retrofitting occurs on time and prior to failure
- identify alternative options should the existing buildings and infrastructure be impacted upon in order to maintain services and connections, e.g. to minimise isolation of communities during an adverse storm event that puts the infrastructure at higher risk
- design retrofitting to a higher standard than the minimum required where possible and practical
- progressively incorporate higher design standards into asset management plans and rolling capital works programs.

The main forcing parameters on a seawall can be separated into the hydraulic responses of the waves and the structural response of the seawall. These are described in Section 3.3. There are three main hydraulic responses that need to be considered for the design of a seawall: wave runup level; wave overtopping; and wave reflection. When designing a seawall, it is important to accurately assess the various loads and the related stresses, deformations and stability conditions of the different structural parts of the seawall. For vertical-front structures, the main loads and structural

responses to determine include the wave forces exerted on the wall, as well as the forces applied by the backfill soil and pore water. The main geotechnical aspects to verify when designing a seawall are the assurance of safety against soil failure (slip circle failure) as well as assurance of limited settlement in the foundation soils.

The main failure modes of seawalls are reviewed in Section 3.4 and can be detailed as:

- undermining, in which the sand or rubble toe level drop below the footing of the wall, causing the wall to subside and collapse in the hole
- sliding, in which the wall topples away from the retained profile
- overturning, in which the wall topples over
- slip circle failure, in which the entire embankment fails
- loss of structural integrity, due to wave impact, or
- erosion of the backfill, caused by wave overtopping, high watertable levels, or leaching through the seawall.

The failure modes described above are mainly caused by three types of coastal hazards, described in Section 3.5, and listed below:

- erosion of sand in front of the seawall during storm events
- wave overtopping (inundation) of the seawall due to elevated water levels and large wave conditions, and
- wave impacts.

Generally mean sea level increase, wind climate change and wave climate change are the major concerns for coastal defence structures due to climate change.

In regard to small seawalls, the main impacts of climate change are described in Section 4.2, and will result in:

- increased wave loading
- increased overtopping and flooding of the seawall (erosion of the backfill), and
- increased scouring at the toe of the seawall.

The potential increase in wave loading will typically require an increase in the mass of the structure to prevent displacement or movement. Modification to the existing seawall crest may be necessary to avoid overtopping exceeding acceptable levels. Adequate toe levels are critical to prevent undermining failure of the structure due to the increase of scour and resulting lowering of the beach levels. A brief overview of the applicable technical adaptation solution is given in Section 4.3.

Two main approaches which can be applicable to the adaptation of seawalls to climate change are reviewed in Section 4.4. Seawalls typically have design and operational lives spanning many decades and therefore climate change is an important consideration for both design of new seawalls and adaptation of existing seawalls. One approach is to consider the complete sea level rise expected to occur over the life of the structure in the initial design of the adaptation plan, and is referred to as the Precautionary Approach. A more favoured approach nowadays, referred to as the Managed Approach, allows for staged adaptation in the future, and is appropriate in the majority of cases where ongoing responsibility can be assigned to track the change in risk, and manage this through multiple interventions.

Seawall monitoring can typically be divided between condition monitoring and performance monitoring. Condition monitoring is the basis for the implementation of a successful preventive maintenance program. Seawall condition monitoring should involve at least visual inspection of the structure, and in some cases, the inspection is augmented with measurements meant to quantify the current structure condition relative to the baseline condition. Seawall inspections can be described according to the following terminology:

- Superficial Inspections: this type of visual inspection can be undertaken many times a year and identifies any defect changes or unusual features of the seawall
- General Inspections: this type of inspection, carried out by trained technical staff, is more formal and detailed, and is recommended to take place approximately every two years. Monitoring of specific locations can be carried out
- Principal Inspections: principal inspections include a detailed examination of all aspects of the seawall, including any areas underwater or with difficult access. These inspections should be carried out at intervals of between two and ten years, depending of the age of the structure and are carried out by qualified engineers
- Special Inspections: these investigations are carried out following specific events such as extreme floods, storms or when any other inspection indicates a cause for major concern.

Performance monitoring of seawalls should mainly focus on the assessment of the principal function of preventing or alleviating overtopping and flooding of the land and the structures behind the seawall due to storm surge and waves.

Section 5.3 provides a review of 15 different technologies, which can be applicable for monitoring and to accurately characterise key structural parameters of seawalls including:

- seawall toe and crest levels
- seawall composition
- structural integrity of the seawall
- wave overtopping
- beach scour and bedrock levels
- watertable levels.

The maintenance solution for a seawall is highly dependent on the type of structure, as well as the use and the environmental conditions it is subjected to (open coast or estuarine). A review of the main types of repair/rehabilitations works, listed below, is provided in Section 5.4.

- modifying loads on the seawall
- remedial works to the seawall toe

- increasing seawall stability
- repair of the wall structure
- replacement of the seawall by a new structure.

Finally, an overview of Asset Management Planning in regard to seawalls is performed in Section 5.5. It is recommended that seawalls be included on the Asset Management Plan of councils with the following key pieces of information:

- location
- surveyed level key parameters (toe and crest levels)
- construction type/description
- grade or rating of overtopping risk
- grade or rating of stability risk
- previous and next scheduled monitoring inspection.

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GLOSSARY

active beach zone	The section of the beach from the offshore limit of onshore/ offshore sand movement under waves to the landward limit of wave uprush during storms
aeolian processes	Pertaining generally to sand or sediment moved and deposited by wind above the mean high water mark
altimetry	The measurement of altitude
benchmark	A mark affixed to a permanent object in tidal observations, or in a survey, to furnish a datum level
berm	(1) On a beach: a nearly horizontal plateau on the beach face or backshore, formed by the deposition of beach material by wave action or by means of a mechanical plant as part of a beach recharge scheme. (2) On a structure: a nearly horizontal area, often built to support or key-in an armour layer
breakout conditions	Relating to the release of water stored within a closed estuary or lagoon when the water level is elevated above the adjacent ocean. As the water level rises, the sand bar at the entrance is eroded by overtopping and scours to allow the water to discharge across the bar to the ocean
coastal zone	The land-sea-air interface zone around continents and islands extending from the landward edge of a barrier beach or shoreline of coastal bay to the outer extent of the continental shelf
concrete mattress	Scour protection using a relatively thin layer of poured concrete, commonly retained in a thin mattress-like bag fabricated from geotextile fabric
depth-limited	The maximum height of a wave that can be transmitted and break in a given water depth. Commonly used as a limiting design condition for shoreline structures in exposed coastal locations where the biggest wave reaching the structure is controlled by the water depth at the strucutre. Larger waves will break offshore in greater depths, not reaching the structure as an unbroken wave
environmental shear	The natural difference in velocity between two fluid streams in nature allows the transfer of energy and mixing to occur at the boundary of the layers, e.g. energy transfer from wind to the water surface causing ripples and waves, fluid movement against a sediment bed causing mobilisation and movement of the sediment
exceedance probability	The likelihood that an event of a given size, on average, occurs or is exceeded once in a stipulated time period (e.g. ten years or 100 years). See also annual exceedance probability
freeboard	A factor of safety usually expressed as a height above the designated inundation level commonly applied for planning purposes
gabion	Building units composed of rocks, rubble or masonry held tightly together within wire mesh containers. Used to form retaining walls and other structures
geotextile	A permeable geosynthetic sheet comprised solely of textiles, used in geotechnical engineering construction. Materials may be either woven or needle punched and are robust Commonly geotextiles provide a filter layer under rock armour or can be fashioned into containers filled with sand used as armour units in a structure

groundwater	Water beneath the surface of the ground, often perched above an impervious layer
groyne	Structure of rock and/or other materials generally built out from the shore seaward in dynamic environments. A groyne creates a physical barrier that slows down or stops the alongshore movement of sand, trapping a sand fillet on the updrift side and correspondingly accelerating erosion downdrift
hydrodynamic	Pertaining to the forces or motion of a liquid
incident wave	Wave moving landward at a particular location and time
mean sea level	The average level of the surface of the sea over a long period of time in all stages of oscillation. Also the average level which would exist in the absence of tides. Approximately 0m AHD
photogrammetry	The process of making surveys, maps and measurements using overlapping vertical aerial photography
pore water pressure	The pressure exerted in the pore water by the free water surface above the sediment
recession	The landward movement of a shoreline over time (e.g. receding shoreline). Can be caused by erosion resulting in more sediment leaving a coastal compartment than is entering it, or as a result of sea level rise inundating the shoreline over time
revetment	In coastal engineering applies to protection structures armouring an existing ground slope or erosion/dune escarpment to prevent further erosion of the slope by waves during storms
rubble mound	Generally referring to a seawall constructed by the placement or tipping of rock in a line parallel to the shore. The seawall may be designed or simply tipped
runup	The rush of water up a structure or beach on the breaking of a wave. The amount of runup is the vertical height above stillwater level that the rush of water reaches
scarp	(or escarpment) A steep face on the side of a hill, a sand dune or the seabed. Commonly refers to the steep dune face eroded by storm waves
scour	Erosion, normally by the action of flowing water or wave action
sediment transport	The main agencies by which sediments are moved are gravity (gravity transport); running water (rivers and streams); ice (glaciers); wind; the sea (currents and alongshore drift). Running water and wind are the most widespread transporting agents. In both cases, three mechanisms operate, although the particle size of the transported material involved is very different, owing to the differences in density and viscosity of air and water. The three processes are rolling or traction, in which the particle moves along the bed but is too heavy to be lifted from it; saltation; and suspension, in which particles remain permanently above the bed, sustained there by the turbulent flow of the air or water
shore-normal	Aligned at right angles to the shoreline and the nearshore contours, extending from the beach towards deep water
significant wave height	The average height of the highest one third of waves recorded in a given monitoring period. Also referred to as H1/3 or Hs. Commonly referenced statistical wave height

stillwater level	The surface of the water if all wave and wind action were to cease. In deep water this level approximates the midpoint of the wave height. In shallow water it is nearer to the trough than the crest. Also called the undisturbed water level
storm demand	That volume of sand located on a beach that can theoretically be eroded and removed offshore by a single storm event or close spaced series of storms. Provides an indication of the susceptibility of a beach to storm erosion
storm surge	The increase in onshore elevation of the mean ocean level associated with a storm. Primarily comprises a tidal component, a barometric component (low pressure) and wind setup caused by strong onshore winds at the shoreline, but does not include wave setup and wave runup
toe	The seaward base of a seawall
tremie concrete	Concrete placement under water by passing the fluid concrete down a pipe or conduit to the seabed where it cures
water table	The upper surface of a zone of saturation, where the body of groundwater is not confined by an overlying impermeable formation. Where an overlying confining formation exists, the aquifer in question has no water table
wave reflection	The process by which the energy of the wave not dissipated by interaction with the seabed or shoreline is returned seaward. Wave reflection may be higher against a hard structure (such as a vertical seawall or natural cliff) than against a natural sandy beach
wave setup	The amount by which the still water level inshore of the breaking wave zone exceeds that outside; in part due to the kinetic energy in the breaking waves being converted into an elevated inshore water level
wave-energy flux	The average rate of transfer of the wave energy past a given point. A measure of the incident wave energy at the shoreline

ACRONYMS

AEP	Annual Exceedance Probability
AHD	Australian Height Datum -
AMP	Asset Management Plan
ARI	average recurrence interval
GPR	Ground Penetrating Radar
IPCC	Intergovernmental Panel on Climate Change

1. INTRODUCTION

The Water Research Laboratory of the University of New South Wales was engaged by the Sydney Coastal Councils Group to compile a literature review providing a critical analysis and reference list of published information related to the assessment of existing seawalls.

The focus of the literature assessment includes:

- defining climate change adaptation within the context of seawall/revetment protection or upgrades
- identifying the key elements and failure modes for small coastal seawall/revetment structures
- remote sensing methods and examples that may be relevant to determining the structure of an existing seawall/revetment (e.g. ground penetrating radar, aerial survey)
- identification of likely impacts of climate change on design parameters for small seawalls/ revetments (e.g. scour depths, wave height, water level, overtopping, watertable)
- degradation of existing seawalls (design life, materials, change to exposure conditions etc.)
- adaptation pathways, options or triggers for existing seawall structures
- economic impacts on adaptation decision making
- identification of climate change adaptation options with relation to upgrading existing seawalls/revetments (e.g. toe protection, increased crest height, upgrade armour, outflanking protection)
- to prepare practical information for assessing seawall performance, and
- local government asset management/registers with specific reference to small seawall structures.

Key words that could assist with the literature review may include but are not necessarily limited to: Seawall, revetment, sea level rise, climate change, adaptation, triggers, remote sensing, ground penetrating radar, geophysical survey, design life, failure mechanisms, maintenance, upgrade, asset management, asset register, crest level, toe design, economic life, lifecycle cost.

2. Background

The literature review focuses on the assessment of the suitability of existing seawalls, under present day and future scenarios including climate change impacts. This section presents background information to the project and the literature review, and includes definitions of seawalls, climate change and climate change adaptation.

2.1 What is a Seawall?

Seawalls can sometimes be referred to in technical literature as revetments. In common usage, a revetment is usually considered to be sloping and flexible, while a seawall may be either vertical or sloping, and either rigid or flexible. In this report the term seawall has been used to include revetments.

The following definitions are presented from standard coastal engineering references.

