GEOTECHNICAL ASPECTS OF SEAWALL STABILITY WITH CLIMATE CHANGE

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Introduction

Existing seawalls and protection structures exist at many locations around the Australian coast where construction details are unknown and the capacity of the structures to withstand storms has not been verified. Seawall asset owners and managers (usually Local Councils) are faced with determining development applications in areas protected by such structures. Often, the responsibility, ownership and liability arising from these structures are not clear, with many structures constructed entirely or in part on Public Land. Frequently, there is conflict between the coastal managers and the community who have varying impressions of their effectiveness in providing protection and their impact on the public beach.

This project has developed methods whereby the efficacy of existing seawalls may be determined. The project was undertaken by the Sydney Coastal Councils Group (SCCG) with funding provided by the Commonwealth Department of Climate Change and Energy Efficiency (DCCEE) through a Climate Adaptation Pathways (CAP) grant. The project was overseen by a National Reference Group comprising expertise from local government, state government, universities with coastal management expertise and industry specialists.

Key elements of the project were as follows:

- Literature review of existing seawall types, remote sensing techniques, options for upgrading, certification requirements - Water Research Laboratory (WRL), University of NSW (UNSW).
- Geotechnical assessment of structure types and common failure modes - WorleyParsons.
- Economic aspects of the decision making process - Bond University under the direction of the Centre for Coastal Management (CCM) at Griffith University (GU).
- Field assessment utilised Ground Penetrating radar and air jetting to gain information on the structure of a buried seawall without disturbing the overlying dune and vegetation - UNSW.
- Three case studies: an open coast seawall at Bilgola, an estuary seawall at Clontarf (WRL UNSW) and the current Gold Coast seawall (CCM GU).

This paper presents the detailed analysis undertaken as one aspect of the project, specifically dealing with the geotechnical issues relating to these seawalls. It documents geotechnical factors relating to seawall stability with emphasis on climate change impacts, particularly rising sea level, to identify:

- Key indicators for an appropriate and inappropriate structure
- Key data that may be collected and added to an asset management system over time

The emphasis is on:

- Describing the function of a seawall/revetment
- Identifying primary failure modes and risks
- Identifying geotechnical issues of stability and how these may change with climate change.

A pro forma checklist has been developed that may be used to assist in identifying where a structure is of concern and more detailed professional advice is required.

The Function and Types of Seawalls

Preamble

A seawall is a shoreline structure built to delineate the boundary between the land and sea, to retain the ground landward of the structure, to protect a stable slope from wave or current erosion or from wave inundation.

There are many types of seawalls depending upon their site-specific purpose. They can be massive or lightweight, rigid or flexible, vertical or sloping. Seawalls may comprise a wide range of materials including concrete, steel, timber, plastic, rock, stone-filled wire baskets and sand-filled geotextile bags.

Seawalls are located in a harsh environment being subjected to severe, dynamic and repeated loading from breaking waves, the relentless rise and fall of the tide and the corrosive nature of seawater and salt spray. The loadings for which seawalls must be designed are difficult to define, being somewhat random in nature and, often, exceeded over the designed lifetime of the structure. Invariably, seawalls must be designed with maintenance in mind and with particular consideration given to the robustness of their fabric.

The geotechnical aspects relating to the stability of each type of seawall may vary; for example, mass gravity vertical structures will behave quite differently, in a geotechnical sense, from flexible sloping structures.

Various types of seawalls and their principal modes of failure are described in the following.

Bulkhead Walls

Bulkhead walls are relatively thin vertical structures driven into the seabed. Usually, bulkheads are installed to establish and maintain elevated grades along shorelines in relatively sheltered areas not subjected to appreciable wave attack and are used commonly as a berthing facility. They serve the dual purpose of a retaining structure and limiting the landward extent of wave erosion. They rely on the depth of penetration into the soil substrata for stability against horizontal loads. If the walls are relatively high they may be supported against horizontal loads also with tiebacks (anchored bulkheads).

Anchored Bulkhead Walls

Anchored bulkheads are used in ports where, commonly, they comprise heavy steel sections. However, much lighter steel, timber, vinyl and fibre reinforced plastic sections are found often around estuary foreshores. This type of wall can be used in newly reclaimed land or open areas where the installation of tie rods is not limited by site constraints. The loading on an anchored bulkhead wall is depicted on the schema in Figure 1.

Free-Standing Bulkhead Walls

Where the retained height is small, bulkhead walls can be free standing without anchoring tiebacks. Free-standing bulkhead walls are used also in areas restricted by landward constraints, such as trees. In areas with geotechnical constraints such as soft soils, bulkhead walls can gain support by deeper toe penetration rather than significant increase in width and footprint. Ideally, the backfill comprises free draining material such as rock-fill. If the backfill is sand or soil then care must be taken to ensure that there is no leakage of the backfill through the interstices of the wall structure, which could result in the loss of the retained material and the formation of dangerous sinkholes behind the wall.

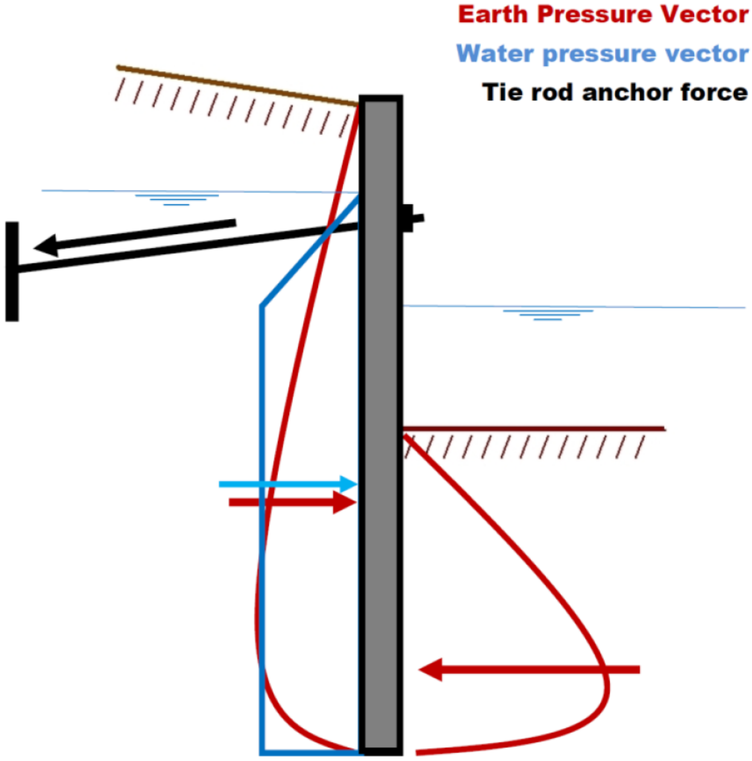

Figure 1 Earth pressure and hydrostatic loading schema for an anchored bulkhead

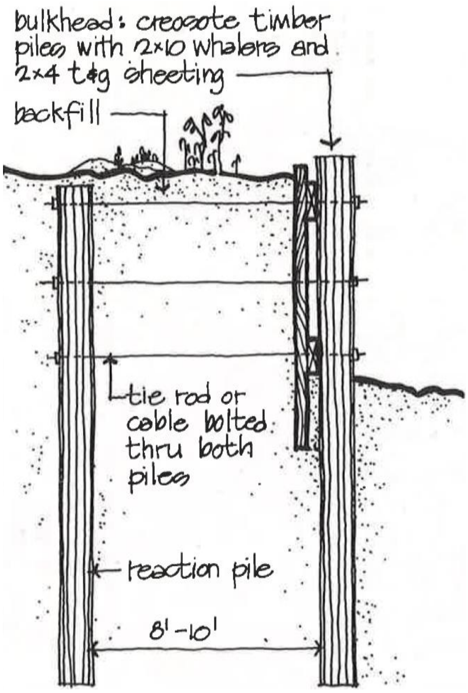

Figure 2: Anchored bulkhead wall
Left: Sand-fill anchored timber bulkhead wall schema (source: Dames & Moore 1980)
Right: Anchored Vinyl bulkhead wall (source: JSTEEL Australasia)

