SCOPAC R&D Project Report

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Exploring some of the challenges for continued use of steel sheet-piles for FCERM in coastal settings

BCP Council & Dorset Council

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Document history

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Contents

1 Introduction

In the SCOPAC region (and elsewhere), coastal Risk Management Authorities (RMAs) maintain many FCERM assets that comprise steel sheet pile walls. These walls are known to suffer from Accelerated Low Water Corrosion (ALWC) problems, and as such many use surface corrosion protection systems such as cathodic protection to extend the life of the piles, with varying degrees of success.

The use of steel sheet piles to replace existing ones is often identified as the preferred long-term approach to ongoing coastal flood risk management (as opposed to retaining, or changing to, masonry/concrete solutions). In setting this long-term strategic direction, the design life of steel sheet piles in the marine environment is typically assumed to be 50 years (the median life expectancy defined in Environment Agency (2013) asset deterioration guidance; see Table 3-4); thus, at least two periods of steel sheet pile replacement over a 100 year appraisal period are frequently included in the economic case in recognition of their rate of degradation in the marine environment. This is not always compared to the whole life costs associated with concrete/masonry walls which are typically designed to be constructed once in a 100 year appraisal period with a design life of 100 years assumed (CIRIA, 2010; CIRIA, 2015).

If steel sheet piles are to continue to be the preferred way of managing coastal flood risk in these areas into the longer-term, then there is a need to understand how the expected scheme design life of these assets can be achieved and potentially extended beyond current day levels using corrosion protection systems such as cathodic protection, in order to maximise investments. In doing so, there is also a need to consider the longer-term sustainability of such an approach based on repeated construction of sheet pile walls over a whole-life appraisal period, such as:

- Where it is not possible to remove and replace sheet piles along existing alignments, the technical and environmental viability of repeatedly encroaching into the water course every 50 years or so, as each round of sheet piles needs to be placed seawards of the previous piles and then possibly tied-back to the previous anchor rods which will be much older than the new wall. Such encroachment would narrow water courses and could alter flows, as well as have implications for environmental designation site features and alter the character and usable space of areas.
- Given the focus of Defra and the Environment Agency (EA) on reducing the carbon impact of the construction industry, including FCERM activities (Environment Agency, 2016), there is a need to assess the relative whole life carbon costs of sheet pile walls compared to other forms of construction as part of future options appraisal. This is something that has not been undertaken widely in the FCERM sector previously but will be a new demand of future schemes.

1.1 Research aims and objectives

The aim of this research is to undertake a desk-based study of some of the challenges posed by the long-term approach to FCERM using steel-sheet piles compared to other methods (i.e. masonry and concrete walls), as described above, in order to illustrate these challenges and to prompt discussion in the wider industry. This aim will be achieved by focussing on experience at Weymouth Harbour in Dorset. This case-study location provides a range of information about all three wall types that have been installed over decades and centuries in the same system, so allowing for ready comparison of the rates of deterioration of steel sheet pile walls to other construction types in the context of a common environment.

In achieving this aim, the following objectives will be met:

1) Understand the rates of deterioration of the various steel sheet pile and corrosion protection systems used in walls around Weymouth Harbour through:
    a) Comparison of actual experience at Weymouth (as far as possible) with (i) what manufacturers expectations are with the same pile / corrosion protection systems, and (ii) EA asset deterioration curves suggest should be expected, accounting for levels of maintenance of the Weymouth assets over the years; and
    b) Comparison to the deterioration rates of steel sheet piles to those of concrete and masonry walls around Weymouth Harbour.
2) Describe the technical and environmental challenges of repeatedly upgrading sheet pile walls using further sheet piles, including learning the lessons of recent works in parts of Weymouth Harbour and preliminary environmental assessment findings from the recent coastal processes study (JacksonHyder, 2018) and FCERM Strategy update (WSP, 2020).
3) Undertake a high-level assessment of the relative whole-life costs over a 100 year strategic appraisal period of different wall construction types, including sensitivity to different maintenance levels and associated wall replacement frequencies, and how these may be impacted by climate change (e.g. rates of asset deterioration for different wall types will be impacted differently by climate change) (Environment Agency, 2017c).
4) Undertake a high-level assessment of the whole-life carbon budget for different wall construction types using the Environment Agency’s Carbon Modelling Tool (Environment Agency, 2021).

2 The case study site – Weymouth Harbour

Weymouth is located on the Dorset coast, approximately ten miles south of the county town of Dorchester. Weymouth Harbour is located at the southern end of Weymouth Bay and opens to the east. It lies at the mouth of the River Wey and has been used for centuries as a port with evidence showing Roman Galleys sailed up the River Wey as far as Radipole where they would beach and unload cargo to transport to the Roman Town of Durnovaria (Dorchester) (https://www.weymouth-harbour.co.uk/history/; date accessed: 24/08/2020).

Walls around Weymouth Harbour have existed in some form for many centuries to support this activity. As the town has grown, land was reclaimed from the sea and walls were extended seawards to protect this newly claimed land. Historically walls were made of timber or masonry blocks; of which some of the latter still exist in parts of the harbour. In the latter 19th and first half of the 20th century, concrete walls tended to be used, whilst more recent wall construction has utilised steel sheet piles – these were constructed seawards of the older masonry block walls in parts of the harbour (Dorset Coast Forum, 2010).

These harbour walls serve two functions:

1) Providing the infrastructure to allow the harbour to operate.

2) Providing flood and erosion protection to the development and infrastructure that has been constructed around the harbour.

Weymouth Harbour is a municipal port. As such the Local Authority, Dorset Council, is the Harbour Authority and so is responsible for maintenance of the walls in support of the harbour operations – which include commercial fishing, dive charters and recreational boating – and to prevent erosion of the land by the sea (the Local Authority is also the Coast Protection Authority in this respect).

The Environment Agency maintains flood defences around parts of Weymouth Harbour that protect people, property and infrastructure from the risk of tidal flooding via the harbour frontage. These flood defences comprise flood walls situated atop of the Local Authority harbour walls and were constructed to their present level of +2.3mOD in 2002. The constructed level of +2.3mAOD was set to provide a Standard of Protection (SoP) of 1:200 years over a 50 year scheme design life and does not include any freeboard due to the available funding at the time of construction and to reduce the impact of the defences on use of the harbour. This level was set following extreme water level guidance in place at the time, though that guidance has since been updated and this level is now below the 2002 design SoP, as illustrated in Figure 2-1 (JacksonHyder, 2018; Halcrow, 2006).

Although there is this technical difference in wall maintenance responsibility, many of the harbour walls are an integral part of the flood walls above and provide flood protection for lower return period events. As such, for the purposes of this study, the walls around the harbour are considered as a single structure for serving the combined functions of flood protection and harbour operations.

The land around Weymouth Harbour is extensively developed and includes the town centre shopping district and many residential properties and local highway links. The area is low-lying and already at risk of flooding and erosion. With accelerating sea level rise and more intense weather events because of climate change, these risks will increase significantly, as illustrated in Figure 2-1. Without investment in managing this flood and erosion risk, Weymouth faces increasing direct losses through flooded assets and infrastructure and indirect impacts such as a failing property market due to blight and increasing social deprivation (WSP, 2020).

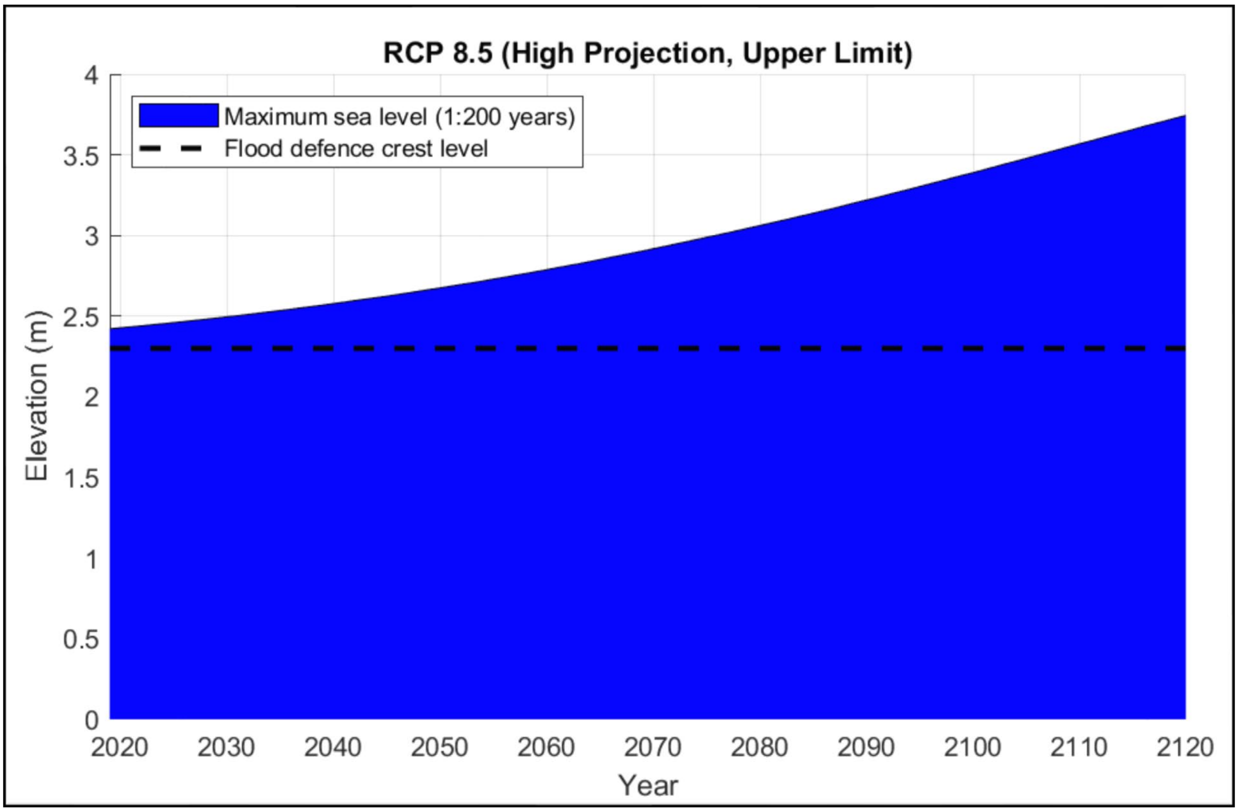

Figure 2-1 Projected rise in the 1 in 200 year extreme water level at Weymouth to 2120 under the UKCP18 'high; emissions projection (WSP, 2020). NB: the present day 1 in 200 year level used in this assessment is +2.43mAOD which is already 0.13m more than the +2.3mAOD level the current flood walls were designed to in 2002 (indicated by the dashed line).

2.1 The long-term strategic approach for Weymouth Harbour walls

The shoreline management plan policy for Weymouth Harbour is to continue to "Hold the Line" over the next century (Halcrow, 2011). The long-term strategic approach to implementing this policy to manage the future risk of flooding and erosion around Weymouth Harbour has been considered in several studies over the past decade, the most recent being the *Weymouth Harbour & Esplanade Flood and Coastal Risk Management Strategy* completed by WSP in 2020. This approach has been further refined through the development of the Strategic Outline Case (SOC) to gain Environment Agency assurance and approval to proceed with further developing the scheme business case (WSP, 2021a).

This strategy promotes a coherent plan for the long-term sustainable flood and coastal risk management of Weymouth Harbour and the Esplanade, bringing together the findings and recommendations from numerous recent studies undertaken by both Dorset Council and the Environment Agency. The preferred strategic approach is to undertake a comprehensive programme of wall replacement and wall raising around both the Harbour and Esplanade frontages. This will both reduce flood risk and replace deteriorating walls, some of which are already at the end of their design life. It is a phased and adaptive approach which provides the opportunity to keep under review several factors including rates of climate change, asset deterioration and changes in spatial planning needs and requirements. It also provides an approach to address all harbour walls, recognising that 2.5km of walls form not only a functional harbour quay wall but also provide a flood risk function to mitigate tidal flooding to residential and commercial property, whilst a further approximately 2km of walls also need to be replaced over-time to provide a coherent system of harbour infrastructure even though these walls provide limited FCERM benefit (WSP, 2020). This strategic approach is summarised in Figure 2-2.

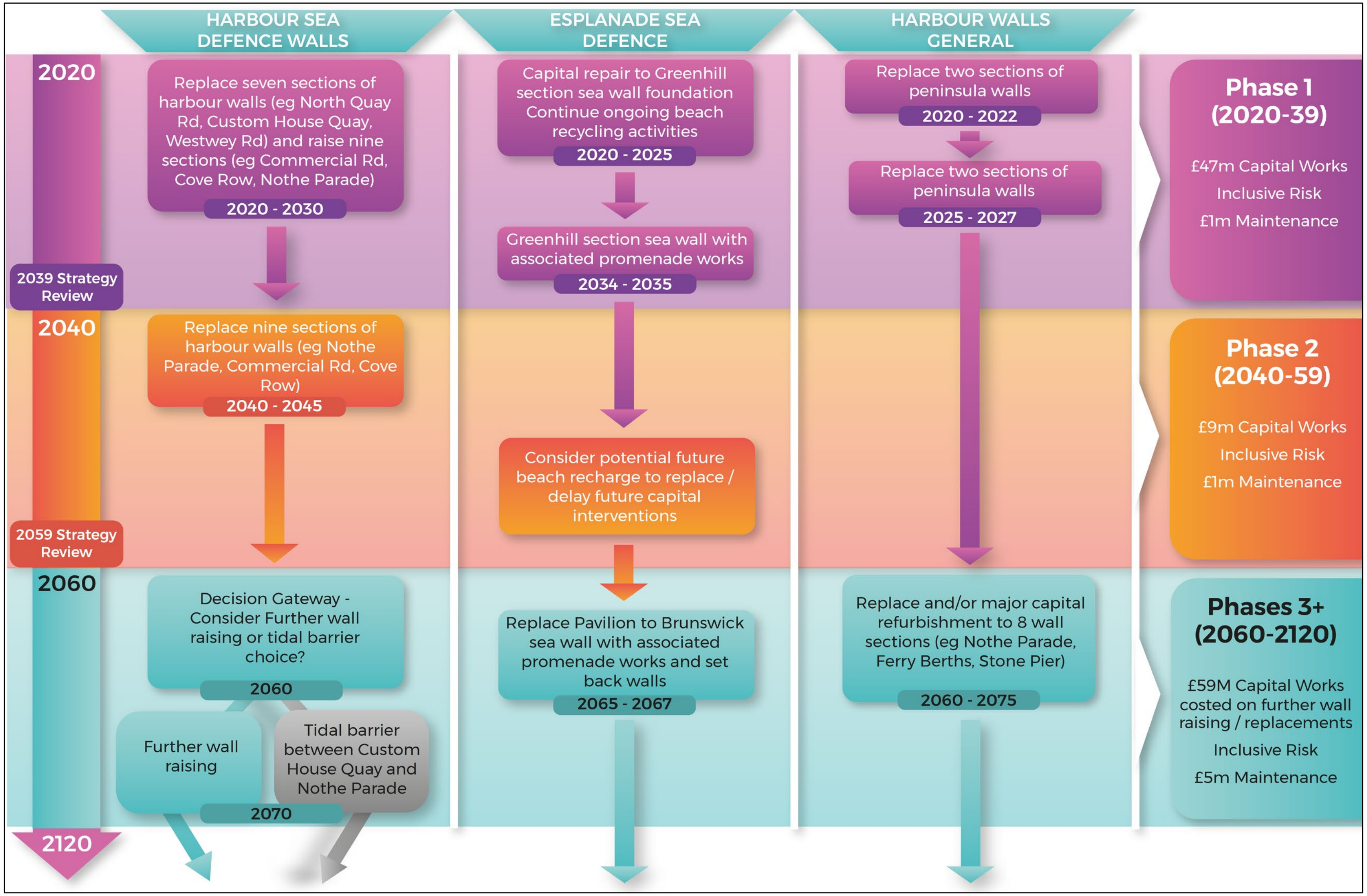

Figure 2.2 Weymouth Harbour and Esplanade Flood and Coastal Risk Management Adaptive Pathway (from WSP, 2020).