Seawall

Seawalls are onshore structures with the principal function of preventing or alleviating overtopping and flooding of the land and the structures behind due to storm surges and waves. Seawalls are built parallel to the shoreline as a reinforcement of a part of the coastal profile. (USACE, 2003, p VI-2-1)

A structure separating land and water areas, primarily designed to prevent erosion and other damage due to wave action (SPM, 1984, p A-30).

Revetment

Revetments are onshore structures with the principal function of protecting the shoreline from erosion. Revetment structures typically consist of a cladding of stone, concrete, or asphalt to armour sloping natural shoreline profiles. (USACE, 2003, p VI-2-1)

A facing of stone, concrete etc., built to protect a scarp, embankment, or shore structure against erosion by wave action or currents (SPM, 1984, p A-28).

Protective structure normally placed on an embankment or profiled fill material, normally to form a seawall (CIRIA, 2007, p 9).

2.2 What is Climate Change?

The Earth's climate system is changing. All aspects of the climate are affected, including temperature, ocean levels and rainfall patterns. The global average temperature is rising, mostly due to increased greenhouse gas concentrations stemming from use of fossil fuels and land clearing (Preston et al., 2008). A progressive increase in mean sea levels (IPCC, 2007; McInnes et al., 2009), as well as possible changes in the behaviour of the severe weather conditions (Abuodha et al., 2006), has implications for coastal protection infrastructure (Ranasinghe et al., 2009; Cardno, 2008). Different ranges and degrees of uncertainty are associated with these changes, complicating greatly the development of climate change adaptation policies (CSIRO, 2002). Consequently, any coastal infrastructure designed and developed needs to be adapted for the uncertainty of the future climate.

2.3 Regulatory Framework

Local governments are responsible for the maintenance of some but not all coastal protection infrastructure, such as seawalls, in order to ensure the protection of the community:

> *Local government provides for the health, safety and welfare of its community and if a council cannot show that it has taken preventative action against any threat to the health, safety and welfare of its community, it faces the possibility of liability costs – costs which can be reduced if a council identifies the threats to its community and implements appropriate strategies to prevent these threats* (LGAT, 2004).

Therefore, these responsibilities create a number of challenges for the local governments in the context of climate change. As explained by Smith et al. (2008), local governments are responsible for identifying potential natural hazards, including those associated with climatic events, within their jurisdiction. This responsibility is now complicated as the local governments have not only to consider historical climate variability but future climate change as well, and the inherent uncertainty in regard to rate or magnitude.

To this effect, national and state sea level rise planning benchmarks have now been adopted (Good, 2011), or are still under consideration, throughout Australia, in order to assist local councils in coastal hazard assessments. These benchmark values, defined as an increase above 1990 mean sea levels, are provided in Table 1.

Table 1 Sea Level Rise Planning Benchmarks Summary

Government	2050 Benchmark	2100 Benchmark	Source
Commonwealth	-	1.1 m[(1)]	(DCC, 2009)
NSW	0.4 m	0.9 m	(DECCW, 2010)
Victoria	-	No less than 0.8 m	(VCC, 2008)
Queensland	0.3 m	0.8 m	(DERM, 2011)
Tasmania	SLR policy not yet published. In practice, values from nearby states are adopted (i.e. 0.9 m rise for 2100).		
South Australia	0.3 m	1.0 m	From 1991 policy on coast protection and coastal development (under review)
North Territory	There are currently no benchmarks in place		
Western Australia	-	0.9 m	(DTCI, 2011)

(1) This value is the high end for scenario for 2100

These benchmark values have been established to be used when planning for sea level rise and will have to be updated in order to take into account changes in national or international projections of sea level rise, such as may be in the next Intergovernmental Panel on Climate Change (IPCC) assessment report expected in 2014.

2.4 WHAT IS CLIMATE CHANGE ADAPTATION?

The response to climate change requires a dual approach (DEWR, 2007):

- management and reduction of our contribution to climate change (defined as mitigation), and
- making adjustments to existing activities and practices so that vulnerability to potential impacts associated with climate change can be reduced and opportunities realised (defined as adaptation).

Mitigation involves actions to reduce greenhouse gas emissions and/or enhance greenhouse gas sinks in order to offset or reverse the effects of climate change. Local governments have already made significant progress towards mitigation, with councils engaged in efforts to reduce greenhouse gas emissions and waste (Smith et al., 2008).

Adaptation aims to reduce the risks associated with future changes in climate. However, it additionally seeks to harness beneficial opportunities that may arise under a changed future climate system (IPCC, 2007). Adaptation is a mechanism to manage risks and adjust economic activity to reduce vulnerability (COAG, 2007). It is adaptation that is the focus of this literature review and the project.

In regard to existing infrastructure, the recommended adaptation action by local government can be summarised as (DEWR, 2007):

- monitor any changes to the condition in structures so that any modifications/retrofitting occurs on time and prior to failure
- identify alternative options should the existing buildings and infrastructure be impacted upon in order to maintain services and connections, e.g. to minimise isolation of communities during an adverse storm event that puts the infrastructure at higher risk
- design retrofitting to a higher standard than the minimum set where possible and practical
- progressively incorporate higher design standards into asset management plans and rolling capital works programs.

Adaptation measures are often prioritised and driven by the vulnerability of a system to climate change. Vulnerability is the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change. Vulnerability represents the potential for an adverse impact to occur but does not necessarily indicate the magnitude of the impact or its probability.

3. Design Criteria of Seawalls

3.1 Literature on the Design of Seawalls

The following documents provide guidance on the design of coastal structures and are considered in industry to provide current best practice methods and advice (though it should be noted that there are numerous other authoritative publications in this area):

- USACE (1995), Design of coastal revetments, seawalls, and bulkheads, US Army Corps of Engineers
- USACE (2003), *Coastal Engineering Manual*, US Army Corps of Engineers
- CIRIA (2007), *The Rock Manual: the use of rock in hydraulic engineering*, 2nd edition, CIRIA C683, London
- EurOtop (2007), *Wave Overtopping of Sea Defences and Related Structures: Assessment Manual*, Environment Agency, UK, ENW Expertise Netwerk Waterkeren, NL, KFKI Kuratorium für Forschung im Küsteningenieurwesen, DE, August 2007. Authors: T Pullen (HR Wallingford, UK), N W H Allsop (HR Wallingford, UK), T Bruce (University Edinburgh, UK), A Kortenhaus (Leichtweiss Institut, DE), H Schüttrumpf (Bundesanstalt für Wasserbau, DE), J W van der Meer (Infram, NL)
- Shore Protection Manual (1984), *Coastal Engineering Research Center*, Department of the Army, Vicksburg, Mississippi USA.

There are numerous Australian Standards which cover materials involved in coastal structures, but there are none which specifically address the design of coastal structures.

AS4997 (2005) *Guidelines for the design of marine structures* excludes rubble coastal engineering structures but contains valuable information on probability and the choice of a design event.

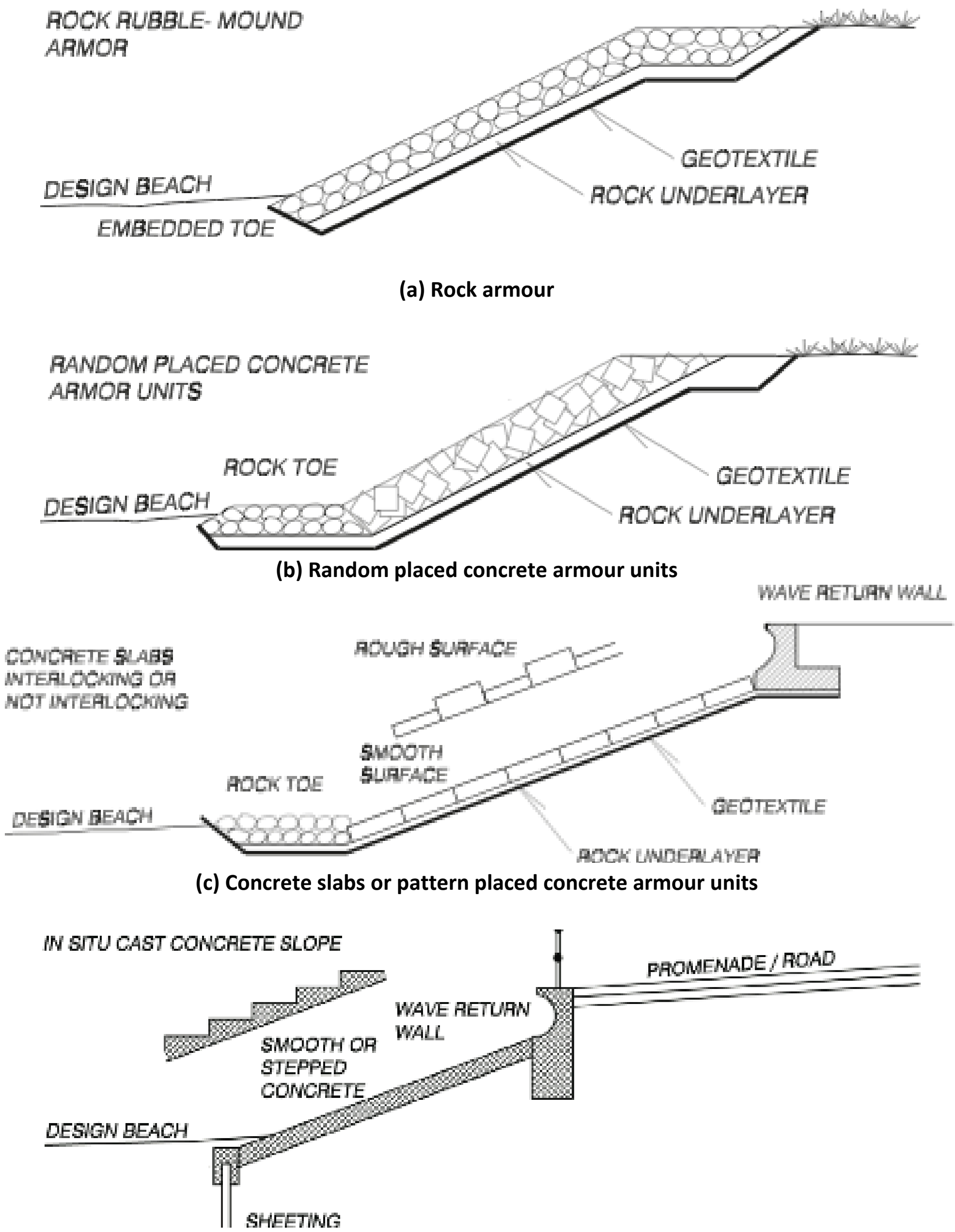
The Institution of Engineers Australia (Engineers Australia) has published the following series of three relevant guidelines for effectively considering climate change and ecological sustainability:

- Engineers Australia (2012a), *Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering*. First published 1991, updated 2012, revised and published September 2012. Prepared by the NCCOE of Engineers Australia, published by EA Books PO Box 588, Crows Nest, NSW
- Engineers Australia (2012b), *Coastal Engineering Guidelines for Working With the Australian Coast in an Ecologically Sustainable Way*. First published 2004, revised and published September 2012. Prepared by the NCCOE of Engineers Australia, published by EA Books PO Box 588, Crows Nest, NSW, and
- Engineers Australia (2012c), *Climate Change Adaptation Guidelines in Coastal Management and Planning.* Published September 2012. Prepared by the NCCOE of Engineers Australia, published by EA Books PO Box 588, Crows Nest, NSW.

  These guidelines can be accessed in electronic format at no charge through the Engineers Australia web site (http://www.engineersaustralia.org.au/coastal-ocean- engineering/ publications).

3.2 Main Types of Seawalls

Seawalls (and revetments) are generally parallel to the shore and can be classified as sloping-front or vertical-front structures. Sloping-front structures can be constructed as flexible rubble mound structures which are able to adjust to some toe and crest erosion or as rigid structures which have a fixed form and position. Sloping-front seawalls are typically built from randomly placed armour (rock or concrete units), pattern-placed concrete armour units (see Figure 1), reinforced concrete, geotextile containers, or gabion baskets, though numerous other less successful materials have been used in the past.



(a) Rock armour

(b) Random placed concrete armour units

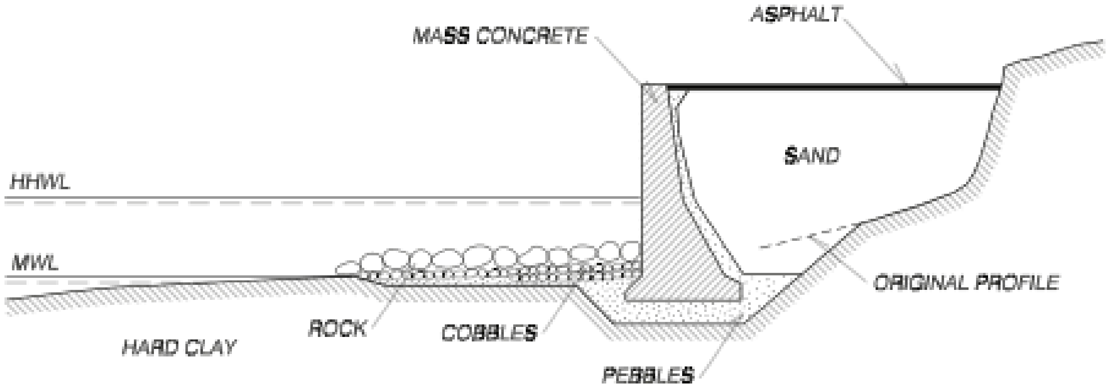
(c) Concrete slabs or pattern placed concrete armour units

(d) Solid concrete

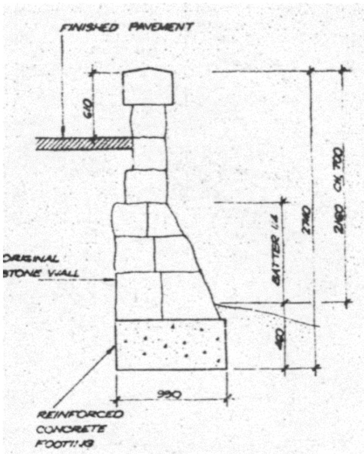
Figure 1 Examples of sloping front seawall structures

(Source: USACE 2003)

Vertical-front seawalls are usually composed of stone or concrete blocks, reinforced concrete, mass concrete, or steel sheet piles. Such vertical structures can either be built as tied-in, gravity or cantilever walls (see Figure 2). Vertical seawalls typically also act as retaining walls to material located behind.