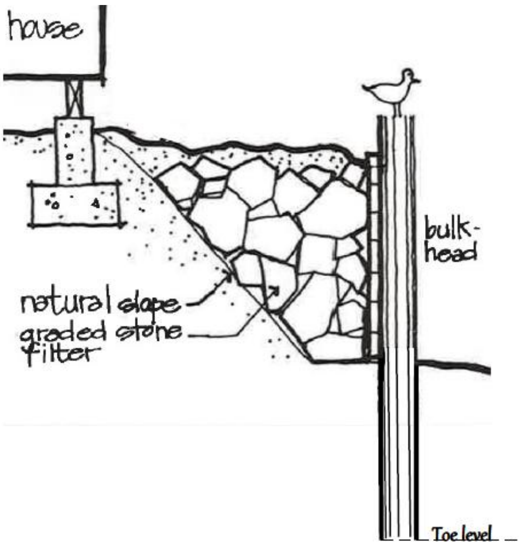

Figure 3: Free-standing bulkhead wall
Left: Free-standing rock-fill timber bulkhead wall schema (source: Dames & Moore 1980)
Right: Free-standing timber Log bulkhead wall (Source: Deborah Lam**)**

Rigid Near-Vertical Concrete and Blockwork Gravity Structures

Concrete and blockwork gravity walls are common as promenades on major beaches, such as Bondi Beach in Sydney. Their small footprint (compared with a sloping seawall) maximises the space available landward and seaward of the structure.

The loading on an gravity wall is depicted on the schema in Figure 4.

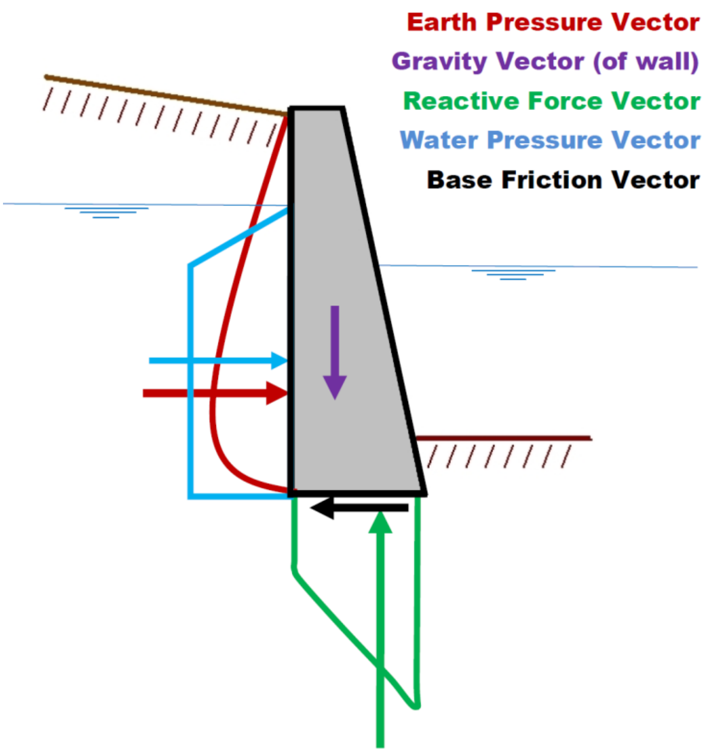

Figure 4 Earth pressure and hydrostatic loading schema for a gravity wall

Sandstone block walls are common around harbours and can be used for aesthetic and heritage reasons to match nearby sandstone block heritage buildings. There can be restrictions in the upgrade of existing sandstone block walls. For example, the Sydney Harbour Foreshores and Waterways Area Development Control Plan requires extension and upgrade of existing sandstone seawalls to have similar sandstone courses to match existing seawalls. These requirements may vary by location and, largely, are architectural detail rather than relating to the function of the upgraded seawall structure.

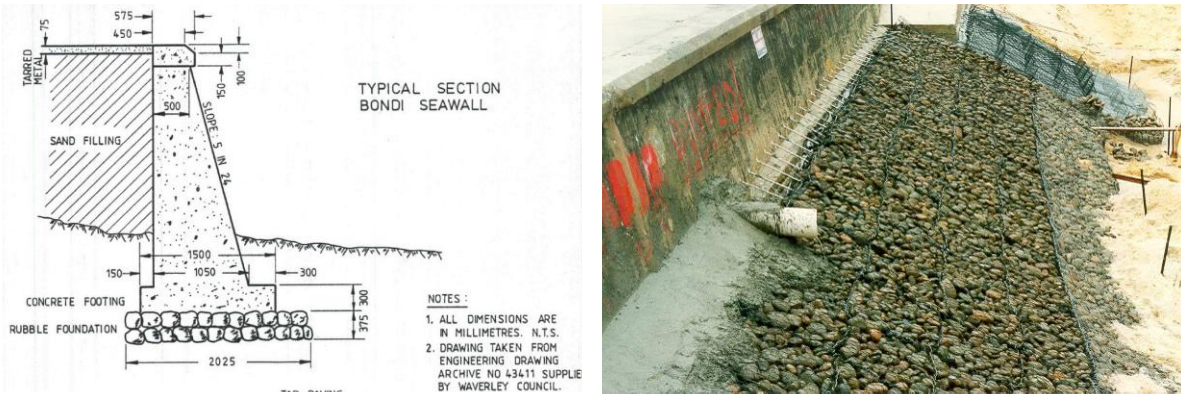

Figure 5: Mass gravity seawall Left: Historical design drawings of Bondi and Bronte seawalls (Source: PWD, 1988) **Right: Bondi seawall with Reno-mattress toe protection being installed** (Source: Lex Nielsen)

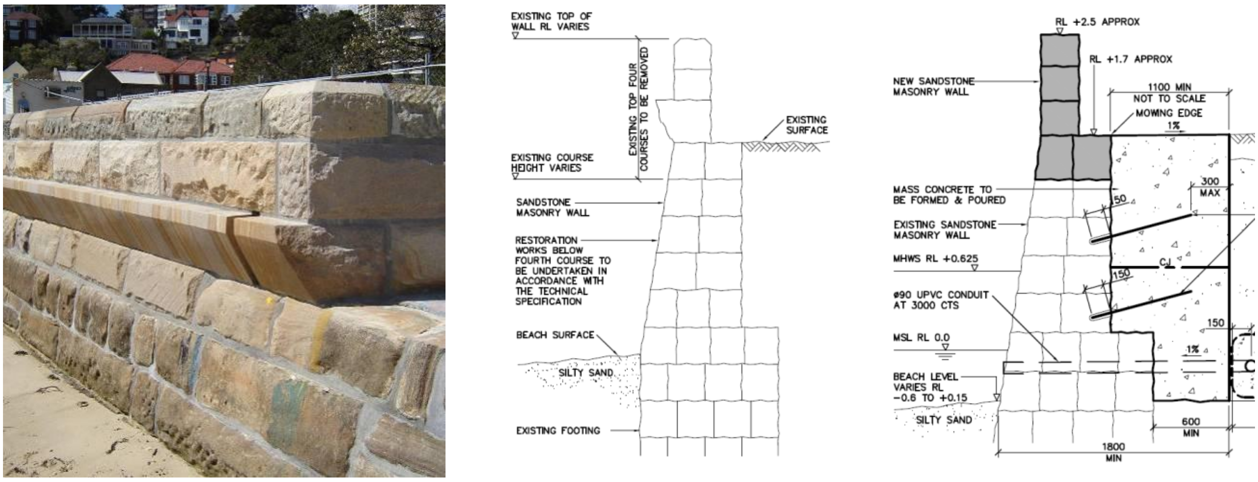

Figure 6: Blockwork gravity seawall Left: Sandstone blockwork seawall; Centre: Original design; Right: Remedial design (Source Woollahra Council)

Rigid Sloping Revetments

Rigid sloping revetments are popular on promenades, especially where there is very heavy pedestrian traffic, such as on main tourist beaches. The facing can be a concrete slab or interlocked bricks, concrete or rock blocks. These revetments have the advantage of being relatively thin, comprising components that can be transported readily to site. Stairs can be incorporated into sloping revetments with minimal protrusion seaward and landward of the revetment, allowing unobstructed access along pathways and foreshore. However, generally they are unable to accommodate settlement or adjustment of the underlying materials.