2.1.1 Economic case

The economic appraisal accompanying this strategy and SOC identified that through the provision of a 1 in 200 standard of protection adaptive pathway over a 100 year appraisal period, approximately £470m present value benefit (PVb) can be realised. This is set against present value costs of £52m (or £113m in cash terms) being required over the next one-hundred years to replace and maintain all the harbour walls; giving a Benefit Cost Ratio in excess of 9:1.

The costings included in the economic appraisal utilised the Environment Agency's long-term costing tool (Environment Agency, 2015a) and are based on the key assumption that all existing walls around the harbour, be they currently steel sheet pile, concrete or masonry block, will be replaced with steel sheet pile walls over the next century, with many of them (especially the steel sheet pile walls) being replaced within the next 20 to 25 years. These walls will then be maintained over the coming century with further raising if required through concrete walls/caps to meet the required crest level as sea levels rise; this may or may not be supported by construction of a tidal barrier at a point in the future.

Given experience of the actual life of steel sheet piles in Weymouth Harbour shows they last anywhere between 40 to 80 years (see Section 3.4), this assumption about only replacing these new walls once within a 100 year period is questionable and at least one further round of wall replacement is likely to be required. The impact of more than one round of steel sheet pile wall replacement on the economic case was tested in the SOC and found to increase the Present Value cost estimate by 7% (WSP, 2021). The research tests the economic case further by considering alternative wall construction materials (concrete/masonry) to assess comparative whole-life costs, as well as additional factors not considered in the SOC such as whole-life carbon and potential for ecological enhancements of SSP, concrete and masonry wall options (see Section 4).

In addition, the strategic assessment was high level and therefore did not consider the cost for maintaining/repairing individual defects on existing masonry/concrete walls in order to increase residual life and so delay need for replacement. Again, the impact of considering such an approach compared to the strategic approach described above is tested in this research (see Section 4).

2.1.2 Environmental considerations

As part of the *Weymouth Bay Coastal Processes Study* (JacksonHyder, 2018), a Preliminary Environmental Information Report (PEIR) was prepared, identifying the key potential social and environmental impacts of different management options and providing recommendations for further assessment work as the schemes progress through further design stages. This involved consultation of key stakeholders (including Natural England, MMO, EA, Jurassic Coast World Heritage Site Team *(now the Jurassic Coast Trust)*, Dorset County Council (now Dorset Council) Natural Environment Team) and a statement of legal, policy compliance and planning requirements and an outline of the consents that are likely to be required (e.g. Water Framework Directive and Habitats Regulations requirements). This included assessment of a management option to replace and raise harbour walls over-time along with construction of a tidal barrier; an option that is broadly in-line with the strategic approach set-out by WSP in 2020. The key relevant points from the PEIR in terms of potential environmental impacts of this strategic approach on the Weymouth Harbour area were identified as follows:

- **Hydrology and Flood Risk:** This option would have a considerable positive impact by reducing the future flood risk to over a thousand residential and commercial properties in Weymouth. Lowering the flood risk by upgrading coastal defences would allow new development within the town to continue and Weymouth would maintain its status as a popular UK tourist destination.
- **Townscape and Visual Impact:** Reducing the frequency and severity of damage to roads, buildings and other structures caused by flooding and overtopping in Weymouth would reduce the negative impact on the townscape caused by these events.

  Upgrading defences in the harbour area may have a visual impact on Weymouth Town Centre Conservation Area, depending on the materials and finishes used in the final harbour and any future tidal barrier design. The harbour wall raising may have an impact on access to the Harbour and views of the Harbour from the adjacent roads, properties and users of local public rights of way and National Cycle Route 26. Further visual assessment work is recommended.
- **Cultural Heritage:** Reduction in flooding would have a positive impact by decreasing the risk of damage to listed buildings and important landmarks during these events.

  Negative impacts of changes to the harbour defences may impact the setting of listed buildings, the Conservation Area, the setting of Nothe scheduled monument and the UNESCO World Heritage Site. In particular, the design of wall raising and any future tidal barrier should take account of their setting. There may be a need for sympathetic design where the existing harbour wall meets the listed Town Bridge. The harbour wall replacement and potential future tidal barrier could potentially impact yet undiscovered below-ground heritage assets depending on the construction method.

  Further detailed work is required to assess the impact of the strategic approach on heritage assets, the significance of the heritage assets and the potential impact on below ground archaeological remains and the settings of the Conservation Area and listed buildings.
- **Ecology and Nature Conservation:** Any future tidal barrier construction may potentially cause:
  - damage or disturbance to Portland Harbour Shore SSSI;
  - loss of habitat supporting scarce marine species due to construction of foundations and supports for a future tidal barrier;
  - loss of sea grass beds (if present in the harbour);
  - loss of masonry habitat supporting marine species;
  - disturbance and displacement of fish when piling in the harbour; and

  - potential for polluted silt to be mobilised within the harbour and spillage from plant and other sources polluting the marine environment.

  Further assessment work is required for the proposed harbour wall replacement/raising and potential tidal barrier works, including an intertidal study for scarce benthic habitat types / species, intertidal study of the harbour walls, analysis of pollution levels of silt and other substrates within the harbour and further desk study to establish the fish assemblage within the harbour and tidal River Wey.

- **Geology, Hydrogeology, Soils and Contamination:** A potential impact from the harbour would be a change in groundwater levels and flow pathways, although this is not considered a significant issue by JacksonHyder (2018). Construction impacts would be mitigated through applying good construction practices and adhering to current guidance and standards.

  Groundwater monitoring undertaken in 2014 for the *Weymouth Bay Coastal Processes Study* identified several locations where the groundwater level showed a close correlation with tidal water levels. In these locations cut off walls or replacement sheet pile walls are proposed to reduce the tidal influence on groundwater levels. Drainage through the new cut offs will minimise the risk of groundwater being retained on the landward side of the wall.

In addition to the above, the PEIR identified the following environmental topics as issues to be scoped out of further assessment, as it is considered potential impacts are temporary during the construction phase and can be mitigated through best practice construction methods and following guidance and standards. These include:

- **Human Environment:** There would be beneficial impacts for local residents and tourists through reduced flooding, continued safe public use of the promenade, and maintenance of accessible beach slopes and widths.

  Negative impacts may include:

  - temporary impacts during construction from potential diversions to public rights of way;
  - temporary impacts on tourism, socio-economics, local population and human health due to potential noise, dust, traffic and visual impacts during construction; and
  - temporary impacts on land use as construction compounds would be required (although their location has not yet been identified).

  Best practice construction techniques would be applied to minimise disruption during construction and following completion of the works.

- **Noise and Vibration:** Temporary construction impacts would be addressed through construction method statements and agreed with the Environmental Health Officer.

- **Air Quality:** Temporary construction impacts would be addressed through construction method statements associated with the works.

- **Traffic and Transport:** Temporary construction impacts on the road network in Weymouth. Harbour access and vessel movements may be restricted as a result of future barrier construction and closure once operational. These effects should be mitigated as far as possible during the further design phases of the proposed work. Changes to harbour access would be consulted on as part of the Transport and Works Act Order (TWAO) consent process.

The information from the PEIR (JacksonHyder, 2018) summarised above, has been used in this research to assess the relative implications of a range of different scenarios using different wall construction methods around Weymouth Harbour (see Section 4.1).

2.2 Weymouth's Harbour Walls – a brief history and current situation

Weymouth Harbour's steel sheet pile (SSP) walls are labelled walls A – G in an upstream to downstream direction, wrapping around the Peninsula to Weymouth Bay. The masonry and concrete walls are labelled 1 – 10 in a clockwise direction around the harbour perimeter starting at Wall 1 on the south face of the harbour (see Figure 2-3).

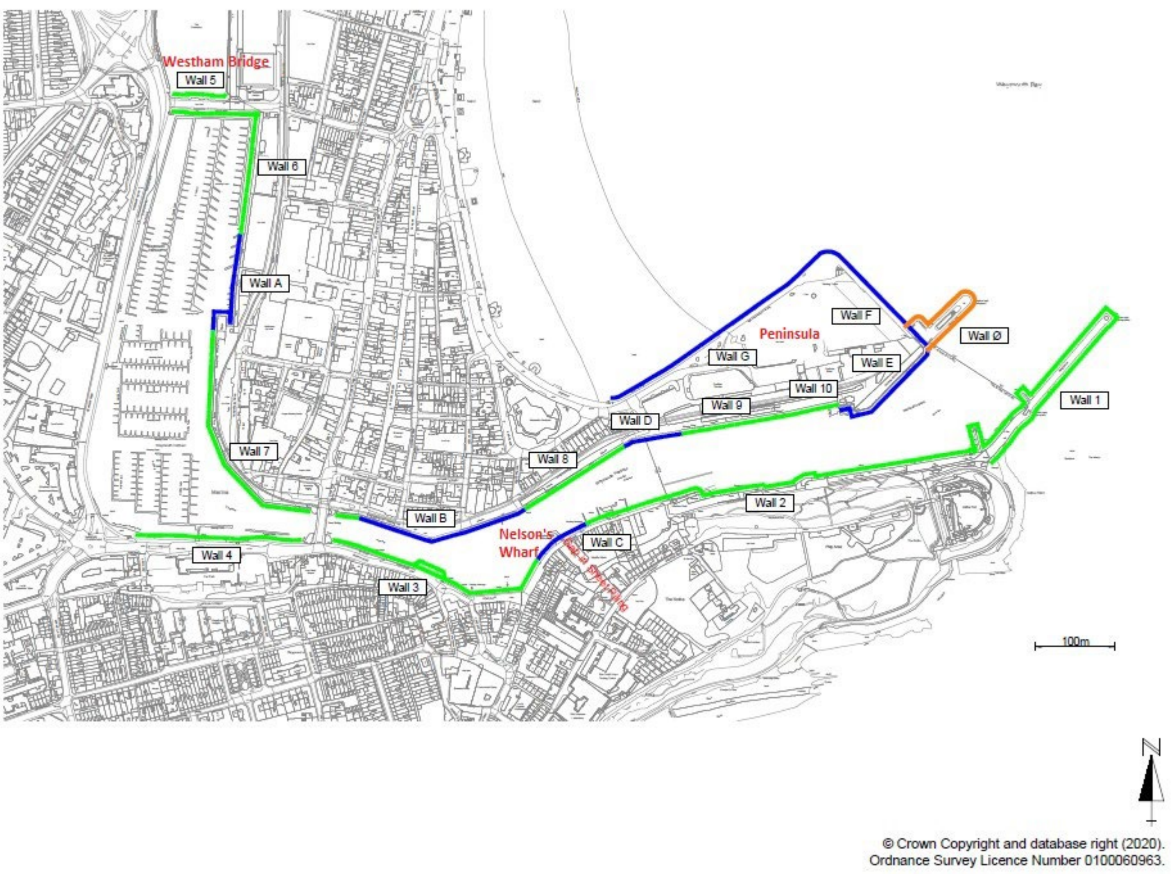

Figure 2-3 Location of Weymouth Harbour's Steel Sheet Pile walls (in blue) and Masonry and Concrete walls (in green).

In total, Weymouth Harbour has 3.8 km of masonry/concrete and 1.2 km of SSP quay wall assets which are owned, operated, and maintained by Dorset Council.

Dorset Council is also the Harbour Authority which maintains the harbour for both commercial and leisure purposes.

2.2.1 Harbour walls construction and current condition summary

The majority of the 4.4 km of walls which make up the harbour are nearing the end of their design life. Table 2-1 summarises the characteristics of the 17 wall sections in the harbour as shown on Figure 2-3. With reference to Table 2-1, the following points should be noted:

- Many of the walls were constructed pre-1980 and are nearing the end of their design life. Only five sections of wall: Wall D; 43 metres of Wall C; and extensions of the capping beam at Walls B, 3 and 7; have had significant remedial or replacement since the late 1980’s.
- Many of the SSP walls around the harbour were constructed around 60 years ago and are therefore starting to fail and requiring immediate works, which includes both capital replacement by piling in a new SSP wall and repairing by patching holes and filling any voids behind the existing SSP wall. The exact age of each section of the SSP walls are not known due to the lack of engineering construction drawings or reports. However, they have all been approximately dated using historic aerial photography.
- Most of Weymouth’s SSP walls are on the pavilion peninsula, which was predominantly reclaimed as land in the 1970’s in order to operate a more substantial ferry service, create more leisure area and additional car parking. With little to no maintenance occurring on these walls since construction, walls E, F & G that bound the peninsula now only have a predicted residual design life of between 0 and 30 years (JBA, 2019a).
- Wall D, also on the pavilion peninsula, was judged to be in critical condition in the Halcrow 2012 condition report. £1.9 million of council funding was approved in 2016 by the former Weymouth and Portland Borough Council (WPBC) (now Dorset Council) to reconstruct the 76 metres long wall D and 25 metres of the 73 metre long wall C (further details below). A new SSP wall was piled in front of the existing wall, and this was completed in spring 2020.
- Wall E, on the south-eastern end of the pavilion peninsula, was constructed in 1971 as a berth to allow an additional 50,000grt ferry to dock in Weymouth. It is relatively sheltered from storm events despite being on the outer edge of the harbour channel. It is currently predicted to have a residual design life of at least 10 years. Works to repair any defects and guarantee its residual design life for at least the next 20 years are due to commence in 2022/23.
- Wall C is 73 metres in length. The western 48 metres up to Nelson’s Wharf was reconstructed in 2001 by piling in front of an old masonry wall and raising its height by installing a concrete capping beam. The remaining 25 metres of wall C was in very poor condition and was subject to repair works between January to March 2022.
- Most of the masonry and concrete walls around the harbour were constructed before or during the early 20th century when Weymouth was fully established as a

cross-channel ferry port. The majority are in good condition, with only minor localised defects across the walls.

- Due to the age of the walls, most engineering drawings are not available and therefore site investigations would have to be conducted to give a more accurate and detailed condition assessment of the walls.
- Wall 9 is a concrete wall and one of the oldest walls in the harbour, with a cross-channel ferry berthing on the wall as early as 1840. It is 143 metres in length and the current configuration was constructed in the 1930’s. Repair works between November 2021 and April 2022 have guaranteed is design life for at least the next 20 years.

Table 2-1 Summary of Weymouth Harbour walls (JBA, 2019a; JBA, 2019b).

Wall Section	**Approximate Age**	**Condition Grade** *(refer to Table 3-5)*	**Estimated residual life (years)** *(based on Table 3-4)*	**Recommended actions (walls A-G) / Serviceability over next 15 years (walls 1 – 10)**
Masonry / Concrete Walls				
1 Stone Pier	Original: 1680s Extension: 1878 Reconstruction or Remedial Works: 1980s	2	30 – 80	In good and serviceable condition with the need for localised repair works.
2 Nothe Parade	Present day alignment: 1774 Reconstruction or Remedial Works: 1860-1872, 1942-1963 and 2000-2001	3	20 – 60	In good and serviceable condition with the need for localised repair works. However not suitable as a present and future flood defence.
3 Trinity Road	Present day alignment: 1774 Reconstruction or Remedial Works: 1888, 1930 and 2001	3	20 – 60	In good and serviceable condition with the need for localised repair works. However not suitable as a present and future flood defence.
4 North Quay	Present day alignment: 1774 Reconstruction or Remedial Works: 1824 and 1932	4	10 – 20	In poor condition and in need of strengthening/repair work or replacement in the short term. The wall is not suitable as a present or future flood defence.
5 Westham Bridge	1921	No asset inspection available		
6 Weymouth Marina	1909	3	20 – 60	In good and serviceable condition with the need for localised repair works. However not suitable as a present and future flood defence.