(a) Vertical concrete gravity wall [Source: USACE (2008)]



(b) Vertical stone gravity wall (Source: Bray & Tatham 1992)

Figure 2 Examples of vertical seawall structures

There is a wide range of seawall types, either sloping-front or vertical-front, located for example within the local government areas of the Sydney Coastal Councils Group as can be observed on the examples given in Figure 3.

(a) Solid Concrete (Mosman Council)

(b) Seabee concrete units (Sutherland Council)

(c) Vertical Sandstone (Pittwater Council)

(d) Concrete stepped face (Manly Council)

Figure 3 Examples of seawall types within the SCCG

These structures typically have a horizontal surface (or cap) at the crest. In some cases the seawall cap can be wide enough to contain a promenade on top of the structure or provide access to the shore. Many structures involve a combination of materials, e.g. a concrete crest wall on a rock structure, or a vertical seawall with a rock toe.

3.3 Wave/Seawall Interactions

As described in USACE (2003), the main forcing parameters on a seawall can be separated into the hydraulic responses of the waves, and the structural response of the seawall.

3.3.1 Hydraulic Responses

There are three main hydraulic responses which need to be considered for the design of a seawall.

The first is the *wave runup* level, as it determines the design crest level of the seawall in cases where no, or only marginal, overtopping is acceptable.

The second is the *wave overtopping*. Wave overtopping occurs when the structure crest height is below the runup level. Overtopping discharge is a particularly important design parameter as it determines the geometric design of the crest level, the structural design of the seawall and the safety of infrastructure, vehicles and people located on/behind the crest.

Finally, *wave reflection* occurs to varying degrees in front of seawalls, depending on the slope and armouring of the seawall. Wave reflection can induce steep waves and create problems for navigation and berthing of boats. This issue is of particular importance for harbour seawalls near navigation areas. Strong wave reflection also increases the sea bed erosion potential in front of protective structures and may contribute to erosion at the seawall toe and of adjacent beaches.

3.3.2 Structure Loading and Structural Responses

When designing a seawall, it is important to accurately assess the various loads and the related stresses, deformations and stability conditions of the different structural parts of the seawall.

For rubble mound structures, the main loads and structural responses to determine can be summarised as:

- stability of the primary (and secondary) armour layers
- structural integrity of the individual concrete armour units
- toe stability and protection
- design of the cross-section.

Due to the complex nature of the flow of waves impacting the armour layer, it is uncommon to calculate wave forces acting on the armour of rubble mound structures. The common approach is to treat the actual forces as a 'black box' transfer function and derive the response of the armour units in terms of movements related directly to parameters of the incident waves.

For vertical-front structures, the main loads and structural responses to determine can be summarised as:

- wave forces on the vertical wall
- wave forces on the concrete cap
- stability of the vertical wall and concrete cap against sliding and overturning
- uplift forces
- settlement of the seawall
- pore pressure behind the wall and drainage
- geotechnical stability of the soil profile.

For vertical-front structures, it is possible either from theory or experiments to estimate the wave loadings and subsequently determine stresses, deformations and stability.

Finally, it is of great importance to assess the foundation loads of seawalls to ensure stability. The main geotechnical aspects to verify when designing a seawall are the assurance of safety against soil failure (slip circle failure) as well as assurance of limited settlement in the foundation soils.

3.4 Failure Modes of Seawalls

The US Corps of Engineers (USACE, 2003), defines the failure of a coastal structure as:

Damage that results in structure performance and functionality below the minimum anticipated by design.

The most common reasons for the failure of a coastal defence structure are (USACE, 2003; CIRIA, 2007):

- design failure: this occurs when either the structure as a whole, including its foundation, or individual structure components cannot withstand load conditions within the design criteria
- load exceedance failure: this results from an underestimation of the design conditions
- construction failure: this can be caused by unsuitable construction techniques or poorly suited construction materials
- deterioration failure: this failure is the result of structure deterioration and lack of project maintenance.

In the particular case of rigid seawall structures, the main failures modes can be detailed as:

- undermining, in which the sand or rubble toe level drops below the footing of the wall, causing the wall to subside and collapse in the hole
- sliding, in which the wall moves away from the retained profile
- overturning, in which the wall topples over
- slip circle failure, in which the entire embankment fails
- loss of structural integrity, due to wave impact
- erosion of the backfill, caused by wave overtopping, high watertable levels, or leaching through the seawall
- corrosion, abrasion and impact damage
- outflanking and end scour.

In the case of flexible sloping-front structures, failures are typically the result of wave action or geotechnical factors, such as slope failure, foundation failure and internal erosion. Toe erosion, slope failure, internal erosion, hydraulic damage and severe overtopping, which can cause erosion of the crest and lee-side damage, are key causes of major damages (CIRIA, 2007).

Following work completed in the UK in the late 1980s and early 1990s, it is documented in CIRIA (1991) that *around 34% of seawall failures arise directly from erosion of beach or foundation material, and that scour is at least partially responsible for a further 14%.*

Figure 4 shows some past examples of seawalls failures within the Sydney area which were the result of excessive toe erosion ((a) and (b)) or erosion of the backfill material (c).

(a) Damaged gabions, Cronulla seawall, 1986

(b) Dee Why collapsed seawall, 1998

(c) North Steyne collapsed seawall, 1950

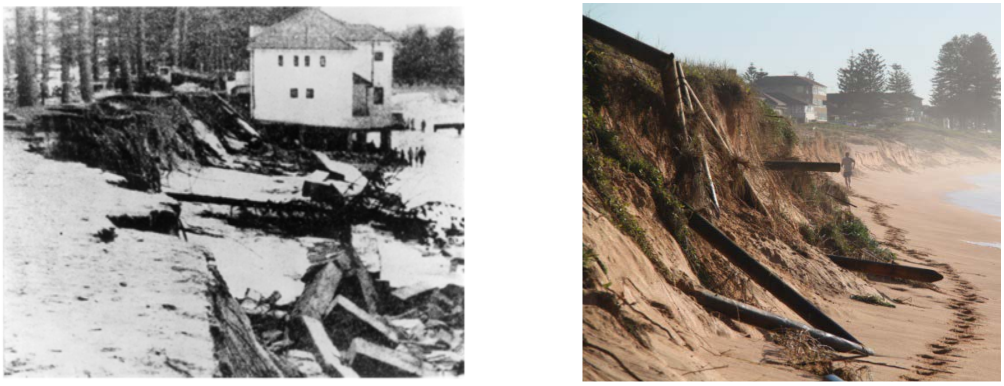
Figure 4 Examples of past seawall failures within the SCCG

3.5 Coastal Hazards Responsible for Seawall Failures

The failures modes described in the previous section are mainly caused by three types of coastal hazards:

- erosion of sand in front of the seawall during storm events
- wave overtopping (inundation) of the seawall due to elevated water levels and storm wave conditions, and
- wave impact due to elevated water levels and large wave conditions.

3.5.1 Erosion Hazard



(a) Loss of promenade at Manly, 1950 **(b) Beach erosion at Narrabeen, 2011**

Figure 5 Example of erosion at beaches within the Sydney region

(Source: WRL)

The erosion of sand during storm events can cause the reduction of beach levels fronting the seawall and consequently undermine the foundations of the seawall (see Figure 5). This can potentially cause failure of the seawall by exposing the toe of the structure to direct wave impact, or by reducing foundation support. For each seawall section, the likelihood of seawall undermining can be related to the following factors:

- seawall toe design and toe levels as determined by previous geotechnical investigations or from design drawings (when available)
- average and minimum levels against the seawall, as determined through analysis of historical profile variations (photogrammetry analysis)
- storm demand or estimated volume of sand eroded (above mean sea level) during the design extreme erosion event
- typical pre-storm volume of sand above mean sea level as determined through analysis of historical profile variations (photogrammetry analysis)
- wave conditions and exposure.

The location of the seawall on the beach system influences the extent to which the structure interacts with coastal processes such as waves and hazards such as erosion. Structures located high up the beach interact with wave and sediment transport processes infrequently, in contrast, structures within the everyday active beach zone interact frequently with hydrodynamic and sediment transport processes.

For short seawall sections or where adequate end protection has not been constructed, erosion and recession of the beach adjacent to the structure may result in outflanking and failure during storm conditions.

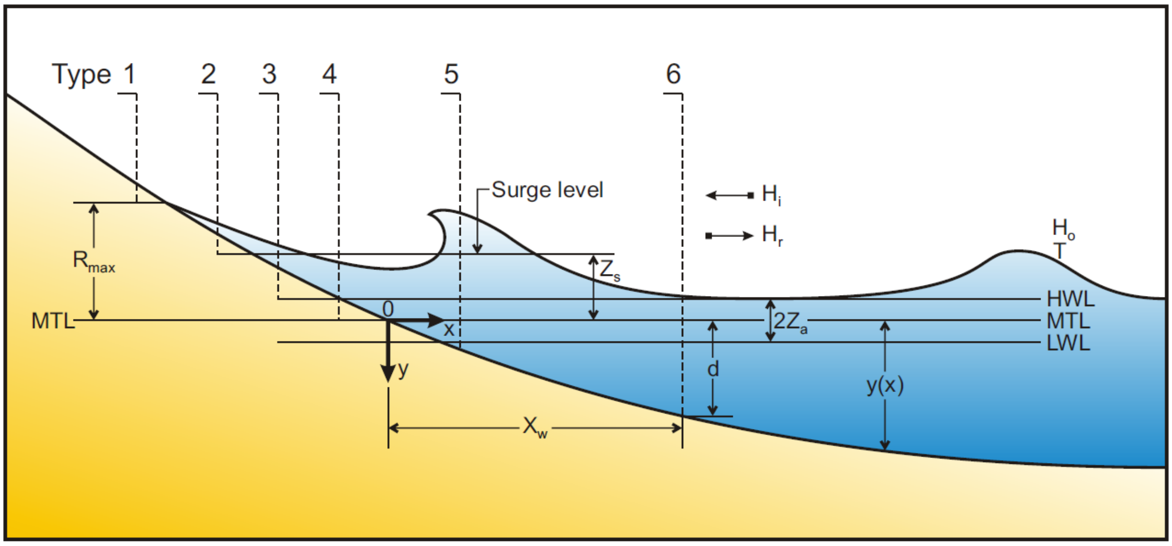


Figure 6 Seawall location according to Weggel classification

(Source: Weggel 1988)

Seawalls are commonly classified using the Weggel (1988) classification system, depending on their location within the active beach system (see Figure 6 and Table 2). The intersection of the structure and beach profile may change over time as beach levels and shoreline position change, particularly on long-term receding beaches and as a result of sea level rise.

Table 2 Weggel seawall classification

(Source: Weggel 1988)

Type	Location of Seawall
1	Landward of maximum level of runup during storms. The wall does not affect either hydraulic or sedimentation processes under any wave or water level conditions, although may affect aeolian processes
2	Above still water level of maximum storm surge and below the level of maximum runup. Exposed only to the runup of waves during storm events
3	Above normal high water and below the still water level of storm surge. Base will be submerged during storms and during exceptionally high astronomical tides but will normally be above water
4	Within the normal tide range; base is submerged at high water
5	Seaward of mean low water; base is always submerged; subjected to breaking and broken waves
6	So far seaward that incident waves do not break on or seaward (of the wall)

3.5.2 Wave Impacts, Overtopping and Inundation Hazard

Wave overtopping of seawalls is caused by direct (and often violent) impact of waves on the structure. Wave impacts can cause damage to the structure, in particular to freestanding parapets and concrete caps. More importantly, the water discharged above the seawall crest constitutes a hazard to not only the structure crest and promenade, but also to people and infrastructure located directly behind the seawall (see Figure 7). Overtopping can also cause saturation of the soil profile, increasing pore water pressure and the chance of failure from sliding, overturning or removal of retained soil.

Overtopping is commonly quantified in terms of volume of water being discharged past the seawall crest and expressed in L/s per metre length of crest.

Figure 7 (Top) Wave overtopping the Manly to Shelley seawall;
(Bottom) Wave runup at Manly LSSC boat ramp and Manly beach stairs (Victoria Parade)
(Photos: James Carley, WRL)

The estimated overtopping rates refer to the zone immediately behind the structure crest and can be related to the published tolerable rates (CEM, 2003; EurOtop, 2007) in regard to structural and people safety. Limits of mean tolerable overtopping rates for seawalls are presented in Table 3 (EurOtop, 2007).