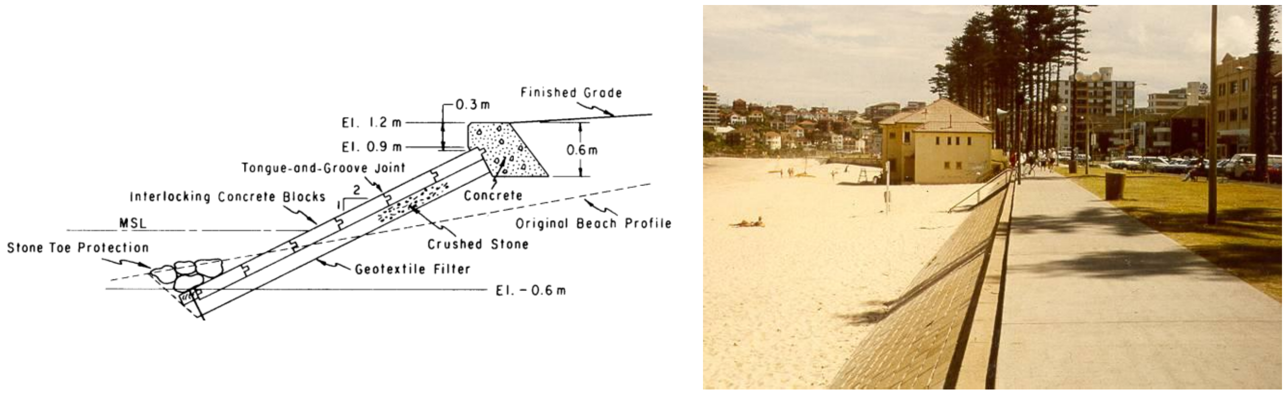

Figure 7: Rigid sloping revetment Left: Typical design for an interlocking concrete slab revetment (source USACE 2011)**; Right: Promenade and seawall**

Semi-Rigid Sloping Pattern-Placed Unit Revetments

Sloping revetments can be classified also as semi-rigid where they comprise units that can tolerate some movement or displacement without total collapse. Pattern-placed unit revetment can dissipate wave energy at the back of beaches and along the foreshore. Pattern-placed units, such as Seabees (Figure 8), can be more stable than randomly placed units, such as rock or concrete cubes, which can result in the use of lighter individual units and, hence, smaller volumes. These revetments can be useful where site constraints limit the use of randomly placed units or where architectural preference is for a regular smooth finished appearance. The size of the armour unit depends on the adopted design conditions and smaller scale versions of the Seabee revetment can be found in front of residential development (Figure 8 right).

Figure 8: Semi-rigid sloping pattern-placed unit (Seabee) revetments Top left: Seabee seawall Prince Street Cronulla; Top right: Small scale Seabee revetment on Wamberal Beach in the Gosford Shire (source Lex Nielsen)**; Bottom: Typical section of original Prince Street Seabee seawall prior to recent upgrade** (Source SSC 1984)

Flexible Near-Vertical Mass Gravity Seawall

Flexible near-vertical mass gravity structures can comprise various materials including sandbags, rock boulders and gabion units. These near-vertical mass gravity structures have a smaller footprint than sloping structures and can be effective in reducing the encroachment of a seawall structure into a waterway, particularly in low wave energy environments.

Figure 9: Sandbag gravity seawall (source: Geofabrics Australasia)

Figure 10: Flexible near-vertical mass gravity seawall Left: Rock boulder gravity seawall (Source Deborah Lam)**; Right: Gabion gravity seawall** (Source Deborah Lam)

Flexible Sloping Rock Rubble Revetments

Flexible sloping rock rubble revetments can be designed for a variety of coastal environments from low to high wave energy. Rock rubble revetments can comprise armour layers, underlayers, filter layers (including geotextiles) and a core. The design of rock rubble revetments will be controlled by the size, shape and quality of rock available from nearby quarries. Flexible revetments often can tolerate a significant degree of displacement and shifting. Typically, the design conditions permit the movement of some 10% of the armour units and 2% damage during the design event.

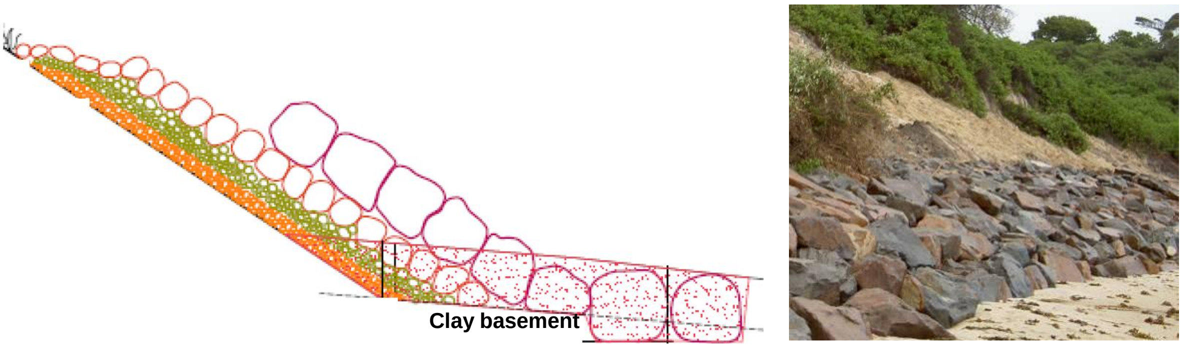

Figure 11: Rock rubble revetment Left: idealised design section (Source Wyong Shire Council)**;**
Right: As built (Source Lex Nielsen)

Flexible Sloping Sandbag Revetments

Sloping sandbag revetments are being used increasingly for revetments on beachfronts. It is a developing technology and guidelines for their design and construction are provided by the geotextile manufacturers. Generally, the service life of sandbag revetments is limited as they are prone to damage by vandalism.

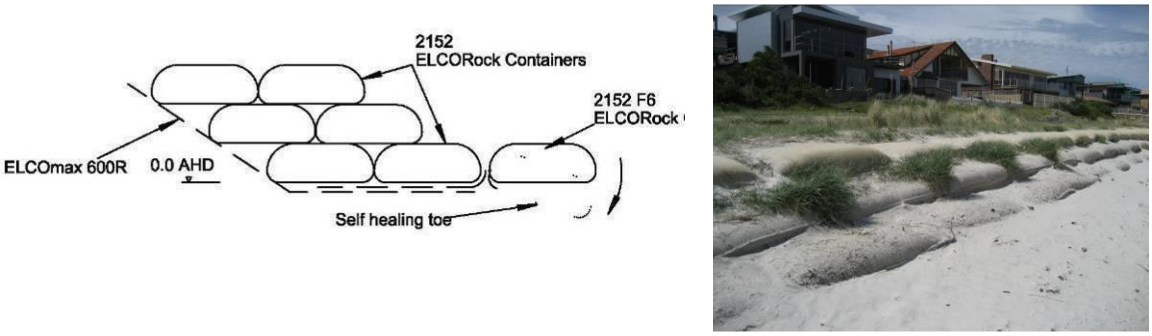

Figure 12: Sandbag revetment (source: Geofabrics Australasia)

Flexible Sloping Rock Mattress Revetments

Flexible sloping rock mattress revetments consist of woven mesh units that are connected together and filled with rock. They are used, commonly, in the rehabilitation and protection of riverine environments and have been used also in beachfront environments, for example, at Bondi (see Figure 5) and Wollongong (Figure 13). The wire fabric is susceptible to damage, vandalism and corrosion.