Wall Section	**Approximate Age**	**Condition Grade** *(refer to Table 3-5)*	**Estimated residual life (years)** *(based on Table 3-4)*	**Recommended actions (walls A-G) / Serviceability over next 15 years (walls 1 – 10)**
7 Commercial Road	Present day alignment: 1831 Reconstruction or Remedial Works: 1930, 1938 and 2001	3	20 - 60	In good and serviceable condition with the need for localised repair works. However not suitable as a present and future flood defence.
8 Custom House Quay	Present day alignment: 1831 Reconstruction or Remedial Works: 1949 - 1952	2	30 – 80	In good and serviceable condition with the need for localised repair works. However not suitable as a present and future flood defence.
9 Ferry Berth 4	Present day alignment: 1840 Reconstruction or Remedial Works: 1860, 1878 and 1933	3	20 - 60	In good and serviceable condition with the need for localised repair works. However not suitable as a present and future flood defence.
10 Ferry Berth 3	Present day alignment: 1840 Reconstruction or Remedial Works: 1860, 1878, 1933 and 2013	No asset inspection due to reconstruction in 2013.		
Steel Sheet Pile Walls				
Ai Angling Club (Larssen 3/20 and LX 16 piles)	1977	5	5 - 10	Installation of new steel sheet pile wall with extension of crest level once the residual life is reached.
Aii Angling Club (LX 20 piles)	1977	2	15 - 45	Installation of new steel sheet pile wall with extension of crest level once the residual life is reached.

Wall Section	Approximate Age	Condition Grade *(refer to Table 3-5)*	Estimated residual life (years) *(based on Table 3-4)*	Recommended actions (walls A-G) / Serviceability over next 15 years (walls 1 – 10)
B Custom House Quay (Larssen 3/20 piles)	1950s Extension of capping beam: 2000	4	5 - 10	Installation of new steel sheet pile wall with extension of crest level once the residual life is reached.
Ci Cove Row (Larssen 3/20 piles)	1950s	4	5 - 10	Installation of new steel sheet pile wall with extension of crest level once the residual life is reached.
Cii Cove Row (LX 20 piles)	2000	1	20 - 60	Installation of new steel sheet pile wall with extension of crest level once the residual life is reached.
D Custom House Quay (Frodingham no.5 piles)	2020	No asset inspection due to reconstruction in 2020.		
E Peninsula Wall (Frodingham no.5 piles)	1971	3	10 – 30	Installation of new steel sheet pile wall once the residual life is reached.
F Peninsula Eastern Wall (Larssen 3/20 piles)	1977	5	0 - 2	Installation of new steel sheet pile wall.
G Peninsula Northern Wall (Larssen 3/20 piles)	1977	5	0 - 2	Installation of new steel sheet pile wall.

2.2.2 Recent works and lessons learnt

Weymouth Harbour has seen four major capital schemes between 2000 and 2020 as aging SSP and masonry/concrete walls have either failed or deemed to be at or beyond their design life. SSP walls B, C and D have seen major schemes alongside the masonry Wall 10.

In February 2012, large cracks started to appear on the surface of Wall 10, the commercial berth which Condor Ferries used as their main berth. The 80 year old masonry wall was showing signs of stress in the years preceding, however very little remedial works were carried out to address concerns. The 5,000gt ferries which used the berth had to temporarily relocate to Poole for nearly 18 months to allow for a full wall replacement to occur. The replacement costs ran into the several millions and caused significant damage to the then Weymouth and Portland Borough Council’s (WPBC) reputation.

Ultimately the multi-million pound replacement scheme was not enough to keep the ferry operator in Weymouth, and they relocated all their cross-channel services to Poole in March 2015 (Dorset Echo, 2015). This was a significant blow to the town’s economy as it was estimated to cost the harbour about £750,000 a year in lost income (BBC News, 2015).

In 2019/20 a 76 metres section known as wall D was replaced due to its deteriorating condition. A new set of SSP were driven in front of the existing structure, with the void between existing and new filled with reinforced concrete and the new sheet piling tied back to the sound sections of the existing tie bars so that the strengthened wall is supported by the existing anchor beams. It was close to 60 years since the original SSP wall was constructed and it was deemed to be in ‘critical condition’ (Halcrow, 2012).

The key lessons learnt from undertaking these recent capital schemes are:

- Regular detailed condition inspections of all walls is essential for pro-active maintenance to extend asset life. This not only delays the need for capital schemes to replace walls but can also allow time to align wider plans for locations and budgets;
- Conduct repair or replacement works as soon as practicable possible once close to reaching residual design life to minimise risk of failure that in turn would lead to disruption to a wider area than just the wall locale;
- The method of construction is important to consider to minimise the impact of vibration, noise and other disruption of the works given the close proximity to property, businesses, roads and other infrastructure;
- Given the close proximity of works to them and the risk of vibration / noise / transport disturbance posed to them, and to ensure appropriate pre-, during- and post- works monitoring is undertaken, regular communications with landowners, property owners / leaseholders and businesses is vital in before and during construction works; and
- Regular contact with the harbour authority to manage any risk of disruption etc. to the working of the harbour.

3 Issues facing steel structures in the marine environment

SSP Walls have been a popular choice of wall over the past half a century in Weymouth Harbour as they are typically cheaper than the alternatives for one round of replacement / capital investment, in terms of both material cost and construction time. The construction method for SSP also allows them to be installed in relatively narrow locations, which is the case for much of Weymouth Harbour.

However, the use of steel structures in the marine environment presents a number of challenges in terms of how to manage material degradation over time. These challenges need to be considered in the initial design of structures and the ongoing maintenance of them. The mechanisms of degradation are varied and are summarised in Table 3-1.

Table 3-1 Mechanisms of metal degradation (from Environment Agency, 2020b).

Mechanisms of degradation	Cause	Effect
Uniform (most common)	Corrosive attack of water (or moisture in the air), acids, bases, salts, oils and certain chemicals	In most cases uniform degradation is objectionable only from an aesthetic standpoint
Pitting	Low dissolved oxygen concentrations, high concentrations of chlorides, poor application of the protective coating system	Localised damage to the surface, formation of a cavity or hole in the material can also cause stress risers
Crevice (general, filiform and pack rust)	Stagnant solution on the surface of a metal	Lowering of oxygen content, depletion of natural corrosion inhibitors, creation of an acidic condition, build-up of chlorides
Galvanic	Two (or more) dissimilar metals are brought into contact in the presence of moisture	One of the metals becomes the anode and corrodes faster than it would in isolation
Lamellar	Degradation that proceeds laterally from the site of the initial corrosion along parallel planes	Layered appearance, lamellar corrosion
Erosion/abrasion	Wear caused by action of fluids containing solid particles in suspension fluids (wet attrition)/wear caused by rubbing and friction (dry attrition)	Rapidly increasing erosion rates
Cavitation	Fluid's pressure drops below its vapour pressure causing gas pockets and bubbles to form and collapse	Can easily reduce the material thickness, erosion at pipe elbows and tees
Intergranular (general and exfoliation)	Associated with impurities within the metal that are concentrated at the grain boundaries	Reduction of adequate corrosion resistance which in turn makes the grain boundary zone anodic relative to the remainder of the adjacent grain surface
Environmental cracking (stress corrosion cracking)	Combination of tensile stresses and a corrosive environment	Potential to result in catastrophic material failure
Environmental cracking (corrosion fatigue)	Combined action of alternating or cyclical material stresses in the presence of a corrosive environment	Reduction of its resistance
Environmental cracking (hydrogen embrittlement)	Dissolved hydrogen assists in a fracture of the metal	Development of local plastic material deformations

Whilst Table 3-1 illustrates that there are a range of mechanisms that cause degradation of metals, including steel sheet piles in the marine environment, the main issue for steel used in construction of assets in wet environments is corrosion. Accelerated Low Water Corrosion (ALWC) is a particularly aggressive form of localised corrosion, defined in the British Standard for Maritime Structures (BS 6349-1:2000) as a type of low water 'concentrated corrosion', that has become a high-profile problem, associated with unusually high rates of metal wastage and holing on unprotected, or inadequately protected, steel maritime structures (Environment Agency, 2020b).

CIRIA (2005, p. 25) states that the implications of the increased rate of steel degradation caused by ALWC, which produces rapid, local metal thinning, can in turn if left unchecked develop into:

- Serious holing and the need for urgent repairs (illustrated in Weymouth Harbour in Figure 3-1).
- Premature structural failure leading to partial or complete reconstruction of a structure or even total shutdown of a facility.

Figure 3-1 Serious holing caused by ALWC at Weymouth Harbour Wall C (captured 2nd February 2022).

CIRIA (2005, p. 25-26) goes on to state that such features have been observed after a service life of as little as 20 years on structures that were originally designed to give 40 to 120 years, and that the forms of failure caused by ALWC are:

- **“Loss of containment or stability**; BS6349-1:2000 warns that loss of backfill material through a holed sheet pile wall can lead to the collapse of pavement surfacing above or structures supported on the backfill. Uneven surfaces in themselves can also prove hazardous. In the case of ports and harbours, significant loss of fill material can, in extreme circumstances, reduce the navigable depth of a berth creating a potential hazard to transport, cargo and maintenance services.

  Loss of containment producing voids behind a steel sheet piled wall will become apparent during inspection, either planned or following the failure of the adjacent supported pavement. The impending loss of containment will be indicated by local thinning or initial holing of steel forming the retaining structure. Often local clouding of the water on a falling tide caused by loss of silty material can warn of a hole.

- **Loss of strength or structural failure**; loss of structural section can weaken the affected structure, potentially leading to failure or the need to place loading restrictions on it. Although ALWC only affects a small percentage of total exposed surface area, it has potentially serious implications to structures where the resultant loss in section from ALWC corresponds to areas of maximum stress. Structural failure has fortunately been rare and sometimes does not occur even when detailed analysis suggests that it should have done so. Nevertheless, it is essential for the owner to be confident that a structure is operating safely and can carry the loads that will be imposed on it.”

ALWC and its implications as described above are observed to be present in the steel sheet pile walls around various parts of Weymouth Harbour (JBA, 2019a); see also Section 3.2.

3.1 Corrosion rates of metals in the marine environment

The Environment Agency (2020b) reports use of metals is one of the few material types where reasonable information on rates of degradation exists. It also goes onto highlight that corrosion rate distribution and aggressiveness upon structural steel can vary considerably, depending upon the setting/environment the steel is in, the presence (or not) of microbiological organisms, soil conditions and measures taken to protect the structure. Corrosion rates can also be variable within a single structure dependent upon the different levels of exposure being experienced. For example, steel structures in marine environments usually include several exposure zones with differing degrees of aggressiveness of corrosion, namely:

- atmospheric zone
- splash zone
- tidal zone
- intertidal low water (ILW) zone
- continuous immersion zone
- mud (embedded) zone.

Figure 3-2 indicates the relative corrosion rate distribution on a typical maritime structure in each of these exposure zones, whilst Table 3-2 compares the range of annual corrosion rates stated in published literature for steel located in each exposure zone that is collated in an Environment Agency (2020b) report.

Another way to think about corrosion loss is to consider the total loss of thickness of steel over time as stated in *BS EN 1993-5:2007 Eurocode 3 – Design of steel structures* and summarised for steel in marine environments in Table 3-3. These total corrosion losses in seawater settings equate to an annual rate of corrosion that aligns to the lower end of mean corrosion rates stated in Table 3-2.

As can be seen from the data in Table 3-2 and Table 3-3, the upper end of typical rates of corrosion stated in published literature is between 0.3 to 0.4 mm/side/year. By comparison, the average corrosion rates due to ALWC is reported to typically be in the range of 0.3 to 1.0mm/wetted side/year, but higher instantaneous rates are probable once ALWC has initiated on a structure (Environment Agency, 2020b).

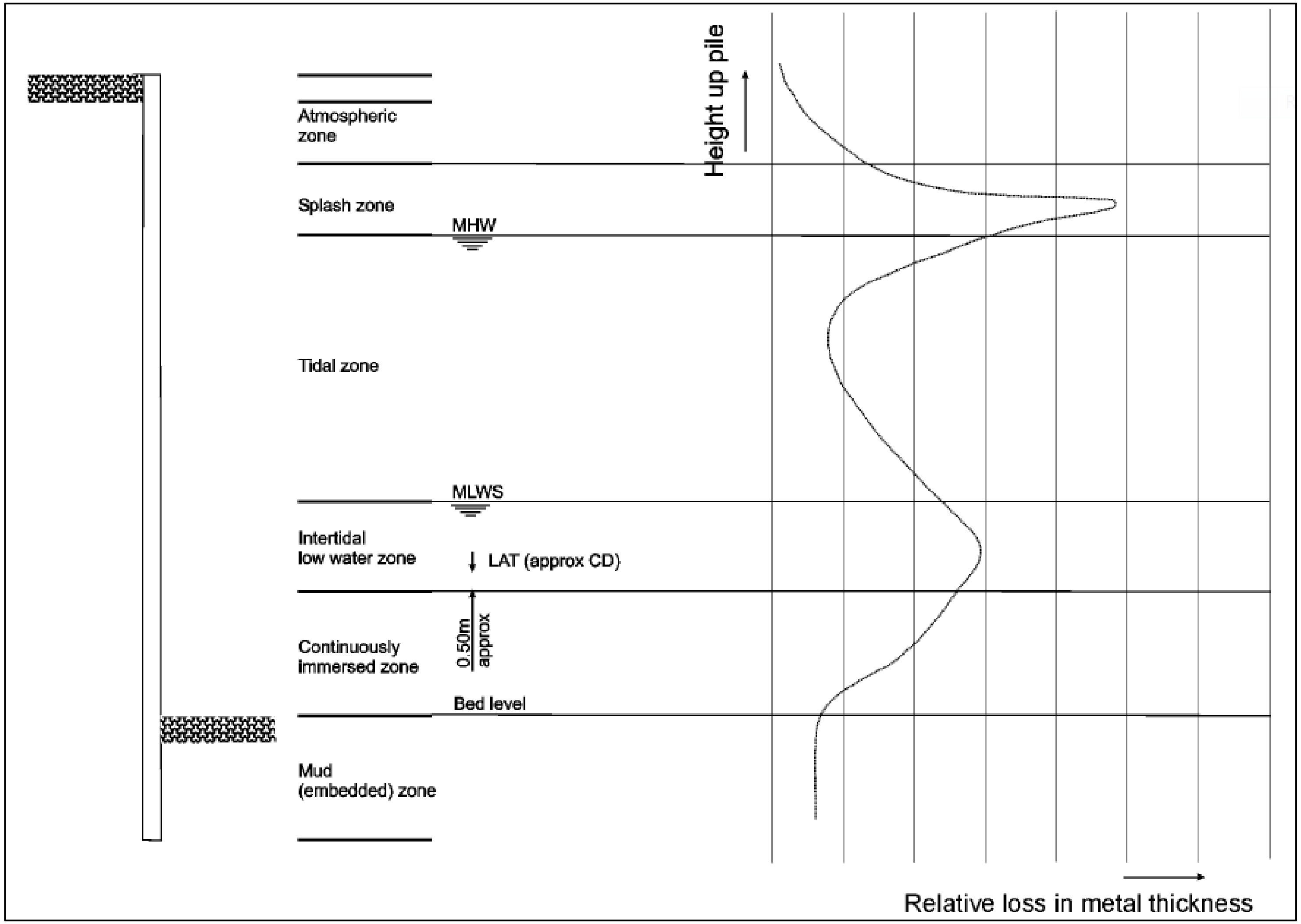

Figure 3-2 Schematic showing corrosion zones and typical profile for 'traditional' corrosion behaviour (from CIRIA, 2005). Note: Corrosion rate distribution and zones of seawater aggressiveness may vary considerably from the example shown, dependent upon the conditions prevailing at the location of the structure (Environment Agency, 2020b).

Table 3-2 Comparative corrosion rates found in literature for metals in the marine environment by exposure zone (from Environment Agency, 2020b).