Table 3 Limits for tolerable mean wave overtopping discharges
(EurOtop, 2007)

Hazard Type	Mean Overtopping Discharge (L/s per m)
Unaware pedestrian, no clear view of the approaching waves, not prepared to get wet, poor/uneven ground surfaces	0.03
Aware pedestrian, clear view of the sea, able to tolerate getting wet	0.1
Trained staff, well shod and protected, expecting to get wet	1-10
Damage to paved promenade behind seawall	200
Damage to grassed promenade behind seawall	50
Structural damage to seawall crest	200
Structural damage to building	(1) 1

(1) this limit relates to the effective overtopping defined at the building

4. CLIMATE CHANGE IMPACTS ON SEAWALLS AND ADAPTATION OPTIONS

This section provides a review of the possible implications of climate change in the coastal zone and of the resulting impacts to coastal defence structures such as seawalls. A review of the potential adaptation measures is then presented, followed by a review of the existing adaptive management approaches for coastal structures.

4.1 IMPLICATIONS OF CLIMATE CHANGE IN THE COASTAL ZONE

The climate change predicted to occur in the Sydney region is summarised in Table 4 (Preston et al. 2008). These impacts will vary from location to location and in various regions of Australia. A typical resource for climate change impacts in NSW is available online (SCCG, 2011).

Table 4 Projected climate change in the Sydney region
(after Preston et al., 2008)

Climate Variable	Range of Projected Change (Relative to 1990)		Source
	2030	2070	
Rainfall (Annual Average)[1]	-3 to+9%	-25 to +10%	CSIRO and BOM (2007)
Rainfall (Annual Extreme 1 Day Rainfall)[2]	+7%	+5%	Hennessy et al. (2005)
Wind Speed[1]	-5 to +4%	-15 to +12two	CSIRO and BOM (2007)
Sea Level[5]	+3 to +17 cm	+7 to +52 cm	Amitrano et al. (2007)

Notes:
[1]Range represents the 10th and 90th percentiles based upon a temperature distribution generated from a range of climate models and emission scenarios.
[2]Defined as range of change in 1-in-40-year rainfall totals. Values represent results from a limited set of climate model projections for central eastern NSW.
[3]The values for drought represent average monthly drought frequencies, based upon the Bureau of Meteorology's criteria for serious rainfall deficiency.
[4]Number of days annually with a 'very high' or 'extreme' fire danger index. Changes are for 2020 and 2050, respectively.
[5]Changes are for 2030 and 2070 respectively, relative to 1990.

The *Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering* (Engineers Australia, 2012a) list six key environmental variables applicable to coastal engineering:

(i) Mean sea level

(ii) Ocean currents and temperature

(iii) Wind climate

(iv) Wave climate

(v) Rainfall/runoff

(vi) Air temperature

Following consideration of the relative likely importance of changes to these primary environmental variables, the guidelines recommend that the interactions between the primary variables and 13 secondary (or process) variables be assessed on a project specific basis, as follows:

(i) Local sea level

(ii) Local currents

(iii) Local winds

(iv) Local waves

(v) Effects on structures

(vi) Groundwater

(vii) Coastal flooding

(viii) Beach response

(ix) Foreshore stability

(x) Sediment transport

(xi) Hydraulics of estuaries

(xii) Quality of coastal waters

(xiii) Ecology

4.2 Implications of Climate Change on Coastal Defences

While it is necessary to assess the importance of each primary and secondary variable combination on a project-by-project basis, generally mean sea level increase, wind climate change and wave climate change are the major concerns for seawalls around the Australian coast.

The risks due to these individual climate variables are outlined in Sections 4.2.1 to 4.2.4 and summarised in Section 4.2.5.

4.2.1 Mean Sea Level Rise

The Intergovernmental Panel on Climate Change has produced major reports in 1990, 1996, 2001 and 2007. Hence the 2007 report is known as the Fourth Assessment Report (AR4). The latest IPCC Summary for Policymakers Report (IPCC, 2007) provides numerous global average sea level rise scenarios for 2095 (relative to the baseline of 1980-1999) in the range of 0.18 to 0.79 m. The central estimate is that the global average sea level will rise by about 0.55 m by the year 2100, with a range of uncertainty from 0.20 m to 0.85 m. Regional and local changes in average sea level will vary from this global average. For planning purposes, most Australian governments (federal and state/territory) have adopted formal sea level rise allowances between 0.8 and 1.1 m on 1990 sea levels for the year 2100 (see Section 2.3). Some of these are under revision and the current values to be adopted should be determined within each jurisdiction.

An increase in mean sea level will exacerbate the impact of the coastal hazards discussed in Section 3.5. Sea level rise will result in higher water levels on the open coastline and within estuaries which may also correspond to an increased rate of shoreline recession. Increased still water levels may also allow land in the lee of seawalls to be more frequently inundated due to wave runup and overtopping. The threat from tidal inundation around lower-lying estuarine foreshores may be significantly exacerbated with sea level rise. The stability of coastal watercourse entrances will also be changed due to alterations to the dynamics of berm heights and breakout conditions. For existing coastal structures, sea level rise will reduce freeboards, increase wave overtopping (frequency and magnitude) and, at depth-limited locations, expose structural elements to larger forces (Burgess & Townend, 2004).

4.2.2 Wind Climate

At present, projections of wind and wave climate changes are not as robust as those developed for mean sea level increases. Climate change may have a direct influence on the frequency, magnitude and direction of local winds from storms. Any changes to either typical or extreme wind climate will have a direct effect on structural wind loadings but also a secondary effect on the distribution of the wave-energy flux presently shaping the coastline. Preliminary projections indicate that trade winds may be weaker and that the westerly wind stream may move further south (CSIRO & BOM, 2007). There is a possibility of increasing severity and frequency of east coast lows. Any significant modifications to the behaviour of tropical cyclones in a changed climate could have especially damaging impacts for some regions in northern Australia (NCCOE, 2004). The latest consensus view (Knutson et al., 2010) is that:

- there is no definitive evidence from recorded data that tropical cyclones are getting stronger or are becoming more frequent
- however, the most intense tropical cyclones may have the opportunity to develop up to 11% stronger peak winds by the year 2100 and the relative proportion of the most intense tropical cyclones would likely increase as a result
- the global frequency of tropical cyclones may decrease by up to 34% due to a more unfavourable state of environmental shear but the extent of tropical cyclone influence is not expected to greatly change.

Changes to the local winds will also have a direct effect on the efficiency of coastal structures, as any increase in extreme wind speeds will result in increased storm surge at the shoreline, leading to higher wave runup and reduced freeboard.

4.2.3 Wave Climate

Again, it should be emphasised that the scientific understanding of the projected changes to storminess, and hence wave climate, is still developing (DECCW, 2010). Young et al. (2011) considered observations of significant wave height from altimetry and found a weak global trend of increasing mean wave height and a stronger increasing trend at the 90th and 99th percentile. However, Shand et al. (2011) found that there was no significant change in wave conditions for the present duration of reliable wave buoy records around Australia. Regardless, it is reasonable to expect that any alterations to storminess (magnitude, frequency and direction) due to climate change will in turn induce alterations in beach erosion patterns. Also, any increase in extreme wave heights will result in increased wave setup at the shoreline leading to higher wave runup and overtopping (Cardno, 2008).

While changes to deepwater wave climate will be critical for nearshore engineering activities, depth-limited wave climate (the maximum height a wave can reach in shallow water without breaking) in inshore regions will increase as a result of mean sea level rise. Higher mean sea levels combined with more eroded beaches will expose existing coastal structures in these regions to more energetic wave conditions. Many seawalls that are rarely impacted by waves may become frequently exposed to small waves and less frequently to larger wave conditions.

4.2.4 Possible Impacts from Additional Variables

While sea level rise and wave climate change would have the greatest direct impact on seawalls, a range of secondary variables could have indirect impacts, depending on the structure type and location. More research is required to better understand the implications of these secondary processes.

Sea level rise is projected to increase saline water intrusion into coastal aquifers and modify the groundwater levels which could undermine infrastructure foundations (DEWR, 2007) or affect the durability of construction materials (concrete, reinforcement etc.) Increased intensity of extreme rainfall events of a given exceedance probability would effectively reduce the design life of infrastructure. By inducing increased flooding particularly in low-lying coastal areas affected by sea level rise and increased storm surge (ATSE, 2008), this would result in a change in drainage as well as the pore pressure on the rear of seawalls. A growing body of research has also found that ocean acidification could be an additional key variable and lead to an accelerate decay of structural materials (Carley et al., 2008).

4.2.5 Summary

The implications of climate change on seawalls are far reaching and complicated by the interaction of different climate change variables. For instance, in the case of open coast seawalls subjected to depth-limited wave conditions, sea level rise will result in an increase in the size of depth-limited waves impacting upon the structure. A result of larger waves will be the increase of scouring under extreme wave conditions with consequential foreshore steepening and possible further lowering of the beach level (Burgess & Townend, 2004).

The potential impact of climate change on local government-managed coastal infrastructure can be summarised as (DEWR, 2007):

- increased coastal erosion and inundation
- increased frequency or permanent inundation of coastal infrastructure and utilities
- destruction, damage and disturbance to council-managed marinas and boat ramps
- increased erosion and/or exceedance of seawalls, jetties and other coastal defences.

In regard to small seawalls, the main impacts of climate change can be summarised as:

- increased wave loading
- increased overtopping and flooding of the seawall (and potential erosion of the backfill)
- increased scouring at the toe of seawall.

4.3 Climate Change Adaptation Measures for Seawalls

IPCC (2007) presents a simple set of three strategic options in response to climate change, namely retreat, accommodate or protect. These three adaptation options serve to illustrate the basic range of possible responses and are reproduced in Engineers Australia (2012a) to guide Australian engineers addressing the impacts of climate change on coastal areas. Climate change adaptation offers a means by which exposure to future climate change risks can be reduced, whilst at the same time exploiting any potential benefits that may arise from climatic changes. Selecting an adaptation option, or pathway, should be done on a project-specific basis and ought to consider the circumstances of the threat, the vulnerability of the region, the tenure of the affected land and the capacity of the responsible authority (Engineers Australia, 2012). When planning new engineering activities, early allowance in design, development approvals and planning may significantly reduce the total cost to the community and provide sustainable and even enhanced environmental outcomes. However, such decisions are dependent on more than just consideration of future design requirements.

Retreat involves no effort to protect the land assets from the sea, but provides an opportunity for natural evolution of the coastline and retention of the sandy beach amenity. Land and structures in highly vulnerable areas of the coastal zone are abandoned and inhabitants resettled elsewhere. The intermediate strategy of accommodation when applied to existing development involves conservation of ecosystems in harmony with continued occupancy and use of vulnerable areas through adaptive management responses for as long as such use remains practical. Protection is generally focused on defence of vulnerable areas, population centres, economic activities, infrastructure and natural resources. It may involve hard and/or soft structural options and frequently will result in loss of habitat and beach amenity.

The type of adaptation solution for a seawall is highly dependent on the type of structure as well as the environmental conditions it is subjected to (open coast or estuarine). Therefore, this section aims to provide an overview of the main seawall parameters that can be modified in order to accommodate the potential impacts of climate change.

For more details on the following methods and examples of precise applications, the reader is referred to Bray & Tatham (1992) and USACE (2003), which both extensively cover the design of sloped and vertical seawalls. Moreover, there are some practical applications of sea level rise vulnerability to seawall structures contained in detailed studies on threatened infrastructure at Fort Denison and Goat Island within Sydney Harbour (Watson and Lord, 2008; Watson and Lord, 2009).

4.3.1 Adaptation to Increased Wave Loading

The potential increase in wave loading will have implications on both armour unit stability for sloping structures, and wave impacts for vertical walls, and will require an increase in the mass or strength of the structure to prevent displacement or movement (Townend & Burgess, 2004).

Such modifications can be achieved through:

- sloping seawalls:
  - increase of the thickness of armour unit layer
  - replacement of the existing armour unit layer by armour units of a larger size or different type
  - addition of rock berm in front of seawall to induce wave breaking
  - increase the height of existing rock berm to induce wave breaking
- vertical seawalls:
  - piling
  - ground and rock anchors
  - sheet piles placed in front of existing seawall complemented by concrete
  - vertical concrete seawall placed in front of existing structure
  - consolidation of seawall backfill
  - addition of rock berm in front of seawall to induce wave breaking
  - Increase the height of existing rock berm to induce wave breaking.

WRL recommends that caution should be taken if altering the rock toe berm of a seawall as this may have secondary impacts on wave runup levels, and the nature of breaking wave impacts on a structure.

4.3.2 Adaptation to Increased Overtopping and Flooding of the Seawall

Modification to the existing seawall may be necessary to avoid overtopping exceeding acceptable levels (EurOtop, 2007) as well as to reduce flooding of the structure. Existing modifications include:

- raising of the crest level
- addition of a vertical or curved crest wall (for sloping structure)
- addition of rock berm in front of seawall to induce wave breaking
- increase of the height of existing rock berm to induce wave breaking
- improved drainage of backfill material behind wall
- improved drainage of promenade to reduce overland flow from overtopping.

Two studies have been undertaken within Sydney Harbour to investigate the vulnerability of historical sites to increased water level due to sea level rise (Watson and Lord, 2008; Watson and Lord, 2009).

4.3.3 Adaptation to Increased Scour at the Toe of Seawall

Adequate toe levels are critical to prevent undermining failure of seawalls due to the increase of scour and resulting lowering of the beach levels. Possible solutions to prevent scour failure include:

- changing conditions which caused erosion (installation of groynes or offshore breakwater, beach nourishment)
- installation of rubble toe protection
- reinforcing of existing rubble toe protection
- gabions
- concrete mattresses
- geotextile sand containers.