Figure 13: Sloping Reno-mattress dune revetment under construction
(Source: NSW Gov., 1990)

Environmentally Friendly Seawalls

Environmentally friendly seawalls aim to comprise low slope grades with a variety of different habitats including hard and soft substrates (DECC & SMCMA, 2009). Structures located in low wave energy environments and in areas with few site constraints are able to incorporate more environmentally friendly principles. Examples of environmentally friendly elements such as low slope grades, vegetative benches and boulders at the toe of a seawall generally improve the stability of seawalls. Generally, these seawalls are more expensive to construct.

Near-vertical seawalls can also incorporate environmentally friendly elements as outlined below:

- Cavities or pools that retain water
- No cement between blocks to provide crevices
- Using rough or textural surfaces
- Addition of boulders at the toe.

Figure 14: Environmentally friendly seawalls Left: Step-type seawall with saltmarsh (Source WorleyParsons) **Right: Estuary bank protection** (Source WorleyParsons)

Geotechnical Failure Modes

Introduction

Geotechnical failures of seawalls occur when the applied loadings comprising earth pressure, hydrostatic pressure and surface loading combine to be greater than the stabilising forces of seawall weight, resisting earth pressure forces and any anchor loads, or when the soil strength and/or stiffness is insufficient to resist the imposed loads within acceptable strains with the Factor of Safety falling below 1.0.

Failures can be a total collapse of a structure or its excessive deformation. Geotechnical failures can result in the redistribution of the imposed loads to other portions of the structure, often with unacceptable deformation. Typical geotechnical failure modes for seawalls are described in Table 1 and are discussed in the following, based on the type of the seawall.

Table 1: TYPICAL SEAWALL GEOTECHNICAL FAILURE MODES

FAILURE MODE	DESCRIPTION	SITE OBSERVATION
Overall / global stability.	A slip failure that extends behind and below the wall.	• Excessive settlement of retained material behind the wall. • Material near the toe is bulging out. • Seawall is tilted landward.
Bearing failure.	Excessive settlement involving some rotation due to high foundation load or softening of the ground.	• Excessive settlement on the wall. • Seawall is rotating. • Material at the toe is bulging out. • Cracking of rigid structures.
Overturning failure.	Rotation of the wall about its toe.	• Seawall is titled seaward. • Gaps between the wall and the retained material are observed.
Sliding at the base and or between wall elements.	Excessive lateral movement of the wall away from the retained material.	• Excessive lateral movement of the wall. • Gaps between the wall and the retained material are observed. • Dislodgement of blocks or armour units.
Toe erosion / scour.	Removal of embedment material or seabed due to wave action.	• The front or underside of the toe is exposed from its embedment, possibly with some slumping or collapse. • The rock armour on the toe has been displaced or buried.
Internal erosion.	Wash out of fine material causing cavities within the soil.	• Localised cavities, sinkholes, and collapse of the material behind the wall.
Overtopping / overwash scour.	Wash out of material behind the wall due to insufficient wall height against tide and wave action.	• Surface erosion on the material behind the wall. • Localised cavities, sinkholes, and collapse at the material behind the wall especially near the surface. • Constantly wet during high tides wave.
Anchor or tie rod pull out.	Insufficient anchor load to resist the lateral force applied on the wall.	• The surface of retained material is bulging out especially near the anchor load. • Wall is tilted seaward (overturning).

Bulkhead Seawalls

Rotational slip failure

Rotational slip failure occurs when the disturbing forces of the soil pressure, groundwater pressure and pressures induced by surface loads exceed the resisting shear stresses in the soil mass. This may occur when the surface loads are increased beyond those for which the structure was designed, such as by increasing the development on a lot (adding a dwelling, putting on a second storey or a swimming pool, adding fill to increase ground levels), when an earth tremor causes liquefaction of the soil mass, thereby reducing the shear strength of the soil, or when toe scour occurs, reducing the resisting passive pressure from the soil in front of the wall. This may cause subsequent rotation of the wall or “kick out” at the toe.

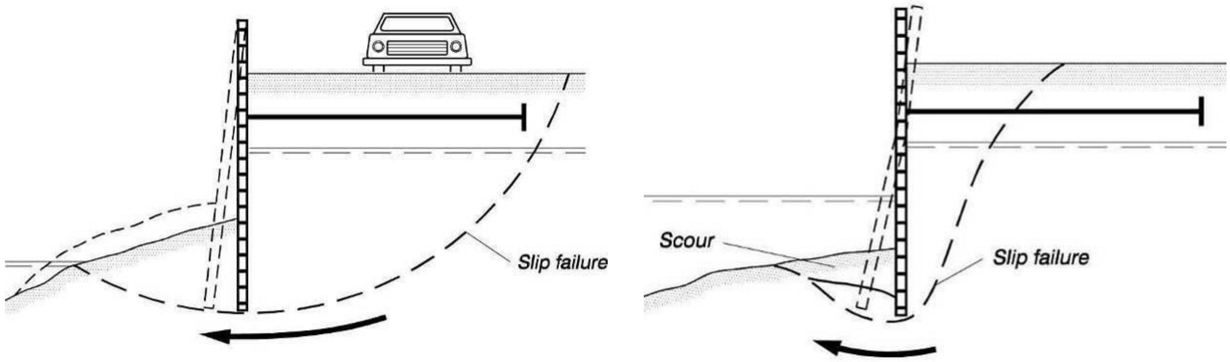

Figure 15: Rotational slip failure of an anchored bulkhead due to increased live load (left) and toe scour (right) (source USACE 2011)

Overwash Scour

When overtopping occurs, the top section of the backfill could be washed away and the backfill could become saturated with wave overwash. This could cause excess water pressure behind the bulkhead, resulting in anchor failure or toe “kick-out” failure. Walls need appropriate drainage from behind the wall to avoid the build-up of the water pressure, increasing the wall loading. Most retaining wall failures result from excess water pressure behind the wall.

Anchor Pull-out

Excess loads from increasing the active soil pressure by developing behind the wall, from increasing groundwater pressure due to poor drainage or wave overtopping, or as a result of an under-designed anchor could lead to anchor pull-out and wall collapse (Figure 16).

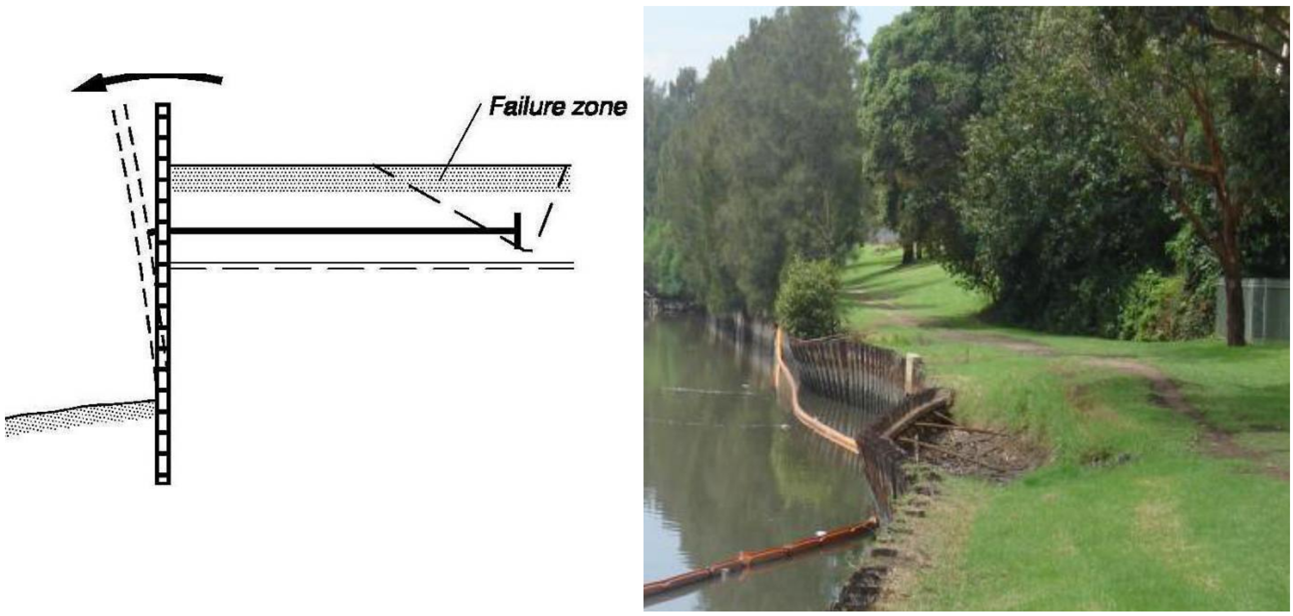

Figure 16: Wall failure by anchor pull-out or tie rod failure (source Left: USACE 2011)