Exposure zone	**Mean corrosion rate (mm/side/year)**			**Upper limit corrosion rate (mm/side/year)**		
	CIRIA[1]	**BS 6349-1:2000[2]**	**Corus[3]**	**CIRIA[1]**	**BS 6349-1:2000[2]**	**Corus[3]**
Atmospheric zone	0.02 – 0.04	0.04	-	0.10 – 0.41	0.10	-
Splash zone	0.08 – 0.42	0.08	0.09	0.17 – 0.30	0.17	0.18
Tidal zone	0.04 – 0.10	0.04	0.05	0.10 – 0.18	0.10	0.11
Intertidal low water zone	0.08 – 0.20	0.08	0.09	0.17 – 0.34	0.17	0.18
Continuous immersion zone	0.04 – 0.13	0.04	0.05	0.13 – 0.20	0.13	0.14
Below seabed level	0.03 – 0.08	-	0.03	0.02 – 0.10	0.015	0.03

[1] *Table 2.1, CIRIA C634, Management of accelerated low water corrosion in steel maritime structures*

[2] *Table 25, BS 6349-1:2000, Maritime structures – Part 1: Code of practice for general criteria* [author note: since the data in Table 3-2 was compiled in the report from which it has been taken, this standard has been updated by BS 6349-1-4-2021 which advises use of corrosion rates in BS EN 1993-5:2007; this data is provided in Table 3-3]

[3] *Corus, Durability and protection of steel piling in temperate climates, 2002*

Table 3-3 Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in freshwater or seawater (abstracted from the UK National Annex (NA) to Eurocode 3: Design of steel structures – Part 5: Piling (NA to BS EN 1993-5:2007)); NB: annual average rate of corrosion added to table by authors for comparison with data in Table 3-2.

Setting	**Loss of thickness (mm) over different design working life durations**					
	5 years	**25 years**	**50 years**	**75 years**	**100 years**	**125 years**
Common freshwater (river, ship canal) in the zone of high attack (water line)	0.15 mm *(0.03mm/side/year)*	0.55 mm *(0.02mm/side/year)*	0.90 mm *(0.02mm/side/year)*	1.15 mm *(0.02mm/side/year)*	1.40 mm *(0.01mm/side/year)*	1.65 mm *(0.01mm/side/year)*
Brackish or very polluted freshwater (sewage, industrial effluent…) in the zone of high attack (water line)	0.30 mm *(0.06mm/side/year)*	1.30 mm *(0.05mm/side/year)*	2.30 mm *(0.03mm/side/year)*	3.30 mm *(0.04mm/side/year)*	4.30 mm *(0.04mm/side/year)*	5.30 mm *(0.04mm/side/year)*
Seawater in temperate climates in the high tide splash zone or in the low water zone	0.55 mm *(0.11mm/side/year)*	1.90 mm *(0.08mm/side/year)*	3.75 mm *(0.05mm/side/year)*	5.60 mm *(0.07mm/side/year)*	7.50 mm *(0.08mm/side/year)*	*Protection system required*
Seawater in temperate climates in the zone of permanent immersion or in the intertidal zone	0.25 mm *(0.05mm/side/year)*	0.90 mm *(0.04mm/side/year)*	1.75 mm *(0.04mm/side/year)*	2.60 mm *(0.03mm/side/year)*	3.50 mm *(0.04mm/side/year)*	4.40 mm *(0.04mm/side/year)*

3.1.1 Impacts of climate change on metal corrosion rates

The primary impacts of climate change on steel sheet piles in the marine (coastal) environment were assessed as part of the Impacts of Climate Change on Asset Deterioration project (Environment Agency, 2020a). This is illustrated qualitatively in Figure 3-3.

Due to the range of variability in the present-day base rates of corrosion (see Table 3-2 and Table 3-3), the Environment Agency (2020a) report concluded that predicting the effects of climate change upon the material degradation is impossible as quoted mean rates vary by a factor of 2 to 3 and the upper limit rates can be several times greater. Consequently, the change in rate occurring for any given structure may still fall within the upper bounds, or even typical ranges quoted, and may only really be estimated at an asset-specific level with base data for that particular asset. The report goes onto state that even though it may not be readily quantified, steel degradation is likely to be affected directly by climate change such as rising air temperatures, changes in humidity and sea level rise, as the chemical reactions tend to increase with increased temperature and exposure to more humid conditions.

Of particular relevance to Weymouth Harbour and sheet pile walls sat in the water column is the impact of changes in areas of wetting and drying due to sea level rise. This could affect (accelerate or decelerate) steel degradation due to changed zones of wetting/drying (see Figure 3-2 above) and so increase the area of walls exposed to higher corrosion rates over time with the inevitable implications that leads to in terms of reduced structure life.

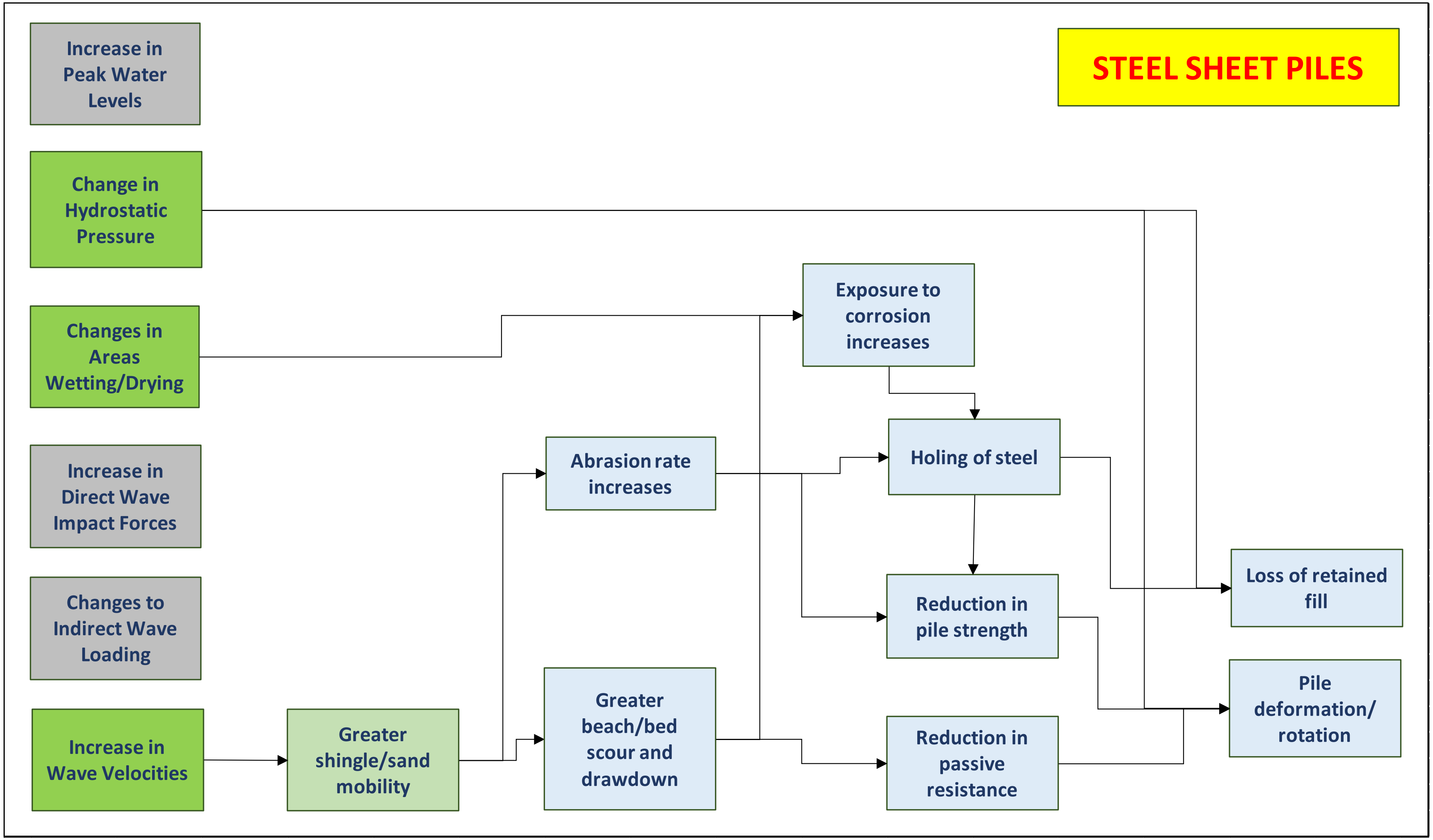

Figure 3-3 Steel sheet pile deterioration pathways due to the impacts of climate change (from Environment Agency, 2020c).

3.2 Implications of corrosion for residual life of steel structures in marine environments

The corrosion of steel structures over time impacts the residual life of a structure, and this is related to both the environment/setting within which a particular structure is located and to the levels of maintenance. The Environment Agency's Practical Guidance on Determining Asset Deterioration and the use of Condition Grade Deterioration Curves (Environment Agency, 2013*)* provides a recent methodology for assessing how these factors relate to the expected rate of deterioration in sheet pile walls in coastal and estuarine settings. This is summarised in Table 3-4 and is predicated on understanding (i) asset condition (see Table 3-5), and (ii) asset maintenance regime (see Table 3-6).

The deterioration rates stated in Table 3-4 suggest that SSP in coastal/estuarine environments may last between 20-80 years (50 year median) depending on maintenance levels. These rates are intended to allow asset managers to estimate when an asset is likely to reach a specific condition grade to allow for strategic planning of asset maintenance and eventual replacement to inform high-level investment plans. As such, it does not explicitly account for localised circumstances where, for example, ALWC becomes established and accelerates deterioration (although this should be implicitly accounted for by the assignment of condition grade through regular inspection). As stated above, CIRIA (2005) highlights that the impact of corrosion, and in particular ALWC, is to significantly reduce the life of a steel structure in the marine environment compared to the expected design life. This is borne out by experience in Weymouth Harbour, where the prevalence of ALWC is considered to be one of the main factors in walls F and G having less than 1 year of residual design life only 45 years after construction (see Table 3-8).

Table 3-4 Expected deterioration rates (to move from one condition grade to the next) for steel sheet piles in coastal / estuarine settings depending on maintenance levels (from Environment Agency, 2013)

Material	**Maintenance regime *(see Table 3-6)***	**Expected deterioration time (years) to specified Condition Grade *(see Table 3-5)* from new**														
		Medium deterioration					**Fastest deterioration**					**Slowest deterioration**				
		1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Cantilevered steel	1	0	10	15	30	40	0	5	10	15	20	0	15	30	50	60
	2	0	15	25	50	60	0	10	15	25	30	0	20	40	60	70
	3	0	20	35	60	70	0	15	20	35	40	0	25	50	70	80
Anchored steel	1	0	10	15	30	40	0	5	10	15	20	0	15	30	50	60
	2	0	15	25	50	60	0	10	15	25	30	0	20	40	60	70
	3	0	20	35	60	70	0	15	20	35	40	0	25	50	70	80

Table 3-5 Asset condition grades from the Condition Assessment Manual (Environment Agency, 2012).

Condition Grade	Description of grade	Extent of defects
1	Very Good	Cosmetic defects that will have no effect on performance
2	Good	Minor defects that will not reduce overall performance of asset
3	Fair	Defects that could reduce performance of asset
4	Poor	Defects that would significantly reduce performance of asset
5	Very Poor	Severe defects resulting in complete performance failure

Table 3-6 Asset maintenance regimes as defined in Environment Agency, 2013.

Maintenance regime	Description of maintenance regime	Maintenance activities assumed under regime
1	Low/basic – do minimum repair/maintenance	Inspection + health & safety repair (annually).
2	Medium	Inspection + health & safety repair (annually). Maintenance activities for maintaining asset at Condition Grade 3 (refer to Table 3-5).
3	High	Inspection + health & safety repair (annually). Maintenance activities for maintaining asset at Condition Grade 2 (refer to Table 3-5).

3.3 Methods for addressing corrosion of steel structures in the marine environment

There is a wealth of guidance on how to design and implement measures to address corrosion of steel structures in the marine environment, including ALWC. The range of potential measures available is particularly well documented in *Management of Accelerated Low Water Corrosion in Steel Maritime Structures* (CIRIA, 2005) and this is summarised in Table 3-7.

As is evident from the information summarised in Table 3-7, some of the methods for addressing corrosion need to be considered in the initial design of steel structures as they need to be integral to the overall design and construction methodology to install them and then maintain them to achieve the design life. Other methods can be added after installation of the steel structure, but even then, consideration of their likely future need should be considered in the initial design so any additional infrastructure can be allowed for (e.g. access to power source for induced current cathodic protection).

Ultimately the decision about which approach (or combination of approaches) to take will be driven by the particular circumstances of the location in which sheet piles are to be installed, giving consideration to the following range of factors described in CIRIA (2005):

- Risk – of ALWC occurring or reoccurring for new build or replacement structures
- Extent and distribution – of ALWC for existing, already affected, structures
- Economics – financial resources available for maintenance and corrosion control; including application and maintenance (i.e. life cycle costs)*
- Effective life – how long it performs its protective function compared with the design, or remaining, life of the structure
- Accessibility – whether the protective measure can be satisfactorily applied, inspected, monitored and maintained
- Disruption – whether the protective measures can be implemented with minimal disruption to operation from installation
- Extent of protection required – given that the effects of ALWC are highly localised, the options are complete (i.e. applied to the whole structure), partial (i.e. applied in specific zone or zones) or focused protection (i.e. local at ALWC patches)
- Personnel – availability of on-site, trained personnel for regular inspection, maintenance and monitoring duties
- Health and safety issues
- Environmental implications.

*With regards to cost of the various methods listed in Table 3-7, very little data has been located on this. The main information located is that contained in the *long term costing tool for flood and coastal risk management* (Environment Agency, 2015a) and can best be summarised as follows:

- Capital construction costs for steel sheet piles are several thousands to tens of thousands of £ per metre, but exact costs depend very much on length constructed over and depth of pile needed. No differentiation is given in relation to steel thickness are material grade.
- Maintenance costs are in the order of several hundred £ per km per year. No differentiation is given to the method of maintenance applied.

Two methods from the below Table 3-7 have been used historically to address corrosion of steel structures in Weymouth Harbour; namely welding patch plates and protective paint coatings have been used as remedial measures to SSP walls that are close to or at the end of their design life. Repairs to Wall Ci were completed in March 2022 (Section 2.2.1), with both the above methods carried out to extend its design life by at least 20 years.

Table 3-7 Summary of the range of methods for addressing corrosion of steel structures in the marine environment, drawing on information contained in [1]Section 6.5.1 of Management of Accelerated Low Water Corrosion in Steel Maritime Structures (CIRIA, 2005), and [2]Durability of Steel Piling (Rowbottom et al, 2019).