4.4 Management Approaches to Climate Change

Seawalls typically have design and operational lives spanning many decades. As a result, projected climate changes need to be factored into planning, design, construction and maintenance, as the timescales of the climate change are within infrastructure design life (Short et al., 2010).

There is, however, little guidance for adaptation of existing seawalls to climate change. One approach is to consider the complete sea level rise expected to actually occur over the life of the structure, in the initial design of the adaptation plan. This is usually referred to as the *Precautionary Approach*.

However, this choice does not allow for a wide range of projected changes in sea level rise or other variables and is based on the assumption that this fixed change will occur (Headland et al., 2011). Potential limitations to this approach is that it has the potential to:

- result in unnecessarily over-built structures with associated costs issues
- have greater environmental and social impacts (i.e. larger footprint)
- under-design in the event that sea level rise proves greater than that projected or accounted for in the design over a set time horizon.

A more favoured approach nowadays, usually referred to as *Managed Approach* (DEFRA, 2006), or Adaptive Management, allows for staged adaptation in the future, and is appropriate in the majority of cases where ongoing responsibility can be assigned to track the change in risk and manage this through multiple interventions. This approach provides flexibility to manage future uncertainties associated with climate change, during the whole life of a structure (see Figure 8). To consider a precautionary approach only could lead to greater levels of investment at fewer locations. A managed approach is therefore important to ensure best value for money from public investment.

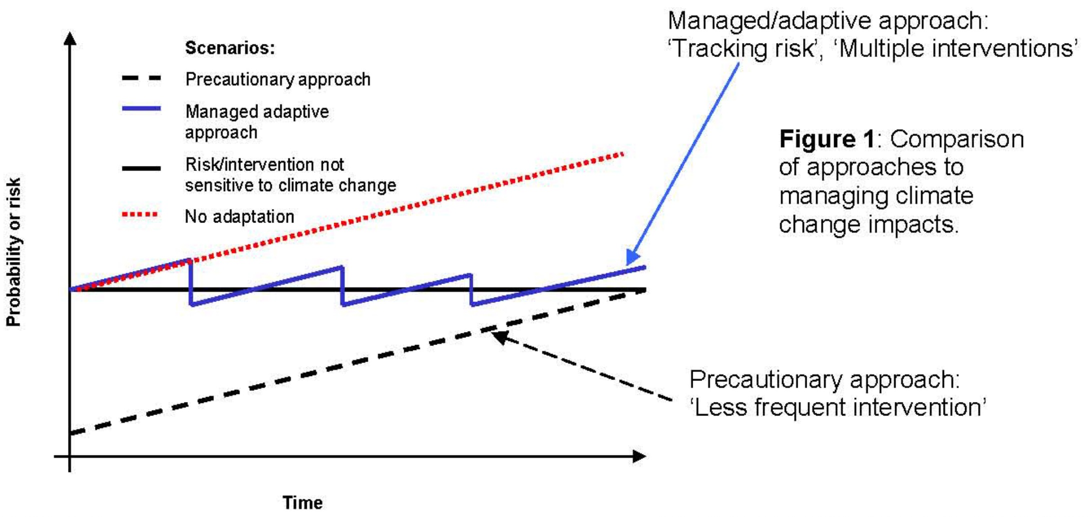


Figure 8 Timing of adaptive management options

(Source: DEFRA 2006)

Adaptive management approaches have proven to be potentially economical for the adaptation of rubble mound breakwaters (Headland et al., 2011) even for cases where sea level rise scenarios are modified over the lifetime of the structure.

Likewise, Carley et al. (2008) investigated the benefits of an adaptive management approach to the existing coastal flood scenarios in Clarence Council, Tasmania. It was shown that (within the limitations of the analysis technique) designing for a 100-year ARI (1% AEP) event in 2100 (with high range sea level rise) would provide a present day protection against an event of 850,000-year ARI, which, depending on the cost of such an adaptation, may be excessively conservative. Similarly, a present day risk level of 100-year ARI (1% AEP) would reduce to approximately 3-days ARI if no intervention was taken by 2100 with a high range sea level rise scenario, indicating the potential risk of no adaptation in the long term.

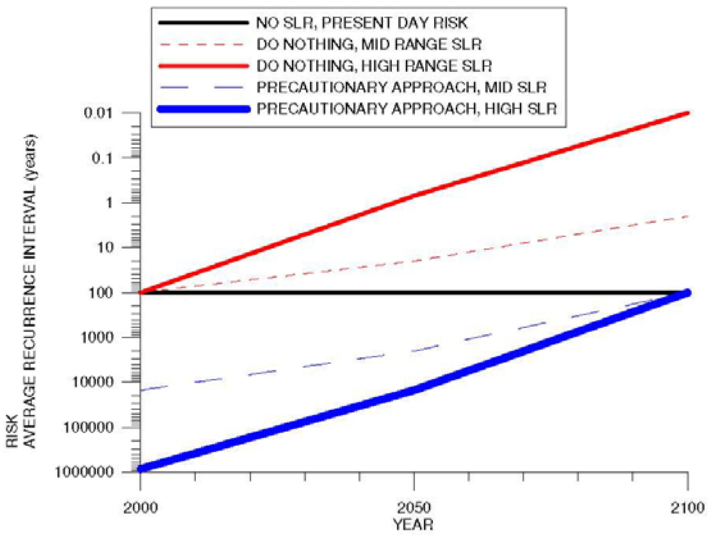


Figure 9 Change in risk of extreme coastal events on Clarence Coast

(Source: Carley 2008)

For some circumstances, a future managed adaptation approach may be technically infeasible or too complex to administer over the structure life of up to 100 years or beyond. These circumstances may occur where multiple interventions are not possible to manage the changes in risk. Therefore, a precautionary approach, perhaps with one-off intervention, may be the only feasible option. This should be assessed on a case-by-case basis.

5. Monitoring and Maintenance of Seawalls

5.1 Introduction

Over the life of a seawall, the structural components are susceptible to damage and deterioration. Damage is usually thought of as structure degradation that occurs over a relatively short period such as a single storm event. Deterioration is a gradual aging of the structure and its components over time; it can progress slowly, and often goes undetected because the seawall continues to function as originally intended. However, if left uncorrected, continual deterioration can lead to partial or complete failure of the structure.

The implementation of an adequate maintenance program is therefore critical in order to ensure that a seawall continues to operate during its designed life. USACE (2003) defines the goal of a seawall maintenance program as *to recognize potential problems and to take appropriate actions to assure the project continues to function at an acceptable level*.

Seawall maintenance consists of the following essential elements:

- seawall inspection and monitoring of both environmental conditions and structure response
- evaluation of inspection and monitoring data to assess the seawall's physical condition and its performance relative to the design specifications
- determining an appropriate response based on evaluation results. Possible responses are no action, rehabilitation, or repair, of all or portions of the seawall.

The main monitoring issues are to assess what parameters of the seawall to monitor, how to evaluate the monitoring data and consequently if preventive or corrective action needs to be undertaken.

5.2 Monitoring of Coastal Structures

The following documents provide guidance on monitoring and maintenance of coastal structures:

- CIRIA (2007), The Rock Manual: the use of rock in hydraulic engineering, 2nd edition, CIRIA C683, London.
- Coastal Engineering Manual (USACE, 2003), Chapter 8 Monitoring, Maintenance and Repair of Coastal Projects, EM 1110-2-1100 (Part VI) 1 June 2006, US Army Corps of Engineers.
- Bray, R N, Tatham, P F B (1992). Old Waterfront walls: Management, maintenance, and rehabilitation. E. & F.N. Spon (Imprint of Chapman and Hall), London, 1992, ISBN 0-419-17640-3, 267 pp.

Seawall monitoring can typically be divided between condition monitoring and performance monitoring.

Condition monitoring is the basis for the implementation of a successful preventive maintenance program. Seawall condition monitoring should always involve at least visual inspection of the structure, and in some cases the inspection can be augmented with measurements meant to quantify the current structure condition relative to the baseline condition. As described in Bray & Tatham (1992), seawall inspections can be described according to the following terminology:

- Superficial Inspections: this type of inspection should be carried out multiple times a year and report any defects changes or unusual features of the seawall
- General Inspections: this type of inspection, carried out by trained technical staff, is more formal and detailed, and is recommended to take place approximately every two years. Monitoring of specific locations can be carried out
- Principal Inspections: principal inspections include a detailed examination of all aspects of the seawall, including any areas underwater or with difficult access. These inspections should be carried out at intervals of between two and ten years, depending on the age of the structure and are carried out by qualified engineers
- Special Inspections: these investigations are carried out following specific events such as extreme events, floods, storms or when any other inspection indicates a cause for major concern.

Performance monitoring of a seawall should mainly focus on the assessment of the principal function of preventing or alleviating overtopping and flooding of the land and the structures behind the seawall due to storm surge and waves. This would typically be undertaken during large wave or high sea level conditions, and preferably when both combine.

5.3 Remote and Non-intrusive Monitoring Techniques of Seawalls

The following sections (Sections 5.3.1 to 5.3.14) provide a review of the different technologies which can be used to accurately monitor key structural parameters of existing seawalls including:

- seawall toe and crest levels
- seawall composition
- structural integrity of the seawall
- wave overtopping
- beach scour and bedrock levels
- watertable levels.

A summary of the reviewed monitoring techniques and range of applications is given in Table 5.

Table 5 Range of Applications for Reviewed Monitoring Techniques

Monitoring Technique	Water Table	Stability of the seawall	Seawall Crest levels	Sand level at toe of sea wall / Bedrock	Overtopping rate /heights	Composition / Structural integrity of the seawall	Buried Toe level
Aerial Photogrammetry	✗	✗	✓	✓	✗	✗	✗
Boreholes	✓	✓	✗	✗	✗	✗	✗
CCTV cameras	✗	✓	✓	✗	✓	✗	✗
Fibre optic deformations sensors	✗	✓	✗	✗	✗	✗	✗
RTK-GPS	✗	✓	✓	✗	✗	✗	✗
Ground Penetrating Radar	✓	✗	✗	✓	✗	✓	✓
Infrared thermography	✗	✗	✗	✗	✗	✓	✗
Jet Probe	✗	✗	✗	✓	✗	✗	✓
Parallel seismic	✗	✗	✗	✓	✗	✓	✓
Pressure sensors	✓	✗	✗	✗	✓	✗	✗
Side scan sonar	✗	✗	✗	✗	✗	✓	✗
Step wave gauges	✗	✗	✗	✗	✓	✗	✗
Tail-scour monitoring	✗	✗	✗	✓	✗	✗	✗
Ultraseismic	✗	✗	✗	✗	✗	✗	✓
Volumetric tanks	✗	✗	✗	✗	✓	✗	✗

5.3.1 Aerial Photogrammetry

Figure 10 Photogrammetry data for Queenscliff, with resulting shore-normal cross-sections
(Source: WRL)

Photogrammetry uses a pair of overlapping aerial photographs to create a stereo model of the ground surface. By referencing the model to ground control points, digital plan and height information can be extracted (Watson and Lord, 2001). The accuracy of data is limited by photo scale, lens distortion, glare and shadowing, survey quality control and changes in vegetation type and density (Evans and Hanslow, 1996). Prior to the 1970s, aerial photography was principally flown at high level and with less control on camera calibration. Evans and Hanslow (1996) estimated the accuracy of photogrammetry derived data as:

- data prior to 1960 at ± 1 to 1.5 m in the horizontal and ± 0.7 m in the vertical, and
- post-1960 at ± 0.5 m in the horizontal and ± 0.2 m in the vertical.

Photography prior to the mid-1970s was flown for other purposes (defence monitoring, broad scale mapping etc.) while vertical photography flown specifically for beach monitoring was broadly undertaken from the mid-1970s.

Elevation data in the form of shore-normal cross-sections can be derived and used to extract the location of contours of interest (seawall crest levels) and beach level above 0 m AHD.

5.3.2 Boreholes

Monitoring of the groundwater level behind a seawall is very important to assess the stability of the structure. While 'one-off' measurements offer the possibility to assess the typical groundwater level, it can be beneficial to equip boreholes with a pressure sensor and a data logger system and perform continuous monitoring over an extended period of time (Spencer et al., 2007). This enables both average groundwater conditions and the response to extreme events (e.g. coastal storms) to be determined. Previous studies performed at numerous NSW sites showed that while average groundwater levels were approximately at 0.5 m AHD, the elevation of the watertable could exceed nearshore wave setup level during extreme events (Carley et al., 2002).

Boreholes can also be used to install inclinometer/tiltometer sensors to enable continuous monitoring of ground movement, and therefore assess the stability of the ground behind the seawall (Huang & Liu, 2009). If predetermined movement tolerances are exceeded, the data logger can collect readings at higher frequency and trigger an alarm or initiate a telephone message or pager. These systems are self-contained, using mobile telephone communications and batteries charged by solar panels.

5.3.3 CCTV Camera

Detection and monitoring of wave runup and overtopping using CCTV pictures has been used in multiple projects worldwide (Tsujimori et al., 2000; Briganti et al., 2005; De Rouck et al., 2007). With such systems, wave overtopping of a seawall can be automatically detected through the analysis of image brightness (density or pixel colour intensity) and allow for the implementation of automatic warning systems. These systems can also allow qualitative analysis of the overtopping distribution and characteristics along the seawall (e.g., longitudinal variability, overtopping front width and falling distance), as well as monitor the stability of the structure and provide crest levels.