Rigid Gravity Seawalls

Rotational slip failure

As with anchored bulkheads, gravity seawalls can experience rotational slip failure. This can occur if the disturbing forces are increased, say, by development behind the wall, rises in groundwater levels or the resisting forces are reduced, say, as a result of toe scour. As illustrated in Figure 17, the counterfort seawall at North Bondi Beach failed with the toe moving outwards following scour of the beach sand in front of it.

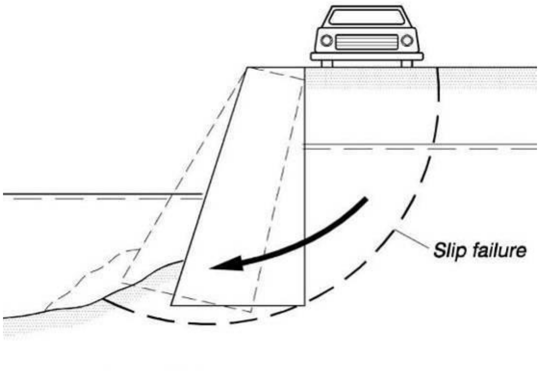

Figure 17: Rotation slip failure of counterfort gravity seawall resulting from toe erosion (source Left: USACE 2011; Right: Waverly Council)

Backfill wash-out

Some seawalls may not collapse when the sand in front of the footing is scoured and the footing undermined. However, this can result in the loss of backfill, as shown in Figure 18.

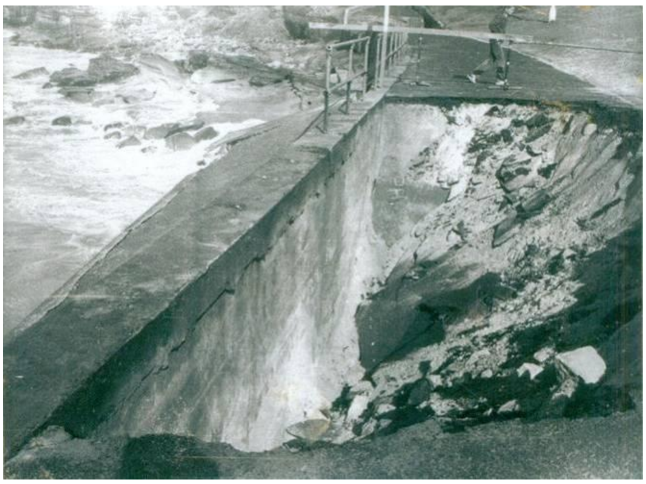

Figure 18: Loss of backfill of mass gravity seawall at South Bondi Beach 13th June 1974 as a result of toe scour and undermining of the footing
(Source Waverley Council; photo by J D Aiosa)

Toe Bearing Failure

In mass gravity structures, toe bearing failure can occur when foundation load exceeds the bearing capacity of the soil (Figure 19). Excessive settlement and overturning can occur where there is insufficient drainage, noting that hydrostatic pressure typically is some five times greater than soil pressure, or where there is toe scour, which can undermine the wall or reduce the bearing capacity due to loss of overburden pressure.

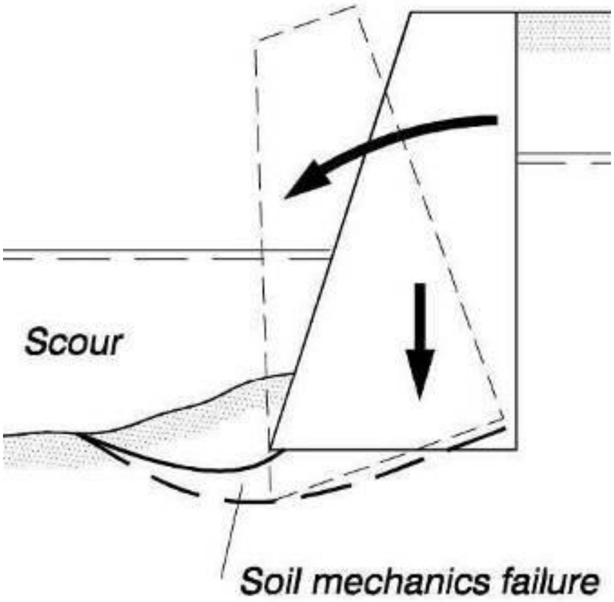

Figure 19: Toe bearing failure schema and plate showing incipient failure
(source USACE 2011)

Sliding and Overturning

Other modes of failure include:

- Sliding of a gravity wall - when the resulting pressure on the rear of the wall from active soil pressure and groundwater exceeds the sum of the frictional resistance over the base of the wall and the passive resistance at the toe, which may be lost due to toe scour.

- Overwash scour - heavy overtopping can cause rear side scour and, thereby, the loss of passive resistance from the backfill. With the wave loads on the front, this could cause a landward overturning of the wall. This could occur with toe scour, as bearing capacity reduces with reducing overburden pressure.

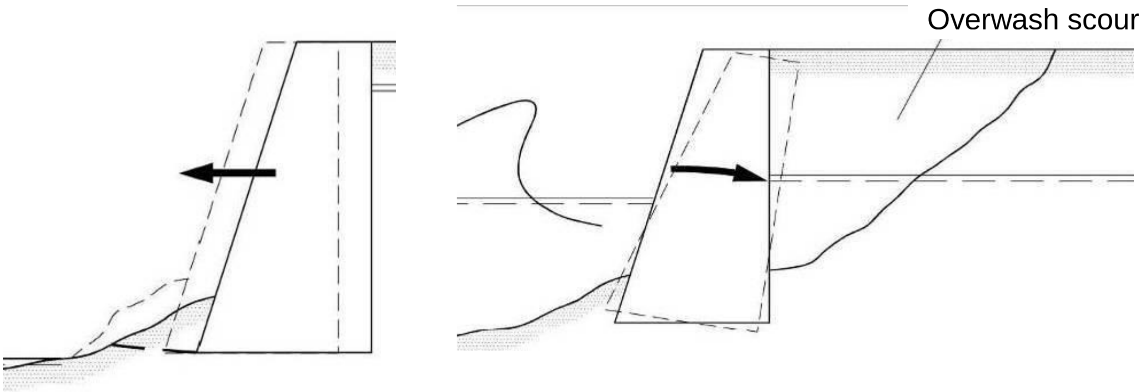

Figure 20: Sliding and overturning failure modes of mass gravity seawalls
Left: Sliding; Right: Overturning (source USACE 2011)

Blockwork Gravity Walls

The failure modes of this type of seawall are similar to those for rigid mass gravity seawalls (rotational slip failure, sliding, bearing and overturning) with an additional component being the dislodgement of individual or a number of blocks. As each wall element may move independently, wave loads may dislodge the wall elements out of position, especially when rear side scour occurs during heavy over-wash (Figure 21). A further failure mode is backfill wash-out through the wall, should there be inadequate filtering between the soil backfill and the blockwork.

Figure 21: Left: Blockwork Gravity Wall (source Chris Adamantidis)**; Right: Blockwork Gravity wall failure due to wave overtopping** (source Chris Adamantidis)

Flexible Mass Gravity Seawalls and Sandbag Revetments

It is common to see mass gravity sandbag revetments on sandy soils constructed to slopes as steep as 0.25H:1V. Such steep slopes are likely to have an unacceptable Factor of Safety against slipping, sliding or overturning unless the thickness of the structure was of the order of the height of the retained sand (Nielsen & Mostyn 2011).