Method	Brief description of method	Application in new build or replacement structures	Application in existing structures	Application in repair works
Corrosion Allowance[1, 2]	This method involves allowing for corrosion in the sheet pile thickness design specification (i.e. specifying additional steel thickness of sheet piles than needed to achieve structural requirement such that the required thickness is achieved at the end of the design list).	Requires assumption to be made on the corrosion rate to determine the thickness of additional steel required. Where long life structures are required, this would probably necessitate an impractically thick section to deal with high corrosion rates associated with ALWC. Therefore, use in conjunction with other protection method such as Cathodic Protection or coatings or Cathodic Protection in combination with coatings. This increases the cost of sheet piles as the additional thickness is applied to the length of the piles and so may be cost-prohibitive. Alternatively, it may prove more economical to increase the pile thickness locally by the attachment of plates.	Not applicable.	Generally use the maximum steel thickness for repair plates determined by ability to bend the plate to the required profile.
Welded patch plates[1]	Rather than increasing the thickness of piles over their full length, use of sacrificial plates in exposure zones subject to greater corrosion rates can provide a similar effect to increasing pile thickness at the design stage. Such plates can be included either at time of construction or added post-construction once evidence of corrosion is observed.	Requires assumptions to be made on where the ALWC will occur and the corrosion rate. There is evidence that ALWC may occur below LAT. Steel plates are more easily and cost effectively welded to the pile prior to installation, however this can cause problems when driving piles. Relies on the steel sheet pile being driven to pre-set level. If the pile hits an obstruction, the patch plate may end up at the wrong level.	Steel plates can be fitted to piles at any time. Used to provide additional thickness at thinned areas.	Used for non-structural repairs making good holing to prevent or halt the loss of backfill and/or the ingress of seawater. Not suitable for more extensive areas of damage where excessive thinning and/or holing has been identified over several pile widths with limited sound metal to weld to.
Higher grade steel[1, 2]	The use of higher grade steel is unlikely to deter onset of corrosion processes such as ALWC. The greater strength provided by higher grade steel can provide a greater factor of safety and therefore tolerance of corrosion, but this potential benefit can be offset by the greater deflection thinner, high strength steels experience under load. This would need to be given careful consideration in the design of sheet pile walls if use of higher grade steel is being considered.	Provides a greater factor of safety against structural failure and increases the effective working life of a given section. The formation of holes with possible loss of fill would probably not be delayed. Deflection of the corroded section also requires to be considered.	Not applicable.	Advantageous to specify low alloy steel composition which is more electrochemically noble than surrounding old steel. Alternatively use thicker section of mild steel (see above). Possible increased difficulty in bending and/or welding low alloy steels.
Corrosion resistant micro-alloyed steel[2]	A more recently developed technology is micro-alloyed steel that displays favourable rates of corrosion in a marine environment compared to conventional sheet pile steels. Likely to be more appropriate to consider use of this material in the design of new structures, and may allow for a smaller corrosion allowance to be applied (see above).	Provides significant reduction of corrosion rate in low water and permanent immersion zones, with proven performance by numerous in situ tests. Loss of steel thickness reduced by factor of 3 to 5 compared to conventional sheet pile steels. Provides considerable weight and cost savings compared to conventional steel piles. Fully equivalent to normal piling grades so that design structural resistances can be determined according to all relevant design codes used for steel sheet piling structures such as EN 1993-5:2007.	*No information found in literature about use of this material for existing structures, but if appropriate to use, likely to have similar implications as for steel welded patch plates (see above).*	*No information found in literature about use of this material for repair works, but if appropriate to use, likely to have similar implications as for steel welded patch plates and/or higher grade steel (see above).*

Method	Brief description of method	Application in new build or replacement structures	Application in existing structures	Application in repair works
Structural modifications[1]	Delay the loss of structural integrity *[caused by corrosion]* by moving the location of maximum bending stress away from the critical low water zone area. Really only viable to consider in design of new structures.	This could be achieved, for example, by adjusting the level of walings and tie rod system. There is evidence that ALWC may occur below LAT. Holing and loss of infill will probably still occur but the structural significance will be reduced.	This could theoretically be considered, but unlikely to provide an economical solution.	Not applicable.
Cathodic Protection[1, 2]	Cathodic Protection (CP) can be in two forms: galvanic CP which uses a more easily corroded metal as a sacrificial anode and is largely maintenance free (if designed and installed correctly and not damaged) until nears the end of design life; or impressed current CP (ICCP) which uses an external power source to promote corrosion of a sacrificial anode. These systems can be installed on sheet pile structures from the outset or after a number of years. Anodes can be expected to last for between 10-20 years before needing to be replaced. If properly designed, installed, commissioned and maintained, it can be fully effective against any form of corrosion up to about the mid tide zone. Allowance for the use of CP systems should be made in the initial design of the structure prior to construction, particularly if the ICCP approach is expected to be required as that will need to have access to a continuous power source and accounted for in ongoing carbon cost calculations (in terms of power usage).	Either galvanic CP or an impressed current CP system can be used in most situations. The choice is often determined by: the design life the mechanical robustness required, and the availability of resources, both funding for the initial installation and suitably trained personnel for the long term monitoring and maintenance, particularly in the case of an ICCP system. CP can either be installed or planned for when the structure is built. The latter approach involves preliminary engineering by a CP specialist and construction related preparations for subsequent installation.	Either galvanic CP or an ICCP system can be retrofitted to an existing structure. It is recommended that a relatively long life for the CP system is proposed because installation is a large proportion of the cost. Can be used in combination (i.e. a hybrid system), for example, to help solve “geometry” difficulties where the distribution of CP current is difficult. Special attention is needed where an existing deteriorated coating is present on the structure (i.e. possible current shielding effects below disbonded coatings). The current density required to arrest ALWC on existing structures and to maintain that condition is likely to be greater than that required for general corrosion considered in most CP standards.	The provision of partial/localised CP by local fixing of a limited number of galvanic anodes adjacent to the repair to extend the life of the repair and the welds. Applying a suitable coating will reduce the rate of consumption of the anodes which would otherwise be rapid. More regular monitoring and timely replacement of anodes will be required for this option.
Protective paint coatings[1, 2]	Paint coatings can be applied to: The whole exposed surface of the structure down to the low water zone. As (1) but to some distance below the low water zone using a limpet dam. Limit to the low water zone only using coatings that can be applied underwater. These can be added at construction stage but are prone to damage during installation which causes some coating to be removed and so loss of effect. Coatings can also be added after installation, though this can also be less effective due to problems of surface preparation and application underwater. A coating design life of 15 to 20 years can be expected from an epoxy coating with a dry film thickness of 400 microns.	Application approach (1) recommended in conjunction with Cathodic Protection (see above). The coating can be field applied (i.e. at the time of the construction or after driving of the pile) or applied under factory conditions (i.e. before driving the pile) with on-site repairs to any damaged areas. Factory applied coating systems should be VOC compliant meeting the current requirements of PG6/23. Field applied coatings will always be inferior to factory application.	In the absence of Cathodic Protection, specifications normally require Application approach (2), typically from the top of the pile to 1m below LAT. Steel surface condition in the submerged zone should be checked to confirm the required depth of coating for each application. Application approaches (1) and (2) can be used in conjunction with Cathodic Protection if the coating is compatible, applied correctly and is well bonded. Field applied coatings will be inferior to factory application due to the inevitable difficulties that will be encountered in surface preparation. For high performance coatings, surface preparation and application should be performed under dry conditions using a limpet dam. Where blast cleaning is impossible more surface tolerant coatings are available which may be applied over under prepared surfaces using less rigorous methods of cleaning (e.g. hand tool, power tool cleaning etc). The durability of such	Application approach (3) is problematic due to high risk of pitting attack if coating applied to the repair area only. Application approach (3) can be used in conjunction with local galvanic CP anodes (see above). The main purpose of the coating will be to reduce the rate of anode consumption. Coatings are available that can be applied and cured underwater but effectiveness can be variable. Since 1995 epoxies for underwater application (i.e. specifically to overcome health risk problems associated with specific curing agent) has reportedly resulted in significant deterioration in ease of application and performance properties.

Method	Brief description of method	Application in new build or replacement structures	Application in existing structures	Application in repair works
			coatings will be less than for high performance coating systems.	
Protective metallic coatings[1]	Aluminium or zinc coatings with suitable sealer topcoats can be applied prior to installation. Can be combined with a paint coating on top. They are not suitable to be installed on existing structures (i.e. post-installation) so need to be considered in the design stage prior to construction.	Can give effective long term protection if applied to the whole surface before installation. Can contain high porosity which is not always possible to seal adequately. May suffer accelerated attack in service if surface only partially coated or if used with improperly controlled impressed current CP. Can significantly reduce current required for galvanic CP.	Cannot be readily applied to an installed sheet piled wall.	Could be applied but would suffer accelerated attack (as for galvanic anodes) if restricted to repair area.
Wrappings[1]	Tape wrappings can be used to protect vulnerable areas and are typically used as part of repairs to existing structures. They are not typically specified for new sheet piles and their effectiveness post-installation is uncertain.	May be considered, but not usual.	Well established for application to skeletal structures particularly in the splash zone but can be installed both above and below water. Surface tolerant systems. Difficult to inspect steel surface and efficacy of protection after application.	Applicability on repaired tubular piles.
Concrete encasement[1, 2]	A concrete encasement can be used to protect steel piles in marine environments. Its use is often restricted to the splash zone by extending the concrete cope to below the mean high water level. However, in some circumstances, both splash and tidal zones are protected by extending the cope to below the lowest low water level which also gives protection against ALWC. Experience has shown that where the splash zone is only partially encased, a narrow zone of increased corrosion can occur at the steel-concrete junction. This is a result of electrochemical effects at the steel-concrete junction and so if applied, consideration is needed to both this issue and ensuring appropriate quality of concrete is used.	Approach has mainly been used in the past for partial protection in the atmospheric, splash and tidal zones (with galvanic CP). Can be used for full protection with the concrete extending down to bed level, in order to minimise the risk of introducing additional corrosion cells but this may not be cost effective.	Can be used to partially protect existing structures in conjunction with galvanic CP. Concrete jackets to bed level have also been successfully applied on tubular piles. Protection in the low water zone can be achieved by welding plates over every outpan (or a number of outpans) and filling the void behind with concrete. As above but without the plates. Typically, steel reinforcing bars are first welded to the inpans of the piles, the face is shuttered, the concrete poured and allowed to cure and finally the shuttering is removed.	Welding of plates and concrete infill specifically at thinned and/or holed locations.

3.4 The experience of SSP wall systems in Weymouth Harbour

Weymouth Harbour walls are constructed of four different types of SSP:

- Larssen 3/20,
- Frodingham no.5,
- Larssen LX16, and
- Larssen LX20 piles.

The four types of piles have different characteristics, with the most significant differences being the thickness of the pile and the type of clutch. The different thicknesses of SSP are detailed in Table 3-9, and they vary between 10.5mm and 17mm.

In addition, these four pile types are also likely to have differing corrosion rates in a marine environment. However, due to the wide range of environments that SSP can be used in, manufacturers tend to not specify degradation rates as they can vary significantly depending on atmosphere, exposure, environment, and climate. It is therefore not possible to use manufacturers degradation rates; thus data obtained from literature, as discussed in Section 3.1, is used here to compare against the actual condition of the SSP walls. Detailed inspections of the four pile types at the end of their initial construction period would have provided greater certainty on the life expectancy of SSP walls in Weymouth dependent on their steel grade, thickness and location, however no such data was found to be available to inform this study.

Table 3-8 below details the age of construction and the current condition of the nine steel sheet pile walls in Weymouth (JBA, 2019a). Estimated rates obtained from design information/literature (see Section 3.1) and the manufacturer stated thickness of a pile are reviewed in Table 3-9. The tidal and splash zones have been analysed as these are two areas where we can expect different deterioration rates, splash zone high and tidal zone low; thus two examples of rates of deterioration of SSP in a marine environment are listed in Table 3-9.

Table 3-10 predicts the rate of deterioration based on the number of years since construction. This prediction is based upon all walls having the same exposure and being situated in the same marine environment.

Table 3-8 Current condition and number of years to reach this condition from new of the steel sheet pile walls in Weymouth Harbour (JBA, 2019a; JBA, 2019b)

Wall Section	Approximate Age	Number of Years Since Construction	Condition Grade	Estimated Residual Life (Years remaining from 2019)	Total Expected Asset Life (Years Since Construction + Residual Life)
Ai Angling Club (Larssen 3/20 and LX 16 piles)	1977	44	5	5 - 10	49 - 54
Aii Angling Club (LX 20 piles)	1977	44	2	15 - 45	59 - 89
B Custom House Quay (Larssen 3/20 piles)	1950's Extension of capping beam: 2000	61 - 70	4	5 - 10	66 - 80
Ci Cove Row (Larssen 3/20 piles)	1950's	61 – 70	4	5 - 10	66 - 80
Cii Cove Row (Larssen LX 20 piles)	2000	21	1	20 - 60	41 - 81
D Custom House Quay (Frodingham no.5 piles)	2020	Construction in 2020			
E Peninsula Wall (Frodingham no.5 piles)	1971	50	3	10 – 30	60 - 80
F Peninsula Eastern Wall (Larssen 3/20 piles)	1977	44	5	0 - 2	44 - 46
G Peninsula Northern Wall (Larssen 3/20 piles)	1977	44	5	0 - 2	44 - 46

Table 3-9 Manufacturer stated thickness of steel sheet piles with rates of deterioration in a marine environment from two literature examples.

Wall Section	**Assumed Design Life of Steel Sheet Piles**	**Number of years since construction**	**Mean rate of Deterioration (Design/Literature) (mm/side/year)** (Fleming *et al*, 2009)	**Mean rate of Deterioration (Design/Literature) (mm/side/year)** (BS 6349-1:2000) *(refer also to Table 3-2)*	**Manufacturer stated thickness of pile (mm)** (Kapoi, 2013) (Arcelor Mittal, 2021) (Continental Steel Pte Ltd, 2021)
Ai Angling Club (Larssen 3/20 and LX 16 piles)	50	44	SZ: 0.075 TZ: 0.035	SZ: 0.08 TZ: 0.04	3/20: 11,7 LX 16: 10.5
Aii Angling Club (LX 20 piles)	50	44	SZ: 0.075 TZ: 0.035	SZ: 0.08 TZ: 0.04	12.5
B Custom House Quay (Larssen 3/20 piles)	50	61 - 70	SZ: 0.075 TZ: 0.035	SZ: 0.08 TZ: 0.04	11.7
Ci Cove Row (Larssen 3/20 piles)	50	61 – 70	SZ: 0.075 TZ: 0.035	SZ: 0.08 TZ: 0.04	11.7
Cii Cove Row (Larssen LX 20 piles)	50	21	SZ: 0.075 TZ: 0.035	SZ: 0.08 TZ: 0.04	12.5
D Custom House Quay (Frodingham no.5 piles)	50	Construction in 2020			

Wall Section	**Assumed Design Life of Steel Sheet Piles**	**Number of years since construction**	**Mean rate of Deterioration (Design/Literature) (mm/side/year)** (Fleming *et al*, 2009)	**Mean rate of Deterioration (Design/Literature) (mm/side/year)** (BS 6349-1:2000) *(refer also to Table 3-2)*	**Manufacturer stated thickness of pile (mm)** (Kapoi, 2013) (Arcelor Mittal, 2021) (Continental Steel Pte Ltd, 2021)
E Peninsula Wall (Frodingham no.5 piles)	50	50	SZ: 0.075 TZ: 0.035	SZ: 0.08 TZ: 0.04	17
F Peninsula Eastern Wall (Larssen 3/20 piles)	50	44	SZ: 0.075 TZ: 0.035	SZ: 0.08 TZ: 0.04	11.7
G Peninsula Northern Wall (Larssen 3/20 piles)	50	44	SZ: 0.075 TZ: 0.035	SZ: 0.08 TZ: 0.04	11.7

Note: SZ: Splash Zone, TZ: Tidal Zone

Table 3-10 Manufacturer stated thickness of steel sheet piles with predicted rates of deterioration in a marine environment from two literature examples.