5.3.4 Fibre Optic Deformation Sensors (SOFO)

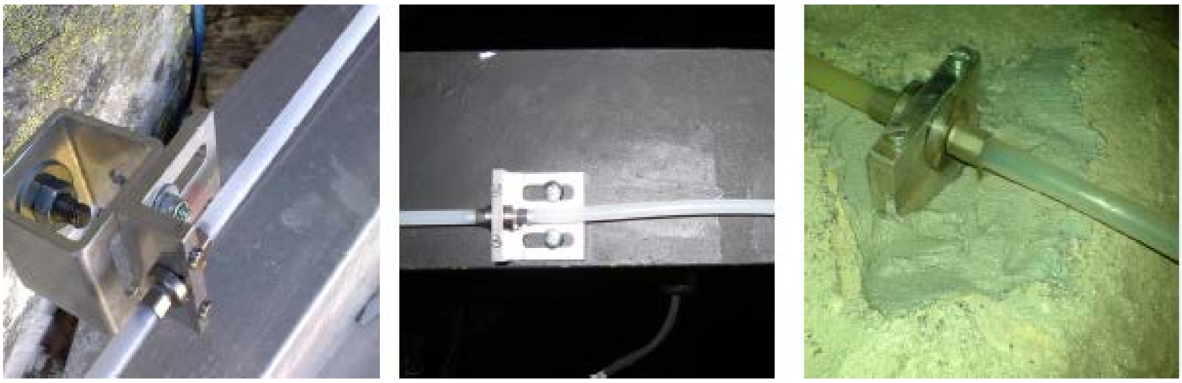


Figure 11 SOFO sensors mounted on different materials

SOFO (a French-based acronym) deformation sensors are transducers that transform a distance variation into a change in the path unbalance between two optical fibres, therefore allowing monitoring of any deformation of the structures they are mounted on. These sensors are specially designed to be embedded into concrete, but are also mountable on the surface of a structure.

These sensors have been used for short- and long-term monitoring of piers and breakwaters in Italy (Del Grosso et al., 2007), during a large maintenance and refurbishment program, allowing monitoring of safety and stability of the coastal structures during nearby dredging and strengthening operations. A precision of 2 µm was achieved within a temperature range of -10°C to 40°C. Further, it was demonstrated that the accuracy of the reading unit was stable for at least 1½ years, even in severe environments.

5.3.5 RTK-GPS (Stations/Surveys)

Monitoring of the stability of an old breakwater in Italy (Del Grosso et al., 2003) was performed through the installation of an array of RTK-GPS autonomous stations on the crest of the structure.

Figure 12 Fully equipped GPS measurement station on the breakwater

(Source: Del Grosso et al., 2003)

Each station had a GPS antenna and a solar panel for the power supply. Considering the particular environmental conditions (coastal environment, saltiness, strong stormy sea) the mobile stations have been protected with external housings fixed to the structure. The mobile stations had a direct electrical power supply to guarantee continuous monitoring. After 16 months of monitoring, measurements showed a strong correlation between the progress of works and the slow displacement of the structure.

Figure 13 Real Time Kinematic Differential GPS (RTK-GPS) mounted on a survey pole and a three-wheeled cart

(Source: WRL)

RTK-GPS surveys of seawalls can also be undertaken to acquire precise characteristics such as location, extent and crest level.

5.3.6 Ground Penetrating Radar

Ground Penetrating Radar (GPR) technology uses electromagnetic (EM) waves transmitted from an antenna which reflect off layers and objects in the ground. These reflections are received with the antenna and create a picture of the subsurface characteristics. As the transmitting and receiving antenna is moved along the surface, recordings are collected and displayed side by side, resulting in a cross-section, also known as radar profile.

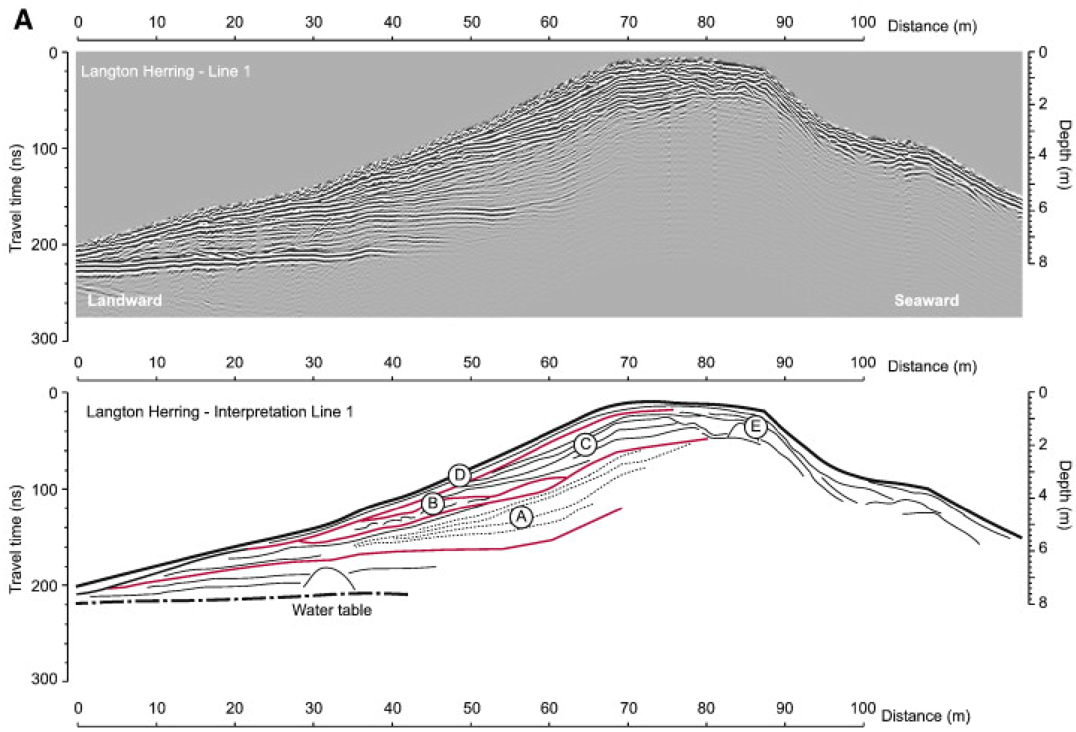


Figure 14 GPR survey and interpretation for Abbotsbury estimating the position of the watertable and bedrock levels

(Source: Bennet et al. 2009)

GPR can be used in a variety of media including rock, soil, ice, fresh water, concrete and pavements, and it can detect objects, voids, cracks and changes in material. One known limitation to use of GPR in the coastal area is the loss of signal quality due to change in conductivity in saline water-saturated media. However, recent studies (Bennet et al, 2009) have showed that these limitations can be overcome with the use of adequate antennas, and that clear identification of bedrock level, as well as watertable level, can be made.

Massengil (2001) showed that GPR can also be used on stepped concrete seawall panels as well as on sandstone vertical gravity seawalls (GBG, 2010) in order to investigate the structural integrity of the wall and the types and conditions of backfill material.

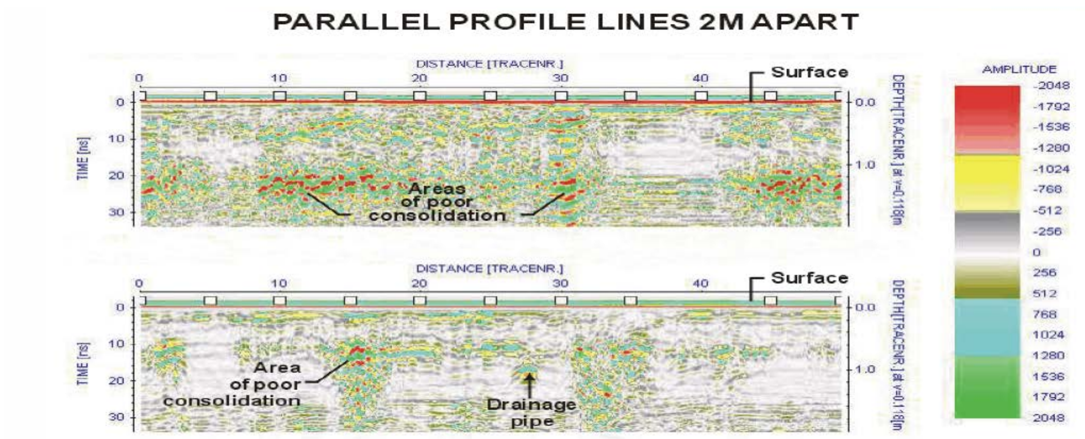


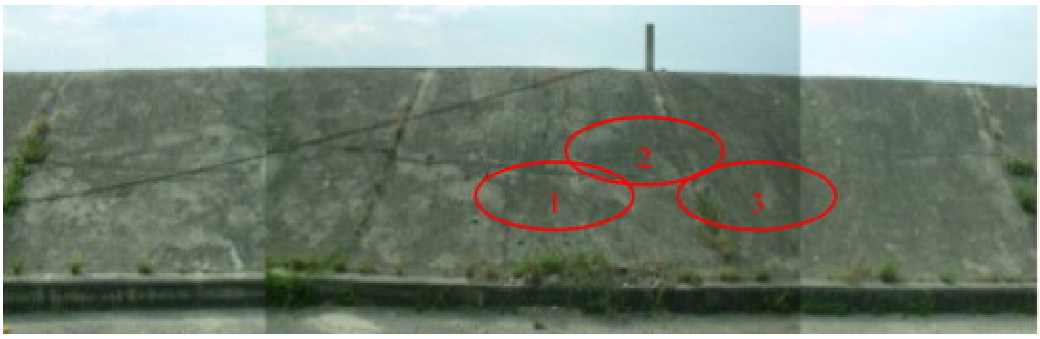
Figure 15 GPR survey from Sydney Harbour seawalls

(Source: GBG 2010)

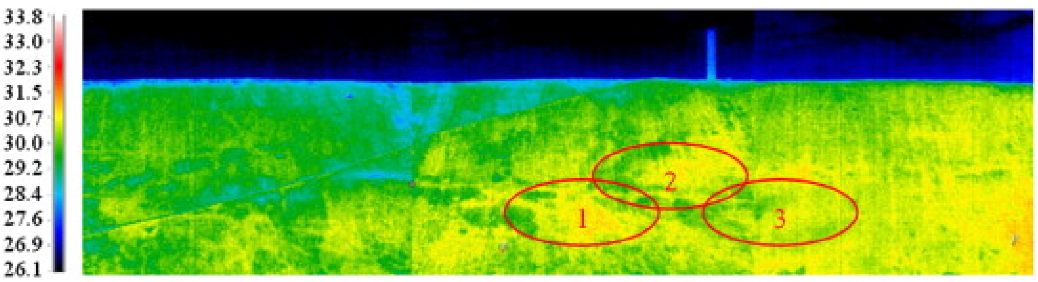
Finally, GPR has also previously been used to assist in the detection of the buried toe of old seawalls (Lord, 1999). While the results from the GPR survey were found to corroborate the results from test pits excavated at the same time, it was recommended that GPR survey be used in conjunction with more traditional survey techniques as a confirmation tool.

5.3.7 Infrared Thermography

Thermography is a non-destructive test method that involves infrared imaging. Thermographic cameras detect radiation in the infrared range of the electromagnetic spectrum and produce images of that radiation. This can allow the identification and localisation of inaccessible deteriorating components prior to failure.



(a) A photograph of the landward side of a seawall



(b) A thermography image of the landward side of a seawall

Figure 16 Thermography investigation at Cingcao seawall

(Source: Lee et al., 2009)

Infrared thermography has been successfully used to assess the conditions of fill material under stepped concrete seawall panels (Massengil, 2001) or for estimating the depth of eroded holes in a seawall (Lee et al., 2009), as can be observed on Figure 16.

5.3.8 Jet Probe

While technically not a non-intrusive sensing method, jet probe investigation can be used to provide useful information in regard to unknown buried toe level or the condition of the backfill material of an existing vertical seawall (Bray & Tatham, 1992), as well as provide information about the existence and position of bedrock. Jet probes are usually employed to investigate homogenous and relatively soft materials such as clay or fine sands, in order to perform reconnaissance surveys or the verification of geophysical survey data (i.e. location of bedrock). Typically, the jet probe is built from a small diameter pipe connected to a water pump. High pressure water is pumped out of the pipe to displace sediment as it is pushed into sandy substrate. A volume of sediment is washed out of the hole by water pressure (called 'outwash') allowing observations of buried sediment texture and composition. The probe stops penetrating when it contacts a boundary with bedrock (or the seawall). The probe length can typically be 3.0 to 5.0 m which would be suitable to assess typical toe levels. This system is relatively inexpensive but can be unreliable if refusal of the probe is caused by debris, or imprecise in the case of extending horizontal or stepped toe protection.

5.3.9 Parallel Seismic Survey

Parallel Seismic Survey (PSS) has been previously used to determine the depth of scour as well as depth of foundation at bridge pier and abutment.

PSS is based on analysis of seismic refraction waves generated in the bridge pile, by hitting it with an impact hammer. The refracted waves are recorded by a vertical array of hydrophones in an adjacent cased hole that has been inserted vertically into the subsurface.