The stability of sandbag armour against sliding on the face of a revetment relies on the interfacial friction between the armour layer and the retained soil. If a geotextile is to be used between armour layers and the soil, consideration needs to be given to both the interfacial friction between the armouring and the geotextile as well as the interfacial friction between the geotextile and the retained soil. Factor of safety against blanket sliding failure of around 1.5 commonly are accepted. However, larger values may be considered, given the dynamic nature of the applied loadings. Typically, for normal beach sand, sandbag slopes on a geotextile underlayer steeper than 4H:1V may not have an adequate factor of safety against sliding (Nielsen and Mostyn 2011). However, the final design must be based on site specific data and rigorous geotechnical analyses. Project specific testing, careful design, rigorous analysis and detailed construction methods and supervision may allow safe batters to be steeper than indicated above.

Other geotechnical failure modes of sandbag revetments include bag pullout and drag down resulting from wave overtopping and collapse as a result of poor friction at the geotextile interface.

Figure 22: Sandbag seawall failures Left: Pull-out of sand bags due to wave overtopping Right: Pull-out of sand bags due to low frictional properties of geotextile
(source Left: Ben Fitzgibbon, Byron Shire Council; Right: Manly Hydraulics Laboratory)

Rigid Sloping Revetments

Push-out and Subsidence

Push-out of slab elements can occur due to uplift pressures resulting from inadequate drainage. Slab elements could be pushed out when the resultant pressure forces exceed the resultant gravity and friction forces. Subsidence can occur when the substratum is incompetent, which can occur due to lack of consolidation prior to construction or as a result of high pore water pressures.

Figure 23: Rigid sloping revetment push-out and subsidence failure modes
Left: Push out schema for sloping slab revetments; Right: Subsidence due to incompetent substrata (source Left USACE 2011; Right Tom Pinzone)

Toe Erosion

Some sloping revetments comprise a sheet pile toe wall which can fail during toe erosion or lowering of beach level.

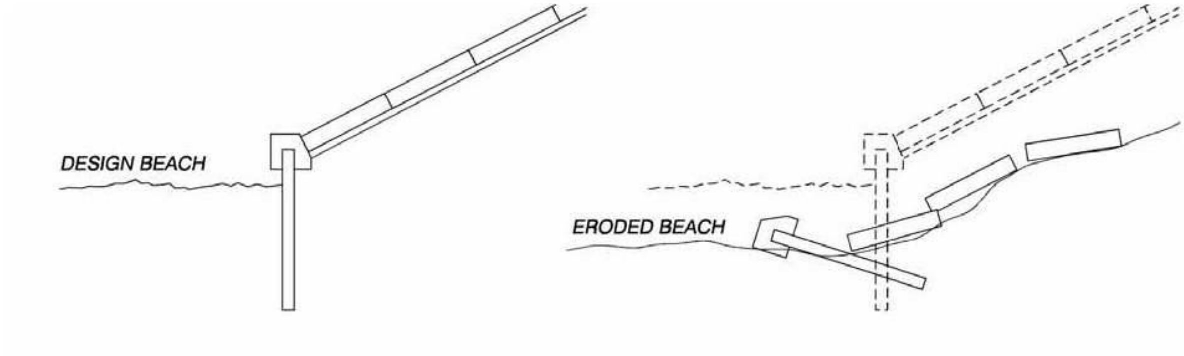

Figure 24: Rigid sloping revetment toe erosion failure schema (source USACE 2011)

Differential Settlements and Global Stability

Other forms of failure include excessive and or differential settlement of the seabed. Depending on the foundation condition, the weight of the structure could cause settlements, thus causing increased overtopping. The settlement usually cause structural failure (i.e., cracks on the concrete). Under a wave trough large anti-stabilizing pressure gradients could be generated, which may cause the generation of a slip failure surface which penetrates into the seabed.

Flexible Sloping Revetments

Back scour failure due to overtopping.

Excess overtopping could cause erosion and subsequent collapse of top of seawall structure (Figure 25).

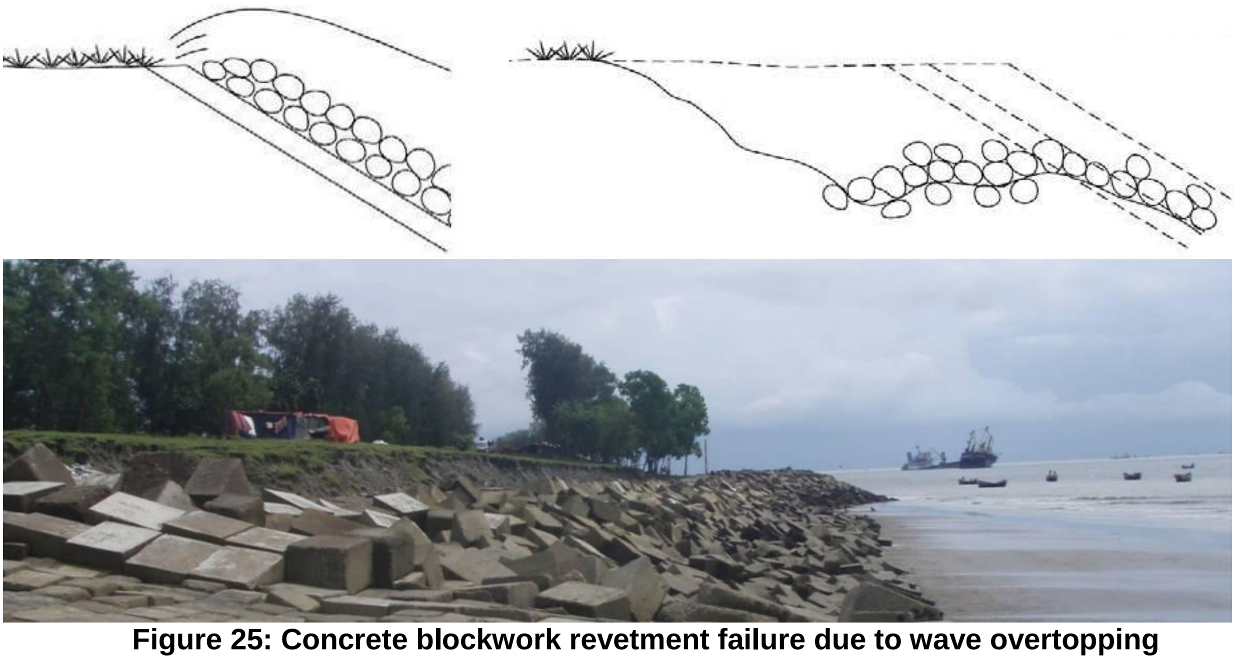

Figure 25: Concrete blockwork revetment failure due to wave overtopping
(source Top: USACE 2011; Bottom: Chris Adamantidis)

Toe Erosion

Lowering of the beach level below the design toe level of the structure could cause subsequent undermining. This can result in subsidence of the toe and/or dislodgement of the armour units.