Wall Section	Assumed Design Life of Steel Sheet Piles	Number of years since construction	Predicted mean deterioration (rate of deterioration*years since construction) (Fleming *et al*, 2009)	Predicted mean deterioration (rate of deterioration*years since construction) (BS 6349-1:2000)	Manufacturer stated thickness of pile (mm) (Kapoi, 2013) (Arcelor Mittal, 2021) (Continental Steel Pte Ltd, 2021)	Estimated pile thickness remaining **(worst case scenario)** (BS 6349-1:2000)
Ai Angling Club (Larssen 3/20 and LX 16 piles)	50	44	SZ: 3.3mm TZ: 1.54mm	SZ:3.52mm TZ: 1.76mm	3/20: 11.7 LX16: 10.5	3/20- SZ: 4.48mm TZ: 6.24mm LX16- SZ: 6.98mm TZ: 8.74mm
Aii Angling Club (LX 20 piles)	50	44	SZ: 3.3mm TZ: 1.54mm	SZ:3.52mm TZ: 1.76mm	12.5	SZ: 8.98mm TZ: 10.74mm
B Custom House Quay **(Larssen 3/20 piles)**	50	61 - 70	SZ: 4.575-5.25mm TZ: 2.135-2.45mm	SZ: 4.88-5.6mm TZ: 2.44-2.8mm	11.7	SZ: 2.4mm TZ: 5.2mm
Ci Cove Row (Larssen 3/20 piles)	50	61 – 70	SZ: 4.575-5.25mm TZ: 2.135-2.45mm	SZ: 4.88-5.6mm TZ: 2.44-2.8mm	11.7	SZ: 2.4mm TZ: 5.3mm
Cii Cove Row (Larssen LX 20 piles)	50	21	SZ: 1.575mm TZ: 0.735mm	SZ: 1.68mm TZ: 0.84mm	12.5	SZ: 10.82mm TZ: 11.66mm
D Custom House Quay **(Frodingham no.5 piles)**	50	Construction in 2020				

Wall Section	Assumed Design Life of Steel Sheet Piles	Number of years since construction	Predicted mean deterioration (rate of deterioration*years since construction) (Fleming *et al*, 2009)	Predicted mean deterioration (rate of deterioration*years since construction) (BS 6349-1:2000)	Manufacturer stated thickness of pile (mm) (Kapoi, 2013) (Arcelor Mittal, 2021) (Continental Steel Pte Ltd, 2021)	Estimated pile thickness remaining (worst case scenario) (BS 6349-1:2000)
E Peninsula Wall (Frodingham no.5 piles)	50	50	SZ: 3.75mm TZ: 1.75mm	SZ: 4mm TZ: 2mm	17	SZ: 13mm TZ: 15mm
F Peninsula Eastern Wall (Larssen 3/20 piles)	50	44	SZ: 3.3mm TZ: 1.54mm	SZ:3.52mm TZ: 1.76mm	11.7	SZ: 4.48mm TZ: 6.24mm
G Peninsula Northern Wall (Larssen 3/20 piles)	50	44	SZ: 3.3mm TZ: 1.54mm	SZ:3.52mm TZ: 1.76mm	11.7	SZ: 4.48mm TZ: 6.24mm

Note: SZ: Splash Zone, TZ: Tidal Zone

In 2019, JBA carried out condition inspections on all SSP walls which included ultrasonic thickness tests to help determine their residual design life (JBA, 2019a). When compared to the literature we generally get comparative results, assuming the piles are of the same grade and quality of steel. The total predicted deterioration in the splash zone range from 1.575mm to 5.6mm and the tidal zone from 0.735mm to 2.8mm. Wall F, a 44 year-old SSP wall is said to have a condition grade of 5, with large holes and voids at bed level and severe corrosion in the splash zone (JBA, 2019a). The literature indicates that the splash zone should have seen between 3.3mm and 3.52mm in loss of thickness. However, we know that the corrosion seen here is much worse; it is greater by 2mm in the splash zone and nearly 1mm in the tidal zone. This is likely due to several factors including atmospheric conditions, salinity of water and wave climate.

At Wall Cii, the results are very similar with the literature indicating that there is an average thickness remaining of 2.4mm in the splash zone and 5.2mm in the tidal zone. Actual mean pile thickness remaining was calculated to be 2.63mm in the splash zone and 4.82mm in the tidal zone.

Wall F is one of the most exposed walls in Weymouth Harbour. The area is relatively sheltered; however, it is subjected to easterly and north-easterly storm events. This direction of event is not the most common on the south coast, however significant wave height has reached 3.77m previously (CCO, 2021). Compared to the literature, the 8mm thick Larssen 3/20 piles have significantly deteriorated, possibly up to twice the rate and works to repair or replace the wall is needed in the coming years.

Wall Aii is in the most sheltered part of Weymouth Harbour. It was also constructed 44 years ago and is said to a have a condition grade of 2, with a remaining design life of 15 to 45 years (JBA, 2019a). The piles, LX 20 piles are 12mm thick. The literature suggests that the total predicted deterioration in the splash zone is between 3.3mm and 3.52mm and the tidal zone 1.54mm and 1.76mm.

Despite the same construction year, Walls F and Aii have condition grades of 5 and 2 respectively. The corrosion of the SSP wall is not only dependent on age, it can vary over a small spatial scale depending on change to exposure and environment, as illustrated in Figure 3-4. Wall Aii is sheltered from significant wave action; Wall F is not. Wall F is in the outer harbour and subjected to full saltwater conditions. Wall Aii is well within the harbour and it is likely the water is less saline due to the presence of the freshwater inputs from the River Wey that discharges to the sea via the harbour, which is likely to influence the corrosion rates; though there is no salinity monitoring data from points around the harbour to confirm by how much salinity may vary. The SSP differ in manufactured thickness by 4mm and may have differing properties due to their type, and this should also be considered.

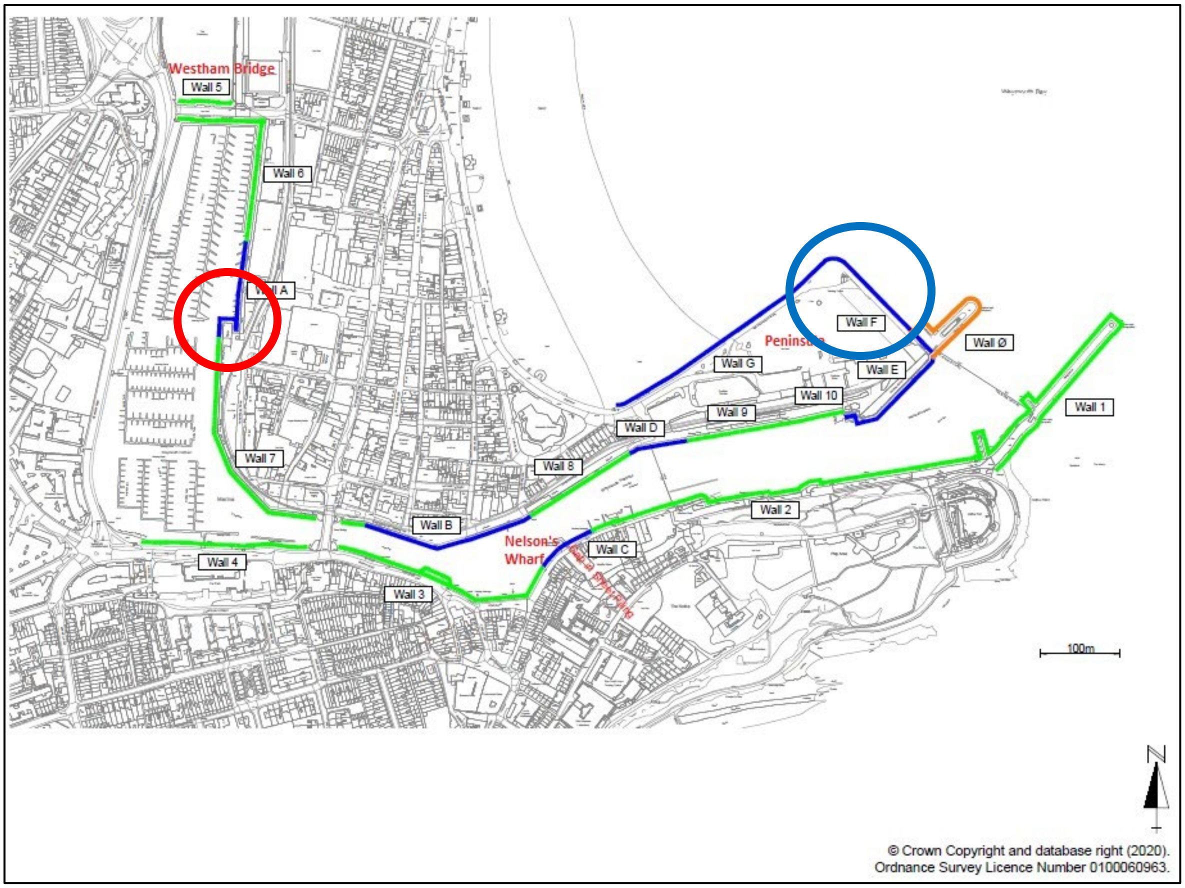

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Figure 3-4 Location of Weymouth Harbour's Steel Sheet Pile Wall F (circled in blue) and Wall Aii (circled in red).

3.4.1 Comparing the experience of SSP walls to the masonry and concrete wall systems in Weymouth Harbour

With reference to Table 3-8 above for SSP walls, and Table 3-11 below for masonry/concrete walls, comparing the expected total actual life of the different wall types in comparably similar low-energy settings within the harbour, it is notable that masonry and concrete walls generally age better than the SSP walls. This may be due to a number of factors such as the corrosion and degradation rates being much less for concrete/masonry walls simply due to the nature of materials used, or different maintenance regimes applied for different wall types since they were constructed. In the generally more sheltered, lower energy parts of the harbour, concrete/masonry walls are shown to last in excess of 100 years, compared to SSP walls which typically last 60-80 years. In the more exposed outer parts of the harbour, comparing SSP walls E, F and G to concrete/masonry Walls 1 and 2 shows that even when exposed to greater wave energy, the concrete/masonry walls last for at least 60 years and often in excess of 100 years (with maintenance), whereas the SSP walls last less than 50 years (without maintenance).

Overall, the masonry/concrete walls are also generally in better condition for their age. Wall 6 at Weymouth marina is now 112 years old and only minor remedial works to re-point masonry blocks and repair mortar has been undertaken since construction. Despite its age, it is still said to have a remaining residual design life of 20 to 60 years (JBA, 2019b). Wall 6 is, however, in the most sheltered part of the harbour and so experiences less wave energy than the walls in the outer harbour discussed above.

Wall A, a SSP wall constructed in 1977, is immediately south of Wall 6 within the inner harbour. The wall has three different types of Larssen piles; 3/20, LX 16 and LX 20 and is subjected to a very similar wave and tidal climate to Wall 6. The majority of wall A is assessed as having 5 to 10 years of residual design life remaining, which is approximately a third that of Wall 6, when comparing relative design expectancy. It should be noted that no remedial works have been undertaken on Wall A since construction.

Table 3-11 Current condition and number of years to reach this condition from new of other wall types in Weymouth Harbour (JBA, 2019a; JBA, 2019b).

Wall Section	Approximate Age	Number of years since significant reconstruction	Condition Grade	Estimated residual life (Years remaining from 2019) (JBA, 2019b)	Total Expected Asset Life (Years Since Construction + Residual Life)
1 Stone Pier	Original: 1680's Extension: 1878 Significant reconstruction: 1980's	31 - 40	2	30 – 80	61 - 120
2 Nothe Parade	Present day alignment: 1774 Significant reconstruction: 1860-1872 and 1896	125	3	20 – 60	145 - 185
3 Trinity Road	Present day alignment: 1774 Significant reconstruction: 1888, 1930 and 2001	133 New capping beam: 20	3	20 – 60	153 - 193
4 North Quay	Present day alignment: 1774 Significant reconstruction: 1824 and 1932	89	4	10 – 20	99 - 109
5 Westham Bridge	1921	100	Unknown	Unknown	>100
6 Weymouth Marina	1909	112	3	20 – 60	132-172
7 Commercial Road	Present day alignment: 1831 Significant reconstruction: 1930, 1938 and 2001	91 New capping beam: 20	3	20 - 60	111 - 151

Wall Section	Approximate Age	Number of years since significant reconstruction	Condition Grade	Estimated residual life (Years remaining from 2019) (JBA, 2019b)	Total Expected Asset Life (Years Since Construction + Residual Life)
8 Custom House Quay	Present day alignment: 1831 Significant reconstruction: 1949 - 1952	69-72	2	30 – 80	99 – 152
9 Ferry Berth 4	Present day alignment: 1840 Significant reconstruction: 1860, 1878 and 1933	88	3	20 - 60	108 - 148
10 Ferry Berth 3	Present day alignment: 1840 Significant reconstruction: 1860, 1878, 1933 and 2013	8	No condition grade due to recent construction.		Not Calculated

4 High-level wall replacement options appraisal

In this section, a high-level assessment of the whole-life technical, socio-environmental, economic cost, and carbon for different wall construction types is provided. This assessment is made for a 100 year strategic appraisal period and draws on the evidence discussed in earlier sections of this report in order to explore the challenges posed by long-term approach to FCERM using steel-sheet piles compared to other methods (i.e. masonry and concrete walls) with reference to the Weymouth Harbour case study location, though the elements considered in this assessment could be applied to other locations along the SCOPAC area or beyond.

4.1 Technical and socio-environmental

The three main wall types in Weymouth Harbour, steel, masonry and concrete have been used successfully for decades and centuries as reliable wall types with little to no consideration for how the walls can ecologically enhance the local environment and community and whether encroachment into the harbour channel has a detrimental impact on its flow rate.

The main determining factors that have previously driven selection of preferred wall types in Weymouth Harbour are:

- cost;
- the required load bearing capacity; and
- the construction methodology available due to the narrow roads in some part of the harbour.

All three wall types have their place in a harbour environment, which is dependent on the use of the quay wall. The technical and socio-environmental pros and cons of the three wall types have been reviewed in Table 4-1, whilst discussion of particular technical and socio-environmental challenges and opportunities is provided in the Sections 4.1.1 to 4.1.3.

Table 4-1 The pros and cons of each wall type from a technical / socio-environmental perspective (drawing on Mass, De Gijt & Van Heel, 2011; JacksonHyder, 2018).

Construction Material	Technical Pros	Technical Cons	Socio-Environmental Pros	Socio-Environmental Cons
Steel	○ Straight forward design ○ Initial low cost ○ Readily available ○ Faster construction ○ High strength ○ Safer and easier to construct	○ Only provides approx. 50 year design life without maintenance ○ Additional costs due to shorter design life ○ Greater corrosion and ongoing maintenance costs ○ Cannot be repaired like for like, can only be patched	○ Uniformity ○ Less encroachment ○ No need to dig foundations ○ Structurally efficient	○ Steel production has a number of environmental impacts ○ Difficult to promote ecological enhancements ○ Piling technique can cause significant vibration and noise levels and have a detrimental impact to migratory fish species and crustaceans
Concrete	○ Design life of between 50 and100 years in both precast and in situ ○ Able to vary colour and finish with relative ease ○ Precast blocks can potentially reduce construction programme ○ Can be combined with other material for a carriable finish ○ Concrete is well understood and can be fully repaired	○ Relatively more expensive initial capital costs compared to SSP, but potentially lower whole-life cost as requires less frequent replacement ○ Long lead in time for materials ○ Longer programme for construction; more so if use low-carbon concrete ○ More complex design ○ Difficult to place underwater	○ Able to incorporate ecological enhancement at the design stage or can be retro-fitted; these in turn can act as carbon stores ○ Potential to filter polluted water	○ Traditional concrete has a number of environmental impacts inc. higher carbon footprint than steel (may be offset by use of low-carbon concrete)

Construction Material	Technical Pros	Technical Cons	Socio-Environmental Pros	Socio-Environmental Cons
Masonry	○ Design life of at least 100 years ○ Locally sourced material can be used	○ Relatively more expensive initial capital costs compared to SSP, but potentially lower whole-life cost as requires less frequent replacement ○ Riskier construction as dry access is required ○ Longer programme for construction ○ Needs substantial foundations ○ Low tensile strength ○ Structure likely to be permeable ○ Maintenance of joints and drainage can be difficult	○ Able to incorporate ecological enhancement at the design stage or can be retro-fitted ○ Crevices and ledges between masonry blocks allow marine life to easily colonise ○ Potential to seaweed and other marine organisms in situ ○ Low impact on the ecological environment ○ Aesthetically pleasing	○ Construction limited to fair weather ○ Difficult transportation and construction in an historic, narrow harbour

4.1.1 Channel encroachment

The recent works to Wall D constructed a new section of SSP wall in front of an existing SSP wall. In doing so, it was necessary to construct the new wall about 1m into the harbour. If SSP walls were to be used in Weymouth Harbour for future walls in all areas, it is likely that a similar encroachment of about 1m would be required all around the harbour (so net encroachment of about 2m if assume 1m on both sides of the harbour). If walls then need to be replaced with SSP every 50 years as is the usual design life assumption for SSP (though not necessarily borne out by experience in Weymouth Harbour – see Table 3.8), then over the course of about 100 years, the cumulative effect will be to narrow the overall area of the harbour by between 4 or 6m (depending on assuming two or three rounds of SSP wall construction); which equates to a 2.5-3% reduction in harbour area for each round of SSP construction.