This refraction-based method is especially efficient at measuring the thickness of the scour zone, even when filled with loose sand, as can happen after a tide cycle. The scour zone or loose sand acts as an acoustical muffler and strongly attenuates the seismic energy transmitted to each hydrophone when the refracted waves pass. The effect of this relative difference in seismic energy attenuation between the scour zone and the competent soil below the scour zone is quite striking, and the transition from transmission through the scour zone to transmission through competent soil is easily identified in the data. A simple extension of this technique allows the depth to the bottom of the foundation to be determined.

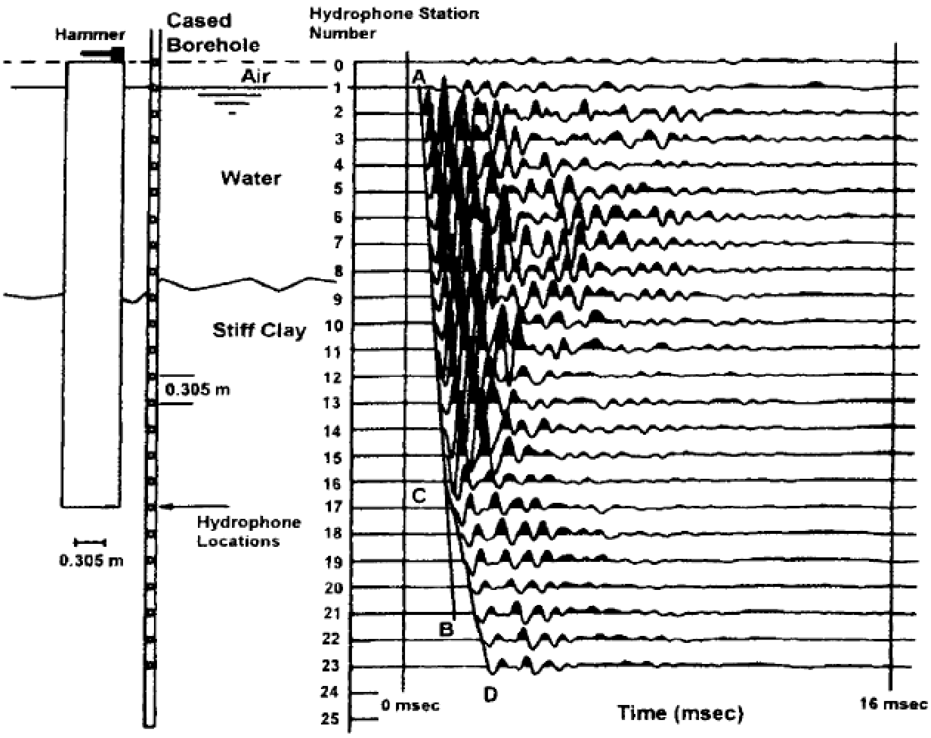


Figure 17 PSS survey. The linear refraction pattern changes at the base of the shaft

(Source: Mercado et al., 2003)

If the depth of the cased borehole is 3 to 5 m deeper than the maximum expected length of the pier (or seawall), then the resulting data also provide the depth of the pier toe. The extension is to record the seismic waves to a depth below the bottom of the pier where the refraction wave converts to a diffraction wave radiating from the bottom of the pier. Straightforward data analysis noting where the first break pattern changes from a straight-line refraction path to a hyperbolic diffraction path identifies the bottom of the pier. Field tests of the PSS technique have successfully detected both the thickness of a soil-filled scour hole and the length of a foundation (Olson et al., 1995; Mercado & O'Neill, 2003).

There is little information available to indicate how successful the PSS technique would be for concrete or stone blockwork, and care should be taken to ensure that the structure is not damaged during investigations. While this method is unlikely to accurately identify previous erosion at the toe of seawall structures, it should be adequate for identifying the toe elevation without requiring significant excavation.

5.3.10 Side-scan Sonar

Side-scan sonar is a commercially available acoustical tool for remotely acquiring a qualitative image of the sea bottom and submerged objects. The resultant image or sonograph provides a strip map of the area on either side of the towing vessel. The image characteristics, ease of interpretation and efficiency of operation result in side-scan sonar being an effective tool for the monitoring of coastal works.

Side-scan sonar can be used to image underwater components in zero visibility and in high velocity flow or where other conditions preclude the use of an optical-based system or diver inspection. This technique has been used extensively to monitor the conditions of seawalls and breakwaters (USACE, 2003).

In side-scan sonar systems, acoustic energy is projected laterally from a pair of transducers mounted in a towed cylindrical body or 'towfish'. Electrical energy, supplied through the electromechanical tow cable, is applied to the piezoelectric transducers in the towfish, causing them to vibrate and create sound waves which travel through the water. Sound is reflected from the seabed or structure, received by the same transducers and transmitted back up to the recorder.

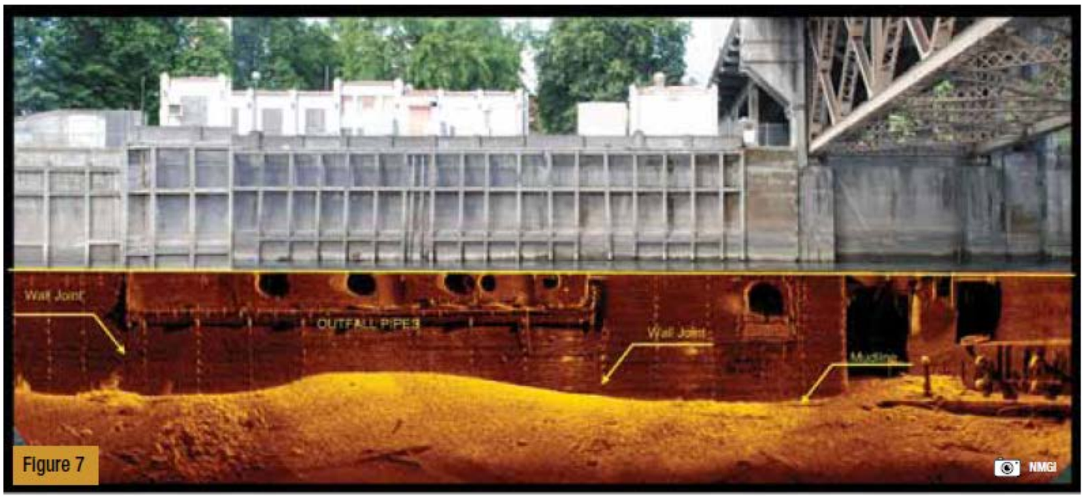


Figure 18 Structural evaluation using composite acoustic imaging techniques

(Source: Abbot 2011**)**

Nowadays, such technology can allow for plan view of the structure and the surrounding sea floor, a vertical view of the structure, and a profiling component allowing for quantitative measurements (scour hole volumes).

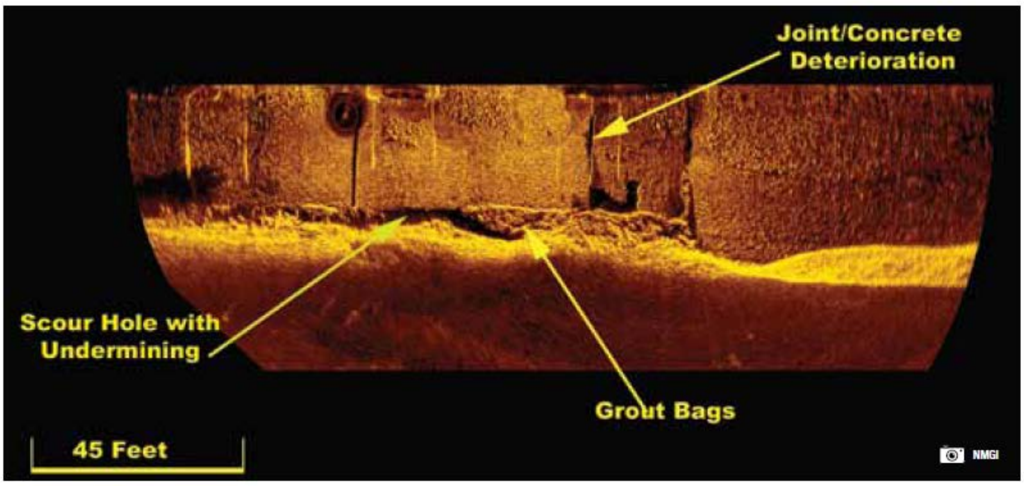


Figure 19 Vertical image of a seawall displaying various stages of structural deterioration

(Source: Abbot 2011**)**

5.3.11 Step Gauges

Step gauges are widely used to monitor or characterise overtopping in the field, as they are easy to install and operate. These instruments measure fluctuations in water surface levels. The step gauge usually consists of a series of electrical contact points (such as modified spark plugs) installed along a sealed pipe at regular intervals. The contact points are connected to a resistance circuit housed within the pipe and power is supplied to the step gauge through an AC voltage transformer. The sea level variation is then monitored by measuring the change in electrical resistivity. Step gauges have been used to monitor the wave runup (De Rouck et al., 2007) by being deployed as a 3D array along the seaward slope of a breakwater. In Japan, step gauges placed along the crest of a seawall have been successfully used, in conjunction with a CCTV camera, to detect dangerous wave overtopping and trigger alarms in order to automatically issue warning signals (Tsujimori et al., 2000).

5.3.12 Tell-Tail Scour Monitoring

Figure 20 Tell-Tail scour monitors at Southbourne

HR Wallingford has developed the 'Tell-Tail' scour monitoring system, which can be installed at new or existing structures and gives a clear indication of the depth of scour under all conditions (within its vertical range). The system records the onset of scour, the depth of scour reached, and infilling of scour holes following storm events. The system is based on a linear array of omni-directional motion sensors, buried in the sea bed adjacent to the structure. The sensors are mounted on flexible 'tails' and are connected via cable through protective conduit to a solid state data recorder. The scour monitors typically operate for two to three weeks before the data needs to be downloaded and the batteries replaced. Under normal conditions, the sensors remain buried and do not move. When a scour hole begins to develop, the sensors are progressively exposed and each begins to oscillate in the flow. Use of an eight level array of sensors provides a measurement of the depth of scour through a tide, thereby indicating if a scour hole has refilled.

Tell-Tail scour monitors have been deployed in front of numerous seawalls in the UK (Sutherland, 2007). In each case beach lowering and recovery during a tide has been detected that could not have been picked up by successive beach profiles measured at low tide.

5.3.13 Ultraseismic

Ultraseismic (US) systems are designed to determine the length and integrity of foundations when the upper portion of the structure is accessible or when other tests have led to inconclusive results. US investigations have been successfully undertaken on shallow wall-shaped substructures such as an abutment or a wall pier of a bridge (Olson et al., 1995). The Ultraseismic method is a sonic reflection technique that uses geophysical digital data processing techniques to analyse the propagation of induced compressional and flexural waves as they reflect from foundation substructure boundaries (impedance changes). The method is particularly useful when there are relatively large exposed areas available for mounting instrumentation such as in the case of vertical concrete or masonry seawalls.

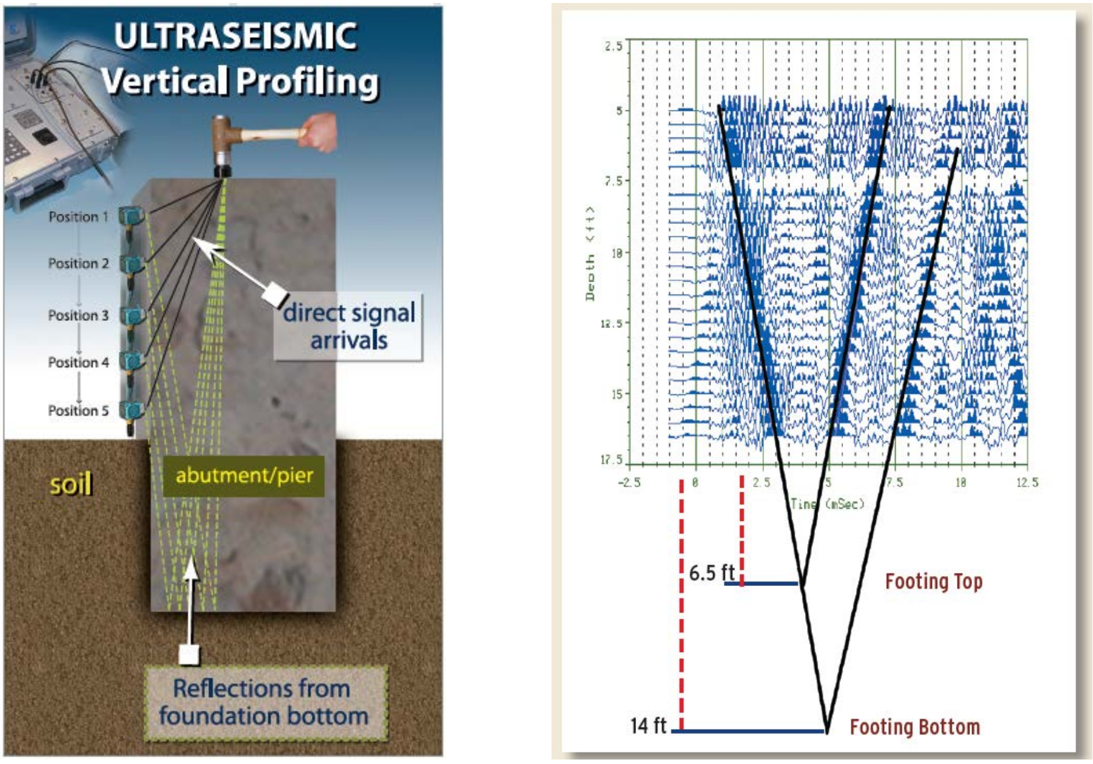


Figure 21 Ultraseismic vertical profiling method. The plot shows several clear breaks, as depicted by the solid black lines

(Source: Olson Engineering)

The US method is typically performed by mounting a receiver on the upper portion of a foundation or wall and then striking the substructure with an instrumented hammer. The US method requires at least 1 to 2 m of the structure to be exposed for receiver attachments, as the larger the exposed area the greater the definition of the reflected events.