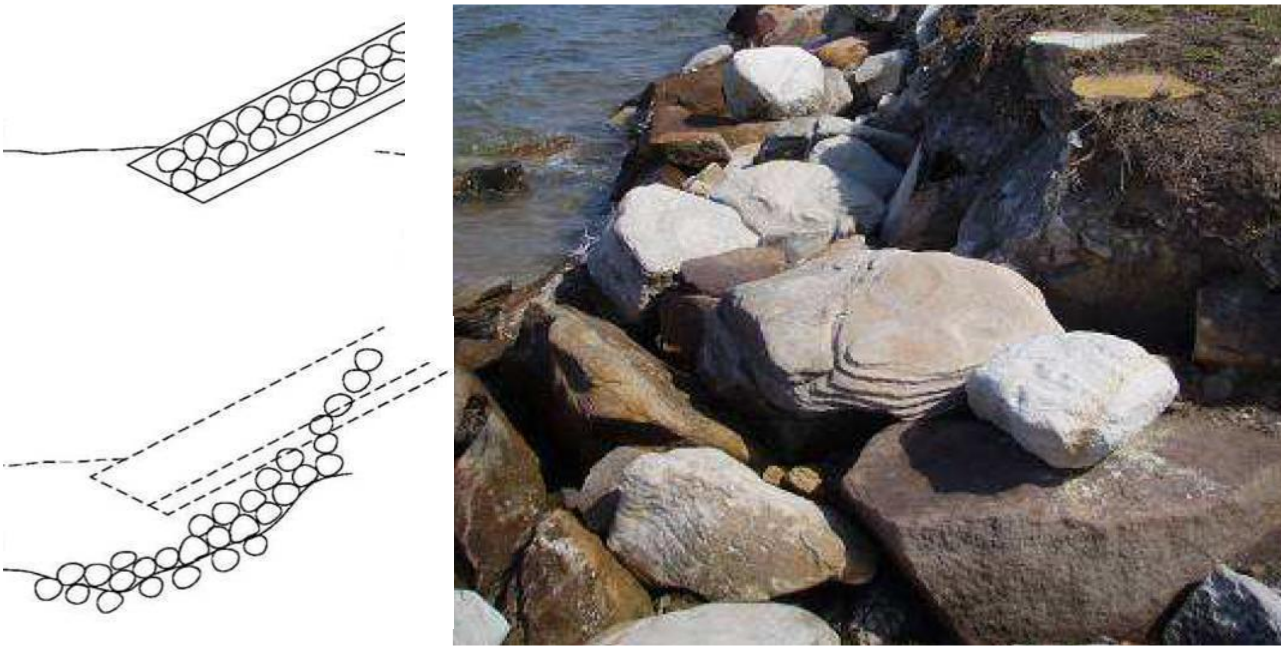

Figure 26: Toe erosion causing subsidence of a boulder wall
(source Left: USACE 2011; Right: Chris Adamantidis)

Washout of Fine Material

Wave-induced elevated pore water pressure gradients can cause the washout of finer embankment materials through the coarser cover and armour layers if the criteria for stable filters between the armour and the embankment are not met. Soil washout may cause cavities, sinkholes and local collapse. This is a common cause of failure of coastal revetment armouring, which results often from the *ad hoc* placement of large rock armouring during a storm event when little thought is put to the proper design of filters and underlayers for rock revetments.

A filter is a transitional layer of well graded gravel, small stone or geofabric placed between the underlying soil and the structure. The filter prevents the migration of the fine soil particles through voids in the structure armouring, it distributes the weight of the armour units to ensure more uniform settlement of the armour layers and permits relief of hydrostatic pressures within the retained soils. For areas above the waterline, filters also prevent surface water from causing erosion (gullies) beneath riprap rock armouring.

A carefully designed filter is essential for the adequate performance of a coastal revetment or seawall. The application of geofabrics as filter blankets, which is becoming widespread in coastal construction, must take careful account of the frictional properties of the geofabric/soil, geofabric/rock and geofabric/geofabric interfaces (Nielsen & Mostyn, 2011). It is to be noted also that geofabric underlayers beneath rock armouring will reduce the stability of the armour units as a result of wave energy reflection and will require a larger rock armour size than would a graded stone filter (CIRIA/CUR, 1991).

Subsidence of Blocks into Fine Material Seabed

Underlayer rock and armour units may sink into seabed if the filter layers are inadequate or if the bearing capacity of the seabed material is reduced, which can occur under elevated wave-induced pore water pressures during storms. This could also cause sliding of main armour.

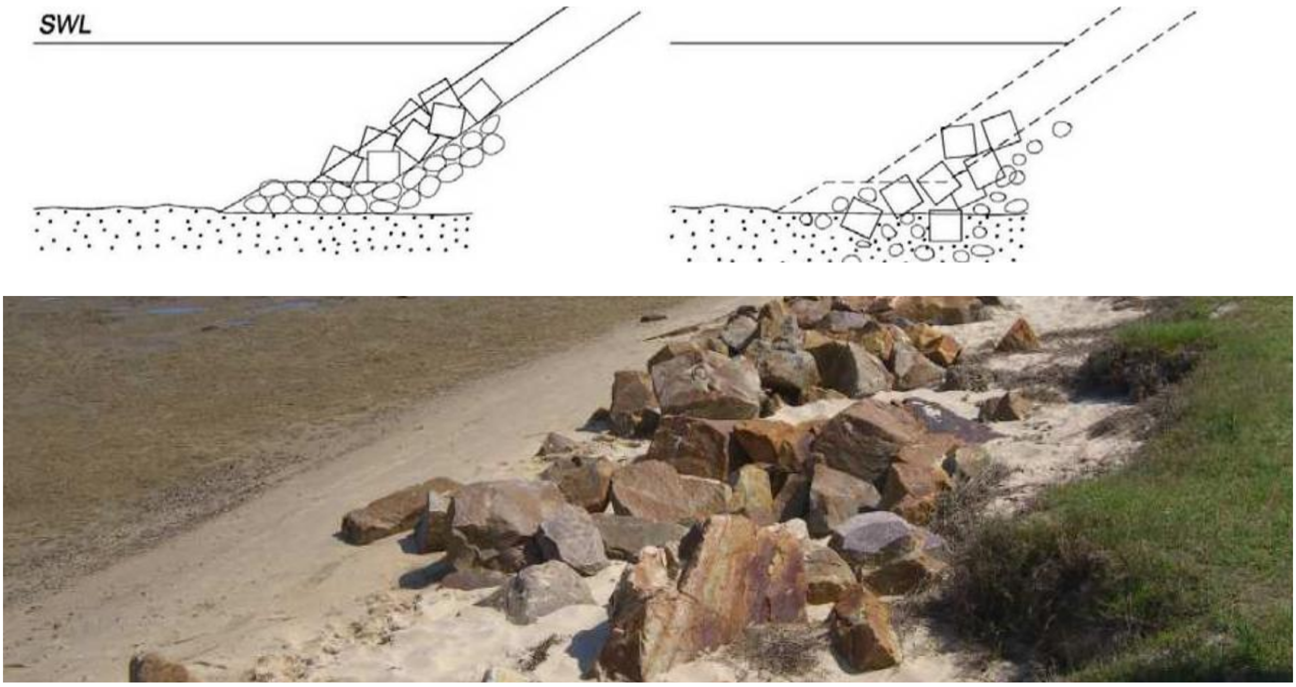

Figure 27: Subsidence of Rock Armour into sand due to inadequate underlayer filtering
(source Top: USACE 2011; Right: Chris Adamantidis)

Climate Change Impacts

Climate Change Variables

Referring to the *Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering* (NCCOE, 2011), the key climate change variables that would impact seawall stability are mean sea level and wave climate. Changes to mean sea level can result in changes to bed levels, water depths, the incident wave climate and ground water levels.

Government planning benchmarks for a rise in mean sea level vary around Australia but can be approximated by around 1 m by 2100. Such a rise in sea level would be significant in most locations, particularly where there is a micro tidal range (< 2 m) or a macro tidal range (< 4 m), which is around most of the Australian coastline. A sea level rise can have various different effects at the foreshore and these are likely to be site specific. Nevertheless, in general, a sea level rise is likely to increase nearshore wave heights with increasing nearshore water depths and decreasing freeboard on the crest levels of foreshore seawalls allowing larger waves to impact seawalls, thereby increasing the risk of wave overtopping. Ground water levels also would rise commensurate with the sea level rise. Changes to the offshore wave climate can affect beach alignments, nearshore wave conditions and, hence, scour levels and wave impact forces.

Effects of Climate Change

On open coast beaches the effect of climate change, specifically a rising sea level, on back beach seawalls and promenades could include the following:

- The width of the beach berm fronting a promenade seawall would reduce. A reduction in beach width will increase the frequency of wave impact onto seawall structures, which may result in increasing toe scour as the structure becomes engaged more frequently with ocean waves.