For masonry and concrete walls, the encroachment is likely to be similar of between 1m and 3m into the harbour dependent on the size of masonry block or the amount of concrete necessary. However, the encroachment will total less than a SSP wall over a 100 year period as only 1 round of replacement is necessary. Over the course of about 100 years, the cumulative effect will be to narrow the overall area of the harbour by between 2 or 4m.

It should be noted that whilst encroachment in Weymouth Harbour has been undertaken in constructing new SSP walls, it is not always possible and/or appropriate to do so in all locations; for example where it would impact designated intertidal habitat and so require compensatory habitat to be provided. In such cases, different construction methods may be required such as removing old SSP and driving new SSP along the same alignment.

4.1.2 Ecological enhancement potential

Whilst harbour walls are having to be replaced for flood protection and erosion control, these structures are also needed for commercially valuable activities in the harbour. However, ongoing harbour wall replacement can also have negative ecological impacts, some of which can potentially be mitigated by positive ecological enhancements which are achievable to different extents depending on the wall construction materials used.

Ecological enhancement of coastal infrastructure on the south coast of England is currently being studied as part of the MARine INfrastructures EFFects (MARINEFF) project, which is funded by INTERREG, aiming to create a collaborative approach to sharing solutions and policy learning between the UK and France (INTERREG, 2022). It is focusing on two different locations; Sandbanks/Whitley Lake area of Poole Harbour in Dorset, and Bouldnor on the Isle of Wight.

The aim of the MARINEFF project is to ‘contribute to reducing the negative impacts of marine infrastructures on ecosystems and turning them into structures that will help protect ecosystems and biodiversity in the Channel area’. The study involves proposing new materials and ecological functions that currently have a negative impact on ecosystems. The project also aims to promote sustainable green tourism by developing new marine infrastructures and generating employment to aid the effort to restock commercial species of fish and shellfish (Channel Manche, 2022a).

Ninety artificial rockpools have been installed along ~200m of concrete seawall at Poole Harbour and Bouldnor. At both sites the rockpools were installed on vertical surfaces comprised of smooth concrete. Extensive surveys to understand the existing species were undertaken before installation to gain a baseline; baseline species identified included barnacled sea snails and types of seaweed (Bournemouth University, 2021).

Figure 4-1 Artificial rockpools constructed on a vertical wall comprised of smooth concrete (Channel Manche, 2022b).

Extensive monitoring was undertaken over a two year period to not only assess any new or re-emerging species, but to also judge their effectiveness at different spatial scales; the tidal height, the wall section (~2m wide), the entire stretch of wall (~80m) and between both sites (Bournemouth University, 2021).

Since installation, a total of 29 new species have been found at the two respective sites, including a *Montagu's Blenny,* a rockpool specific species which has never been seen before in Poole Harbour (Bournemouth University, 2021). The study to date has been deemed a success in assisting and protecting ecosystems and biodiversity. A system that can be retro-fitted to an existing structure, at relatively low cost, using low carbon concrete and have little impact on local communities, is a positive step and there is all likelihood that we will see the installation of artificial rockpools on new and existing concrete structures across the south coast when the benefits of this study can be verified.

The artificial rockpools, also known as Vertipools, have previously been installed at a commercial port at Fishbourne on the Isle of Wight (Artecology, 2022). Due to planning conditions, the port authority was required to deal with the designated and protected marine features present. The artificial rockpools allow for a practical solution for clients, designers, contractors and regulators to meet local and national goals on ecological enhancement (Artecology, 2022).

Figure 4-2 Artificial rockpools (circled) constructed on the car ramp stanchions at Fishbourne, Isle of Wight (Artecology, 2022).

A group of six artificial rockpools have been installed in an array between mean high and low water, which are grouped to maximise their effect in increasing biodiversity across the structure (Artecology, 2022). ABPmer have consistently monitored the rockpools and have noted over 30 species from the array in the first year, an increase in 100% in species richness (Artecology, 2022).

The project team has noted three successful outcomes of the project:

1) The ferry operators which use the port are said to be encouraged by the results and would actively look at encouraging port authorities in using the rockpools when maintaining or replacing harbour infrastructure.

2) Community engagement has been widely used during the project and is said to have been positive.

3) The key outcome has been the positive net gain on biodiversity in a busy port environment in one of the busiest shipping areas in the UK (Artecology, 2022).

In addition to the two above studies, a further example of ecological enhancement of coastal infrastructure is the Ecoformliner Wall that has recently been installed as part of the North Portsea Island Coastal Defence Scheme. This has incorporated ecological enhancement in the form of concrete eco panels (Coastal Partners, 2021; Mackley, 2021). The Ecoformliner Wall (see Figure 4-3) is the first textured seawall specifically designed for inter-tidal ecology in the UK, and will provide a habitat for marine plant and animal species. The design provides shelter but also retains moisture to provide habitat for marine flora and fauna to thrive (Mackley, 2021).

Figure 4-3 Ecoformliner Wall Curve at the North Portsea Island Coastal Defence scheme (Coastal Partners, 2021).

The wall was imprinted during construction, which means the texturing is part of the actual sea defence giving it a design life of 100 years. It has had a successful trial, but not without difficulty as texturing was found to be a delicate and lengthy process. The panels are relatively large and had to be treated with great care in order for the design to stay completely intact and time had to be given in order for the wax pre-treatment to cure and then release from the concrete (Mackley, 2021).

As well as the environmental benefits, the Ecoformliner Wall is expected to have practical advantages. The vegetation should reduce temperature fluctuations, reduce salt ingress and egress into the local ground water and absorb wave energy (Mackley, 2021). These are seen as key benefits due to the location of the wall, Langstone Harbour near Portsmouth, which is both a Special Area of Conservation (SAC) and a Special Protection Area (SPA).

To date, this study has found that ecological enhancements are more widely used on concrete and masonry walls rather than SSP walls. Enhancements can be installed to concrete and masonry during construction and retrospectively in order to allow marine flora and fauna to thrive. From discussion with Bournemouth University, we understand that there are some ongoing trials of attaching artificial rockpools retrospectively to SSP walls (similar to the Vertipools described above, but with different fixings) but to date no findings are believed to have been published on their success or otherwise. From a practical point of view, due to the limited and still ongoing research about attaching such features to SSP walls, there remain more uncertainties about how this can be best achieved compared to the greater confidence of applying such enhancements to concrete/masonry walls; for example, is it better to do post-installation of ecological enhancement once SSP walls have been placed, or can ecological enhancements be incorporated during the design stage to SSP walls. Further understanding of these questions would be a useful focus of further research.

4.1.3 Potential for low-carbon concrete

Concrete is the main construction material globally, making up 70% of coastal and marine infrastructure. Traditional concrete is a poor substrate for biodiversity and is considered toxic to many marine organisms due to its surface chemistry which can impair settlement. Additionally, the carbon footprint in order to produce traditional concrete is large due to large quantities of carbon dioxide during calcination and fossil fuels are used in the burning process (ECOncrete, 2019).

Many of Weymouth’s existing concrete walls are nearing the end of their 100 year design life and many require a full replacement in the coming decades due to both their condition and to increase their flood defence level. The development of concrete material science in recent decades means it is now possible to choose from a number of more ecologically and environmentally friendly concrete products (compared to traditional concrete).

There are a range of low carbon concrete solutions already available including ECOncrete, CEMFREE (DB Group, 2022) and Green Concrete (Specify Concrete, 2022). Taking the ECOncrete product as an example, this product has been used in port and marine environments across the world (ECOncrete, 2022a). The product allows a project team to meet environmental goals as it can act as a carbon store and filter polluted water, but also business goals as it is priced competitively (ECOncrete, 2022b).

In the USA, ECOncrete has been used widely at a number of different locations, including San Diego and New York City. In San Diego, ECOncrete was used to design a single layer of rock armour that brings structural support and artificial habitats. 74 Interlocking units were constructed using ECOncrete and were constructed in a way to mimic rockpools and cove habitats for marine life (Figure 4-3) (ECOncrete, 2022c). In New York City, similar units were constructed around two existing piers to add structural stabilisation, create a wider tidal zone habitat and allow for opportunity for the community to engage in local marine life. Monitoring has revealed high biodiversity, with a resurgence of native species and sound protection of the existing piers (ECOncrete, 2022d).

ECOncrete can provide a low carbon solution to the pressures of coastal development and the increasing coastal urbanisation. The technology provides high performance environmentally sensitive concrete which also increases strength and durability. It also reduces the carbon footprint as it significantly reduces fossil fuel emissions during production and lowers the amount of carbon dioxide present in the concrete by up to 70%. Furthermore, it causes a reduction in carbon footprint through biological processes. The more marine organisms there are in our oceans, the more carbon can be stored in calcitic skeletons of marine organisms (ECOncrete, 2019).

ECOncrete has been successfully used retrospective to increase biodiversity and ecologically enhancement areas. However, it is yet to be used and proven as a viable type of concrete to constructed quay walls that require a high load bearing capacity.

Figure 4-3 Interlocking unit constructed in San Diego (ECOncrete, 2020c).

4.1.4 Potential for low-carbon steel sheet piles

Steel is widely used in the marine environment but continues to use production methods that produces large amounts of carbon, with low-carbon options still in their infancy.

In 2021, ArcelorMittal started to produce the EcoSheetPile^{TM} Plus, a SSP that produces only 370kg of CO_2 per tonne compared to high carbon SSPs at 2.3 tonnes of CO_2 per tonne. The product uses 100% recycled material and 100% renewable energy sourced from a sustainable power grid. Third party studies note that the EcoSheetPile^{TM} Plus is the most sustainable construction material, with a case study showing an 88% difference in greenhouse gas emission being the EcoSheetPile^{TM} Plus and a high-carbon alternative (ArcelorMittal, 2022a).

This product has potential to be used in FCERM settings, however some of the carbon reductions seen in its production are offset by potential higher emission in transport, installation and maintenance (ArcelorMittal, 2022b). No case studies can be found where the product has been used in the marine environment in the UK and this research will need to be carried out to give confidence to both designers and contractors before the product is utilised.

4.2 Economic (costs)

To enable comparison, whole life capital cost estimates have been calculated in order to assess the relative cost of replacing harbour walls with the three differing wall types over a 100 year period.

Table 4-2 summarises the whole life replacement and maintenance costs estimated for each wall around Weymouth Harbour. Capital replacement costs have been derived using a combination of Environment Agency guidance (2015a; 2015b) and recent experience as harbour wall D was replaced with a SSP wall in 2019. It should be noted that the Environment Agency guidance gives no distinction between concrete and masonry wall costs.

Maintenance costs, which are based on significant maintenance every 20 years, have been taken from Dorset Council’s most recent studies into the condition of Weymouth harbour walls and details costs and recommended maintenance (JBA, 2019a; 2019b).

Table 4-2 Estimated whole life capital and maintenance costs of replacing the three different wall types over a 100 year period.

Wall Section	Total Wall Length (m)	Cost of replacing and maintaining with a Concrete wall for a 100 year period (assuming one round of construction)	Cost of replacing and maintaining with a Masonry wall for a 100 year period (assuming one round of construction)	Cost of replacing and maintaining with a Steel Sheet Pile wall for a 100 year period (assuming two rounds of SSP construction)
Masonry / Concrete Walls				
1 Stone Pier	583	£7,096,859	£7,096,859	£21,983,181
2 Nothe Parade	525	£6,390,825	£6,390,825	£19,796,175
3 Trinity Road	300	£3,651,900	£3,651,900	£11,312,100
4 North Quay	214	£2,605,022	£2,605,022	£8,069,298
5 Westham Bridge	210	£2,556,330	£2,556,330	£7,918,470
6 Weymouth Marina	157	£1,911,161	£1,911,161	£5,919,999
7 Commercial Road	330	£4,017,090	£4,017,090	£12,443,310
8 Custom House Quay	149	£1,813,777	£1,813,777	£5,618,343
9 Ferry Berth 4	143	£1,740,739	£1,740,739	£5,392,101
10 Ferry Berth 3	150	£1,825,950	£1,825,950	£5,656,050
Steel Sheet Pile Walls				
Ai Angling Club (Larssen 3/20 and LX 16 piles)	42	£511,266	£511,266	£1,583,694
Aii Angling Club (LX 20 piles)	28	£340,844	£340,844	£1,055,796
B Custom House Quay (Larssen 3/20 piles)	200	£2,434,600	£2,434,600	£7,541,400
Ci Cove Row (Larssen 3/20 piles)	28	£340,844	£340,844	£1,055,796
Cii Cove Row (LX 20 piles)	29	£353,017	£353,017	£1,093,503
D Custom House Quay (Frodingham no.5 piles)	76	£925,148	£925,148	£2,865,732

Wall Section	Total Wall Length (m)	Cost of replacing and maintaining with a Concrete wall for a 100 year period (assuming one round of construction)	Cost of replacing and maintaining with a Masonry wall for a 100 year period (assuming one round of construction)	Cost of replacing and maintaining with a Steel Sheet Pile wall for a 100 year period (assuming two rounds of SSP construction)
E Peninsula Wall (Frodingham no.5 piles)	169	£2,057,237	£2,057,237	£6,372,483
F Peninsula Eastern Wall (Larssen 3/20 piles)	168	£2,045,064	£2,045,064	£6,334,776
G Peninsula Northern Wall (Larssen 3/20 piles)	335	£4,077,955	£4,077,955	£12,631,845
Totals	**3,836**	**£46,695,628**	**£46,695,628**	**£144,644,052**

The replacement frequencies assumed in the cost estimates presented in Table 4-2 have been set at two rounds of SSP wall replacement, and 1 round of concrete and masonry replacement over a 100 year period; reflecting the different expected design life of the three wall types. Masonry and concrete walls have a design life of at least 100 years, and in some cases in Weymouth Harbour, have well exceeded this life with regular maintenance. SSP walls assume a design life of up to 50 years, although recent experience shows that this could be shorter or longer for this wall type in different parts of Weymouth Harbour; for example, with ALWC being prevalent in the harbour and being one of the main factors in walls F and G having less than 1 year of residual design life only 45 years after construction (see Table 3-8).

In comparing the relative costs presented in Table 4-2, it is also important to note that it is notoriously difficult to accurately estimate cost associated with replacing harbour walls as no one location is the same. Numerous factors can cause estimates to vary considerably, including the design height of the wall, the necessary load bearing capacity, estimated wave action, the number of construction stages needed, licences and permits and price and availability of materials and labour (GreenCoast, 2019). As such, for the purpose of this study only high level cost estimates for replacing walls with masonry or concrete have been calculated using the following indicative rates:

- For concrete and masonry wall replacement, the cost rate of £10,932 per metre was used. This is taken from Environment Agency (2015a; 2015b) guidance and is representative of reinforced concrete quay wall, masonry facing, including water cavity to the rear, some piled, counter walls at up to 6.5m in height. It should be noted that this rate information is for a wall in a fluvial setting, to which most of Weymouth Harbour is. Costs for coastal projects are limited in numbers and vary significantly (Environment Agency, 2015b).
- For SSP wall replacement, the cost rate of £17,854 per metre was used. This rate is based on the 2019 actual out-turn costs to replace the 76m harbour wall D with a cantilevered SSP wall (see Section 2.2.2). This cost is representative of recent market prices, pre-Brexit and Covid-19, and gives the best indication of costs to replace SSP quay walls in a harbour setting.

  The actual out-turn costs to replace harbour wall D was used in preference to the EA 2015 cost rate information because it represents actual cost rates. In the cost estimation report, only the cost for building a new reinforced concrete quay wall, with masonry face is given. ‘Piling to quay wall’ is represented with a cost of £3,167 per metre, which this study has found to be significantly less than actual out-turn costs as it is not representative of piling a brand new SSP wall. (EA, 2015b).