5.3.14 Volumetric Tank

The importance of wave overtopping at a seawall can be assessed by installing volumetric overtopping tanks on the seawall crest (Franco et al., 2009; Pullen et al., 2009) . Typically, the equipment includes a steel overtopping tank (Figure 22), suitable for collecting individual overtopping volumes. The water level in the tank can be directly inferred and recorded from measurements of pressure sensors installed on the bottom of the tank. Overtopping events produce a sudden increase in the water level inside the tank; given the area of the collecting tank, it is possible to know the volume of each overtopping event.

Figure 22 Two overtopping tanks on the crest of vertical seawall

(Source: Pullen et al., 2009)

When designing the tanks, consideration has to be given to the estimated volume and frequency of overtopping in order to have sufficient volumetric capacity as well as a suitable capacity for the water to flow out, in between overtopping events, without interfering with the quality of the data recorded.

5.4 Maintenance and Rehabilitations Methods of Seawalls

The selection of maintenance solution for a seawall is highly dependent on the type of structure as well as the use, or the environmental conditions it is subjected to (open coast or estuarine). This section aims to provide a brief list of technical solutions that have been successfully used in order to prevent failure or repair damage. For more details on the following methods and examples of precise applications, the reader is referred to Bray (1992), which extensively covers repair and rehabilitation case studies across the UK.

5.4.1 Modifying Loads on the Seawall

Where a wall has been overloaded or is at risk of exposure to conditions exceeding the design criteria, it may be possible to reduce the loading by modifying the immediate surrounding environmental conditions. Typical possibilities include the following:

- reducing the level of ground behind the wall
- reducing the depth of water available in front of the wall (rock berm)
- modification of the wave conditions (offshore breakwater, beach nourishment).

Where a wall has an inadequate factor of safety against overturning or sliding, one solution is to reduce the pore water pressure or active earth pressure on the back of the wall by modifying the backfill. Such works include the following:

- excavating the fill behind the wall and replacing it with a reinforced earth structure, or with cement
- grouting up the backfill to reduce the active pressure on the wall
- reinforcement of the backfill through the use of stone columns, polyurethane injection, etc.
- improving drainage of backfill material.

Where the main cause of wall distress is the surcharge applied to the backfill, one solution is to carry the loads on the slab not supported on the filling. Possible methods are the following:

- concrete surface slab supported partially on the wall and bored piles behind the wall
- concrete surface slab fully supported on bored piles behind the wall.

5.4.2 Remedial Works to the Seawall Toe

Repairs to the toe of quay walls or harbour seawalls typically have to be carried out underwater and the following methods of repair can be considered:

- grout-filled bags
- tremie concrete
- injected grouted aggregate
- geotextile sand containers
- cut off sheet piles at the toe (e.g. steel piles driven or vibrated, concrete or vinyl sheet piles potted, jetted or vibrated).

Prior to considering repair strategies for the toe of an open coast seawall, the possibility of changing the conditions which cause erosion should be considered. If the erosion is caused by wave reflection from the wall, changes to the slope of the wall or the installation of protection material should be considered. Such works include the following:

- changing conditions which caused erosion (installation of groynes or offshore breakwater, beach nourishment)
- installation of rubble toe protection
- concrete or tremie concrete
- gabions
- concrete mattresses
- geotextile sand containers.

5.4.3 Increasing Seawall Stability

Where the soil mass under, behind or in front of the wall has an inadequate factor of safety against a deep slip failure, it may be possible to improve the stability of the wall by placing rock on the toe as a counterweight. Ground and rock anchors have been successfully used to increase the resistance of seawalls to slide or overturn. Finally, piling through the wall can improve the bearing strength of the wall. Typical possibilities include the following:

- rock placed in front of wall
- ground and rock anchors
- piling.

5.4.4 Repair of the Wall Structure

Where a masonry wall has been damaged above the water, the damaged area should be cleaned (water pressure jet), sometimes enlarged, and repaired using concrete. Grouting of the wall can be carried out to improve the wall integrity, by bonding together individual stones, as well as to reduce the permeability of the wall. It is possible to use pressure pointing to repair and seal cracks. Various masonry techniques exist to ensure that individual stones in the wall act together as one coherent structure, and if conventional masonry techniques are not sufficient, it may be necessary to tie the wall with stainless steel rods. Where individual stones have decayed or fallen out, it is important to initially repair the body of the wall, by grouting or adding a concrete backing, before undertaking any masonry work. If degradation to the wall facing is considerable, the most efficient solution may be to replace the complete face with a complete new rock face.

The protection of the upper surface of revetments is of utmost importance to avoid erosion of the backfill material and reduce overtopping. Concrete or asphalt are typical solutions to avoid this problem, unless visual appearance is of significant importance. A list of the typical methods for repairing seawalls is provide below:

- patching of the wall structure above or below water
- grouting of wall structure
- crack and joint sealers
- masonry bonding, stitching, dowelling and wedging
- replacement of stone
- additional skin of masonry stone
- protection of the top surface or backfill
- sprayed concrete.

5.4.5 Replacement of Seawall by a New Structure

Where the existing wall is beyond repair, the structure can be replaced, completely refaced or reconstructed. If ground conditions are suitable and the appearance of the wall is not important, one solution is to drive sheet piles in front of the wall and use ground anchors to secure the top of the wall. The space between the sheet piles and the original wall is then typically filled with concrete. An alternative solution to the previous method is to place a vertical concrete wall in front of the original structure. If the front appearance of the seawall is important, but its structure is beyond repair, the outside face of the wall can be retained or simulated by a replica, but with the soil loads carried by a new wall behind. Typical possibilities include the following:

- sheet piles placed in front of old seawall with the cavity between wall layers then filled by concrete (if appearance of the original wall is not important)
- vertical concrete seawall placed in front of old structure(if appearance of the original wall is not important)
- retain the outside face of the original wall and build a new wall behind (if appearance of the original wall is important).

5.5 Asset Management Plan and Register for Seawalls

Asset Management Plan (AMP) and Asset Register systems are critical tools for managing local government assets and infrastructure such as seawalls.

An Asset Management Plan is defined by the International Infrastructure Management Manual (2011) as *a plan developed for the management of one or more infrastructure assets that combines multi-disciplinary management techniques (including technical & financial) over the life cycle of the asset in the most cost effective manner to provide a specific level of service.*

A dedicated Seawall Asset Management Plan, as part of the Integrated Reporting Framework, has the potential to:

- satisfy the requirement for councils to provide an inventory of managed assets (LGA, 1993)
- ensure that maintenance and capital work programs are adequately funded to maintain appropriate conditions and safety of seawalls
- assist in prediction of future issues and needs, as well as to establish strategies to overcome identified problems
- assist in the evaluation of coastal hazards and the establishment of a Coastal Zone Management Plan (DECCW, 2010).

An AMP typically covers the following areas:

- Asset System Description : this defines the objectives of the AMP, such as developing effective management strategies, improving the efficiency of maintenance actions, assisting in the establishment of risk management strategies
- Standard of Service Definition : this describes how the asset is intended to perform (i.e. maximum allowed overtopping rate, safety rate) as well as minimum condition grade

- Current Asset Performance : typically is a list of all existing assets, with unique identifiers, including ages, estimated remaining life, current condition, current safety issues
- Past and Planned Actions: this reviews recent and past inspection surveys and what actions are planned to ensure that the seawalls are above the minimum required condition grade and satisfy the Standard of Service requirements
- Costs : this section usually provides an estimation of past and short-, medium- and long-term costs for maintaining or repairing the seawalls in order to maintain the Standard of Service.

As a minimum, it is recommended that seawalls be included on the AMP of councils with the following key pieces of information:

- location
- elevation of key parameters (toe and crest levels)
- construction type/description
- grade or rating of overtopping risk
- grade or rating of stability risk
- last and next monitoring inspection.

6. CONCLUSIONS

The Water Research Laboratory of the University of New South Wales was engaged by the Sydney Coastal Councils Group to compile a literature review providing a sound background and reference list of published information related to the assessment of existing seawalls and their adaptation to climate change.

Seawalls (and revetments) are generally parallel to the shore and can be classified as sloping-front or vertical-front structures. Sloping-front structures can be constructed as flexible rubble mound structures which are able to adjust to some toe and crest erosion, or as rigid structures which have a fixed form and location. They can be built from either randomly placed armour (rock or concrete units), with pattern-placed concrete armour units, reinforced concrete, geotextile containers or gabion baskets. Vertical-front seawalls are usually composed of stone or concrete blocks, mass or reinforced concrete, or steel sheet piles. Such vertical structures can either be built as tied-in, gravity or cantilever walls (see Figure 2). Vertical seawalls also typically act as retaining walls to material located behind.

Adaptation to climate change aims to reduce the risks associated with future changes in climate. However, it additionally seeks to harness beneficial opportunities that may arise under a changed future climate system. Adaptation is a mechanism to manage risks and adjust economic activity to reduce vulnerability. In regard to existing infrastructure such as seawalls, the recommended adaptation action by local government can be summarised as:

- monitor any changes to the condition in structures so that any modifications/retrofitting occurs on time and prior to failure
- identify alternative options should the existing infrastructure be impacted upon in order to maintain services and connections, e.g. to minimise isolation of communities during an adverse storm event that puts the infrastructure at higher risk
- design retrofitting to a higher standard than the minimum required where possible and practical
- progressively incorporate higher design standards into asset management plans and rolling capital works programs.

Generally mean sea level increase, wind climate change and wave climate change are the major concerns for coastal defence structures due to climate change.

In regard to small seawalls, the main impacts of climate change are described in Section 4.2, and will result in:

- increased wave loading
- increased overtopping and flooding of the seawall (erosion of the backfill), and
- increased scouring at the toe of the seawall.

The main forcing parameters on a seawall can be separated into the hydraulic responses of the waves and the structural response of the seawall, and are described in Section 3.3. There are three main hydraulic responses which need to be considered for the design of a seawall: wave runup level;

wave overtopping; and wave reflection. When designing a seawall, or planning seawall adaptation, it is important to accurately assess the various loads and the related stresses, deformations and stability conditions of the different structural parts of the seawall. For vertical-front structures, the main loads and structural responses to determine include the wave forces exerted on the wall, as well as the forces applied by the backfill soil and pore water. The main geotechnical aspects to verify when designing a seawall are the assurance of safety against soil failure (slip circle failure) as well as assurance of limited settlement in the foundation soils.

The main failure modes of seawalls are reviewed in Section 3.4 and can be detailed as:

- undermining, in which the sand or rubble toe level drop below the footing of the wall, causing the wall to subside and collapse in the hole
- sliding, in which the wall topples away from the retained profile
- overturning, in which the wall topples over
- slip circle failure, in which the entire embankment fails
- loss of structural integrity, due to wave impact
- erosion of the backfill, caused by wave overtopping, high watertable levels, or leaching through the seawall
- outflanking.

The failure modes described above are mainly caused by three types of coastal hazards, described in Section 3.5, and listed below:

- erosion of sand in front of the seawall during storm events
- wave overtopping (inundation) of the seawall due to elevated water levels and large wave conditions, and
- wave impacts.

Two main approaches applicable to the adaptation of seawalls to climate change are reviewed in Section 4.4. One approach is to consider the complete sea level rise expected to occur over the life of the structure in the initial design of the adaptation plan, and is referred to as the Precautionary Approach. A more favoured approach nowadays, referred to as Managed Approach, allows for staged adaptation in the future, and is appropriate in the majority of cases where ongoing responsibility can be assigned to track the change in risk, and manage this through multiple interventions.

Seawall monitoring can typically be divided between condition monitoring and performance monitoring. Condition monitoring is the basis for the implementation of a successful preventive maintenance program. Seawall condition monitoring should involve at least visual inspection of the structure, and in some cases the inspection is augmented with measurements meant to quantify the current structure condition relative to the baseline condition. Performance monitoring of seawalls should mainly focus on the assessment of the principal function of preventing or alleviating overtopping and flooding of the land and the structures behind the seawall due to storm surge and waves.

Section 5.3 provides a review of 15 different technologies which can be applicable for monitoring and to accurately characterise key structural parameters of seawalls including:

- seawall toe and crest levels
- seawall composition
- structural integrity of the seawall
- wave overtopping
- beach scour and bedrock levels
- watertable levels.

The type of maintenance solutions for a seawall is highly dependent on the type of structure, as well as the use or the environmental conditions it is subjected to (open coast or estuarine). A review of the main types of repair/rehabilitations works, listed below, is provided in Section 5.4.

- modifying loads on the seawall
- remedial works to the seawall toe
- increasing seawall stability
- repair of the wall structure
- replacement of the seawall by a new structure.

7. REFERENCES

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Sydney Coastal Councils Group Inc.

councils caring for the coastal environment

Level 14, Town Hall House

456 Kent Street

GPO Box 1591

SYDNEY NSW 2001

t: +61 2 9246 7326

f: +61 2 9265 9660

e: info@sydneycoastalcouncils.com.au

w: www.sydneycoastalcouncils.com.au.com.au