- Initially, there will be a relative deepening of the seawall toe. However, while the relative toe levels may become deeper, reducing the risk of failure due to toe scour, if the beach width reduces to allow more frequent wave impact on a seawall then, once that occurs, toe scour will commence and progress rapidly, reducing overall wall stability.

- There would be a relative reduction in crest level, which will increase the risk of wave overtopping. The risk of revetment failure increases substantially with increased rates of wave overtopping discharge.

- Incident wave heights are likely to increase with rising sea levels as water depths increase should toe scour occur.

- With a rising mean sea level there would be a commensurate rise in ground water levels at the coast.

Climate Change Impacts

These changes have the potential to reduce the stability of seawalls and revetments in the following ways:

- Increased wave heights would reduce the stability of revetment armouring, causing the dislodgement of armour units and, hence, revetment failure.

- Increased toe scour could induce toe failures and slip failures to both revetments and seawalls.

- Increased water levels and wave heights could result in dangerous overtopping, crest failure of revetments and scour behind revetment and seawall structures. This could induce slip failures, overturning and bearing failures due to removal of backfill or increased hydrostatic loading.

Potential Remedial Works

Remedial works that could be undertaken on open coast seawalls and revetments to ameliorate the adverse impacts of climate change include:

- Constructing “falling toe” scour blankets for mass gravity seawalls, such as shown in Figure 5 (right).

- Extending toe protection for flexible revetments by increasing the extent and mass of the toe armour.

- Increasing armour size on flexible sloping revetments by placing an additional layer of larger units, building upon what is there already.
- Increasing revetment crest levels by placing armour on top or by constructing a wave deflector wall.

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SSC (1984), *Prince St – Nth Cronulla Seabee Seawall with Flexible Rock Mattress Scour Blanket Proposal*, Drawing Sheet 1 of 5 of Sutherland Shire Council.

USACE (2011), *Coastal Engineering Manual – Part VI*, EM 1110-2-1100, U.S. Army Corps of Engineers, September.

SEAWALL PRELIMINARY ASSESSMENT FORM

DATE:		**INSPECTED BY:**	
LOCATION:			
GPS:			

SEAWALL TYPE: (tick)

- ☐ Bulkhead Wall (i.e., sheetpile wall, pile)
- ☐ Rigid mass gravity seawalls (i.e., concrete wall)
- ☐ Flexible mass gravity seawalls (i.e., concrete block, sandstone blocks, rock blocks)
- ☐ Rigid / Semi-Rigid revetments (i.e., concrete slab elements)
- ☐ Flexible revetments (i.e., rock rubble revetment)
- ☐ Sandbag revetments
- ☐ Other:

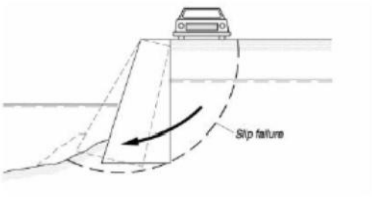
DIMENSIONS & DETAILS OF THE SEAWALL: Record if it is an estimate or measure.

- Wall material (rock, sandbag, etc): ____________________
- Crest width: ____________________
- Toe width: ____________________
- Height of protection / Wall: ____________________
- Embedment depth: ____________________
- Slope angle: ____________________
- Wall element size (if any): ____________________
- Retained material (sand, clay, etc.): ____________________
- Filter behind wall (yes, no, NA):____________________
- Other comments:____________________

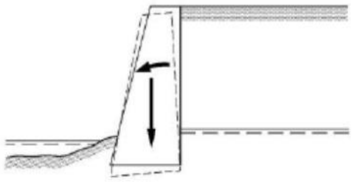
SKETCH:

OBSERVATION	**YES/ NO/ NA**	**COMMENTS (i.e., size of cracks, distance from wall, movement, settlement, etc)**
A. TOE CONDITION		
1. Is the material near the toe bulging out?		
2. Is the toe exposed from its embedment?		
3. Has rock armour been displaced?		
B. WALL CONDITION		
4. Has the wall element moved relative to other wall elements?		
5. Has the wall moved laterally away from the retained material?		
6. Has the wall tilted toward the sea?		
7. Has the wall tilted toward the land?		
C. TOP OF WALL CONDITION		
8. Has the wall settled excessively?		
9. Has any gap been observed between the wall and the retained material?		
10. Is the wall too low and the surface of retained material continuously wet due to high tide, or wave overwash?		
D. RETAINED MATERIAL CONDITION		
11. Has the surface of the retained material immediately behind the wall settled excessively or cracked?		
12. Has the surface of the retained material (i.e., 2 to 3 m away from the wall) settled or cracked?		
13. Is there any evidence of surface erosion?		
14. Is the surface drainage **not** working properly?		
15. Is there any localised settlement / collapse, or cavity behind the wall?		
16. Is the surface of the retained material (i.e., 2 to 3 m away from the wall) bulging out?		

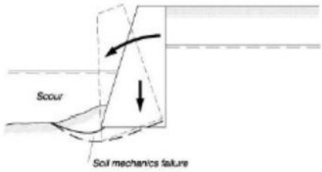
Select the following images of the potential failure modes that best suit the site observation. (If required, select more than one)



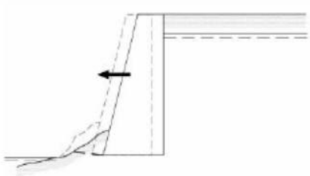
○ **Overall / Global Stability**



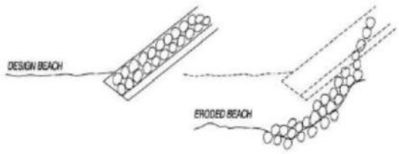
○ **Bearing Failure**



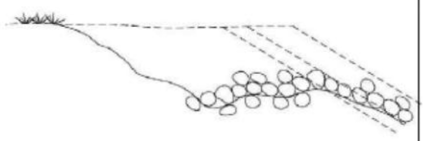
○ **Overturning**



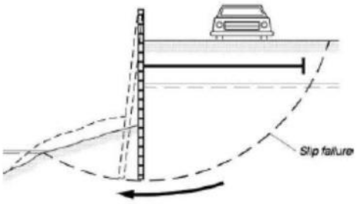
○ **Sliding at the base**



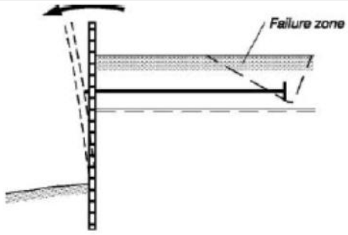
○ **Toe Scour / Erosion**



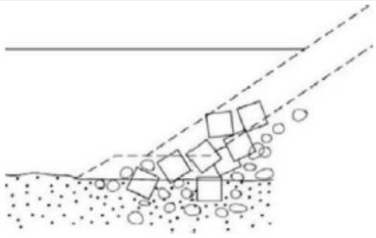
○ **Overtopping**



○ **Rotational slip failure**



○ **Anchor failure**



○ **Filter layer failure**

POTENTIAL FAILURE MODE (BASED ON OBSERVATION ABOVE)	**When "Yes" to any of the questions as numbered above:**
○ Overall / global stability	1, 7, 11, 12
○ Bearing failure	1, 3, 6 or 7, 8
○ Overturning	2, 6, 9
○ Anchor or tie rod pull out	2, 6, 9, 16
○ Sliding at the base / dislodgement of blocks	3, 4, 5, 9
○ Internal erosion	3, 4, 9, 11, 14, 15
○ Toe Erosion / scour	2, 3
○ Overtopping / overwash scour	9, 10, 11, 13, 14, 15

Other comment (i.e., structural condition of the wall, corrosion, spalling, vandalism, etc.)

Is further assessment by a geotechnical consultant required? (Y/N)	
Is any remedial action / work needed to be undertaken immediately? (Y/N)	
If known, what is the remedial action required?	