  Maintenance costs have been assumed at £125 per metre per annum for masonry/concrete walls, and £200 per metre per annum for SSP walls. These estimated costs have been derived from the most recent condition surveys in Weymouth harbour (JBA 2019a; 2019b). The types of maintenance assumed for masonry and concrete walls are repointing blockwork, filling any voids behind the wall face, replace sealant on expansion joints and toe protection due to scour. SSP walls usually require more costly and extensive maintenance by patching/welding holes in the piles, filling voids behind the wall, removing corrosion product, repainting and cathodic protection if applicable to extend its design life. These measures can add up to 20 additional years to the design life of an SSP wall based on experience at Weymouth Harbour.

4.3 Whole-life carbon

In line with Environment Agency guidance (Environment Agency, 2016; 2021), in order to assess the potential carbon impact of different wall construction approaches at the strategic level being considered in this study, the Environment Agency's Carbon Modelling Tool (v7.7, issued 8th July 2022) was used to assess the following scenarios (assuming the walls are defined as "Tidal – Retaining" walls in all cases):

1) Replace all harbour walls with steel sheet piles once in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete. *An unlikely scenario given experience in Weymouth Harbour, but included in analysis as this is the assumption in the SOC (see Section 2.1.1).*

2) Replace all harbour walls with steel sheet piles twice in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete. *The most likely scenario given experience in Weymouth Harbour.*

3) Replace all harbour walls with steel sheet piles three times in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete. *An unlikely scenario given experience in Weymouth Harbour, but included in analysis for comparison.*

4) Replace all harbour walls with concrete walls once in 100 years; assume concrete thickness of 2m.

5) Replace all harbour walls with concrete walls once in 100 years; assume concrete thickness of 3m.

Table 4-3 summarises the key dimensions assumed in defining the area (in m^2) of SSP and volume (in m^3) of concrete assumed in the carbon calcs. Table 4-4 then summarises the carbon budgets for each of the five scenarios generated by the Carbon Modelling Tool using the details stated in Table 4-3 in the following way:

- For the scenario of one round of steel sheet pile walls in 100 years, it is assumed that this involves 57,540m^2 of SSP wall, and 57,540m^3 of concrete. For scenarios involving two or three rounds of steel sheet pile walls in 100 years, these values are multiplied accordingly.
- For the scenario of constructing concrete walls once in 100 years, it is assumed that a concrete volume of 115,080m^3 is required for a wall thickness of 2m, and a concrete volume of 172,620m^3 for a wall thickness of 3m.

From this assessment of carbon budgets, it can be observed that if only one round of wall replacement were to be assumed in a 100 year appraisal period, comparing scenarios 1, 4 and 5 shows that use of SSP once in 100 years has an estimated whole life carbon total of 101,971 tonnes CO2e, compared to 97,616 to 146,424 tonnes of CO2e for the concrete wall options. In this case, use of concrete to construct a 2m thick wall once in 100 years a slightly lower carbon impact compared to using SSP once in 100 years, whereas a 3m thick concrete wall is estimated to have a higher carbon impact than SSP.

If whole life carbon were considered comparing just these three scenarios then the preferred option of SSP wall replacement all around Weymouth Harbour as identified in the SOC (see Section 2.1.1) would potentially not be the lowest carbon option depending on the assumptions made (in this case the thickness of the concrete walls).

However, as demonstrated in Section 3.4.1 SSP walls in Weymouth Harbour do not last 100 years, whereas concrete (and masonry walls) exceed 100 years life; therefore it should be assumed in a whole-life assessment that SSP walls would need to be replaced at least two times in a 100 year period.

As such, a more appropriate whole-life assessment in terms of carbon budget at least requires comparing scenario 2 and with scenarios 4 and 5. Doing so shows that replacing SSP walls twice in 100 years gives a whole life carbon total of 203,941 tonnes CO2e; this is greater than the total estimated for both scenarios 4 and 5 irrespective of the wall thickness assumed. The preferred option in this case in terms of whole life carbon would clearly be to use concrete or masonry walls.

Taking this further and assuming that SSP walls may have to be replaced three times in a 100 year appraisal period (e.g. year 0, year 50 and year 100), comparison of scenario 3 with scenarios 4 and 5 is required. Replacing SSP walls three times in 100 years gives a whole life carbon total of 305,912 tonnes CO2e; this is even greater than the total whole life carbon estimated for both scenarios 4 and 5, irrespective of the wall thickness assumed. In this case, the preferred option would again be for concrete wall replacement all around Weymouth Harbour in respect of whole life carbon.

Based on this relatively simplistic assessment using the Carbon Modelling Tool, it is demonstrated that at the strategic level it is important to consider a range of wall construction types and to develop a reasonable level of confidence in the likely wall dimensions and replacement frequency at this strategic level; rather than delaying this to the more detailed assessment required at Outline Business Case stage onwards.

It should also be noted that it was not possible to compare all wall construction options in terms of whole life carbon, as the Carbon Modelling Tool does not include data with regard masonry wall construction methods. Additionally, due to the Carbon Modelling Tool being something of a black-box tool, it is not clear what is and is not included by way of carbon associated with each material / construction methodology, nor if it includes for the carbon intake potential for ecological enhancements that can be fitted to varying degrees to the different wall construction methods.

Whilst this work demonstrates the case for thinking more deeply at the strategic level about whole-life CO2, it also causes further questions to be asked about the weight given to total whole life carbon in the decision-making process when put alongside other decision criteria to select a final preferred option to move forward with. For example, should more weight be given to the lowest carbon option even if it is more expensive than a cheaper, but higher carbon, option? Who then pays for the additional cost? To examine this a little further in this research, the UK Government’s

Department for Business, Energy and Industrial Strategy guidance (BEIS, 2021) on valuing carbon in monetary terms (£/tCO2) has been used to multiply the Whole Life Carbon (tonnes CO2e) values in Table 4-4 and give a monetary estimate of the CO2 values in cash terms. These calculations are shown in Table 4-5. The difference in monetary terms between the various scenarios is then compared in Table 4-6.

From Table 4-6 it is observed that if comparing more than one round of SSP wall replacement to a concrete wall, there is a potential monetary difference in cash terms of potentially millions to tens of millions of £ (depending on concrete wall thickness) if two rounds of SSP is needed, which is the most likely scenario in Weymouth Harbour.

Table 4-3 Key parameters used to calculate inputs to the Carbon Modelling Tool.

Wall Section	Total Wall Length (m)	Assumed total length of pile (m)*	Volume of Concrete (m3) for wall replacement - 1m wall thickness	Volume of Concrete (m3) for wall replacement - 2m wall thickness	Volume of Concrete (m3) for wall replacement - 3m wall thickness	Area of SSP (m2) for wall replacement
Masonry / Concrete Walls						
1 Stone Pier	583	15	8,745	17,490	26,235	8,745
2 Nothe Parade	525	15	7,875	15,750	23,625	7,875
3 Trinity Road	300	15	4,500	9,000	13,500	4,500
4 North Quay	214	15	3,210	6,420	9,630	3,210
5 Westham Bridge	210	15	3,150	6,300	9,450	3,150
6 Weymouth Marina	157	15	2,355	4,710	7,065	2,355
7 Commercial Road	330	15	4,950	9,900	14,850	4,950
8 Custom House Quay	149	15	2,235	4,470	6,705	2,235
9 Ferry Berth 4	143	15	2,145	4,290	6,435	2,145
10 Ferry Berth 3	150	15	2,250	4,500	6,750	2,250
Steel Sheet Pile Walls						
Ai Angling Club (Larssen 3/20 and LX 16 piles)	42	15	630	1,260	1,890	630
Aii Angling Club (LX 20 piles)	28	15	420	840	1,260	420
B Custom House Quay (Larssen 3/20 piles)	200	15	3,000	6,000	9,000	3,000
Ci Cove Row (Larssen 3/20 piles)	28	15	420	840	1,260	420
Cii Cove Row (LX 20 piles)	29	15	435	870	1,305	435
D Custom House Quay (Frodingham no.5 piles)	76	15	1,140	2,280	3,420	1,140

Wall Section	Total Wall Length (m)	Assumed total length of pile (m)*	Volume of Concrete (m3) for wall replacement - 1m wall thickness	Volume of Concrete (m3) for wall replacement - 2m wall thickness	Volume of Concrete (m3) for wall replacement - 3m wall thickness	Area of SSP (m2) for wall replacement
E Peninsula Wall (Frodingham no.5 piles)	169	15	2,535	5,070	7,605	2,535
F Peninsula Eastern Wall (Larssen 3/20 piles)	168	15	2,520	5,040	7,560	2,520
G Peninsula Northern Wall (Larssen 3/20 piles)	335	15	5,025	10,050	15,075	5,025

*In lieu of any other data, a total pile length of 15m has been assumed all around the harbour based on WSP (2021b).

Table 4-4 Carbon Modelling Tool outputs for each wall replacement scenario assessed.

Scenario	1	2	3	4	5
Scenario Description	**Replace all harbour walls with steel sheet piles once in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete**	**Replace all harbour walls with steel sheet piles twice in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete.**	**Replace all harbour walls with steel sheet piles three times in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete.**	**Replace all harbour walls with concrete walls once in 100 years; assume concrete thickness of 2m.**	**Replace all harbour walls with concrete walls once in 100 years; assume concrete thickness of 3m.**
Capital - Materials (A1) (tonnes CO2e)	46,608	93,216	139,824	56,386	84,578
Capital - Transport (A2) (tonnes CO2e)	3,885	7,770	11,655	6,249	9,374
Capital - Installation (A5) (tonnes CO2e)	2,037	4,074	6,110	2,650	3,975
Operational - Use (B1) (tonnes CO2e)	20	39	59	0	0
Operational - Maintenance (B2) (tonnes CO2e)	6,268	12,537	18,805	7,957	11,935
Operational -Repair (B3) (tonnes CO2e)	1,217	2,434	3,651	1,989	2,984
Operational - Energy (B1) (tonnes CO2e)	0	0	0	0	0
Replacement - Materials (B4) (tonnes CO2e)	23,593	47,187	70,780	0	0
Replacement - Transport (B4) (tonnes CO2e)	1,640	3,281	4,921	0	0
Replacement - Installation (B4) (tonnes CO2e)	477	953	1,430	0	0
Refurbishment (B5) (tonnes CO2e)	15,667	31,335	47,002	22,302	33,453
Demolition (C1 -C2) (tonnes CO2e)	2,674	5,347	8,021	2,072	3,108
Residual (D) (tonnes CO2e)	-1,745	-3,490	-5,235	-858	-1,287
Whole Life Carbon (tonnes CO2e)	**101,971**	**203,941**	**305,912**	**97,616**	**146,424**
Whole Life carbon - slope uncertainty	12%	12%	12%	0%	0%

Table 4-5 Whole Life Carbon expressed in monetary (cash not discounted) terms using £/tCO2 values published by the UK Government's Department for Business, Energy and Industrial Strategy (2021).

Scenario	1	2	3	4	5
Scenario Description	**Replace all harbour walls with steel sheet piles once in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete**	**Replace all harbour walls with steel sheet piles twice in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete.**	**Replace all harbour walls with steel sheet piles three times in 100 years; assume encroach 1m into harbour each time, with that distance back-filled using concrete.**	**Replace all harbour walls with concrete walls once in 100 years; assume concrete thickness of 2m.**	**Replace all harbour walls with concrete walls once in 100 years; assume concrete thickness of 3m.**
Whole Life Carbon (tonnes CO2e) (from Table 4-4)	**101,971**	**203,941**	**305,912**	**97,616**	**146,424**
Whole life carbon value in £, using the Low Series 2022 rate (£124/tCO2)	£12,644,361	£25,288,722	£37,933,083	£12,104,344	£18,156,516
Whole life carbon value in £, using the Central Series 2022 rate (£248/tCO2)	£25,288,722	£50,577,444	£75,866,167	£24,208,688	£36,313,031
Whole life carbon value in £, using the High Series 2022 rate (£373/tCO2)	£38,035,054	£76,070,108	£114,105,162	£36,410,647	£54,615,971

Table 4-6 Comparing whole life carbon monetary (cash not discounted) values between different SSP and Concrete wall scenarios.

	Difference in £ value of whole life carbon between compared scenarios using values from Table 4-5 (NB: red cells mean SSP carbon is more expensive than compared concrete wall option)		
Scenarios being compared	**Low Series 2022 rate (£124/tCO2)**	**Central Series 2022 rate (£248/tCO2)**	**High Series 2022 rate (£373/tCO2)**
1 round of SSP versus 2m thick concrete wall	-£540,017	-£1,080,035	-£1,624,407
2 rounds of SSP versus 2m thick concrete wall	-£13,184,378	-£26,368,757	-£39,659,461
3 rounds of SSP versus 2m thick concrete wall	-£25,828,740	-£51,657,479	-£77,694,515
1 round of SSP versus 3m thick concrete wall	£5,512,155	£11,024,309	£16,580,916
2 rounds of SSP versus 3m thick concrete wall	-£7,132,207	-£14,264,413	-£21,454,138
3 rounds of SSP versus 3m thick concrete wall	-£19,776,568	-£39,553,135	-£59,489,192

5 Summary & conclusions

In the SCOPAC region (and elsewhere), coastal Risk Management Authorities (RMAs) maintain many FCERM assets that comprise steel sheet pile (SSP) walls. These walls are known to suffer from Accelerated Low Water Corrosion (ALWC) problems, and as such many of these walls use surface corrosion protection systems such as cathodic protection to extend the life of the piles, with varying degrees of success.

The use of SSP to replace existing walls is often identified as the preferred long-term approach to ongoing coastal flood risk management in these areas (as opposed to retaining, or changing to, masonry/concrete solutions). In setting this long-term strategic direction, the life of SSP in the marine environment is typically assumed to be 50 years (the median life expectancy defined in Environment Agency (2013) asset deterioration guidance); thus, at least two periods of steel sheet pile replacement over a 100 year appraisal period are frequently included in the economic case in recognition of the rate of degradation of steel sheet piles in the marine environment. This is not always compared to the whole life costs associated with concrete/masonry walls which are typically designed to be constructed once in a 100 year appraisal period with a service life of 100 years or more (CIRIA, 2010; CIRIA, 2015).

If SSP walls are to continue to be the preferred way of managing coastal flood risk in these areas into the longer-term, then there is a need to understand how the expected scheme design life of these assets can be achieved and potentially extended beyond current day levels using corrosion protection systems such as cathodic protection in order to maximise investments. In doing so, there is also a need to consider the longer-term sustainability of such an approach based on repeated construction of SSP walls over a whole-life appraisal period.

This research has undertaken a desk-based study of some of the challenges posed by a long-term approach to FCERM using SSP walls compared to other methods (i.e. masonry and concrete walls), as described above, in order to illustrate these challenges and to prompt discussion in the wider industry; using experience at Weymouth Harbour in Dorset as a case-study. This case-study location was selected as it provides a range of information about all three wall types that have been installed over decades and centuries in the same system, so allowing for ready comparison of the rates of deterioration of SSP walls to other construction types in context of a common environment. The information presented in this report shows that around Weymouth Harbour:

- It is notable that masonry and concrete walls generally age better than the SSP walls; this may be due to a number of factors such as the corrosion and degradation rates being much less for concrete/masonry walls simply due to the nature of materials used, or different maintenance regimes applied for different wall types since they were constructed. In the more sheltered, lower energy parts of the harbour, concrete/masonry walls are shown to last in excess of 100 years, compared to SSP walls which typically last 60-80 years. In the more exposed outer parts of the harbour, comparing SSP walls F and G to concrete/masonry Walls 1 and 2 shows that even when exposed to greater wave energy, the concrete/masonry walls last for at least 60 years and often in excess of 100 years (with maintenance), whereas the SSP walls may only last about 50 years (without maintenance).

- Overall, the masonry/concrete walls are also generally in better condition for their age. The majority of the concrete and masonry walls are in excess of 100 years old yet are considered to still be in a good to fair condition in the main, whereas the majority of SSP walls – built much more recently – are in a poor to very poor condition – indicating that the life expectancy of SSP walls in this setting is 50-60 years. It is important to note that none of the SSP walls around Weymouth Harbour have undergone routine maintenance and corrosion protection systems have only been used when a wall is at or close to the end of its design life. This research has highlighted that a range of corrosion protection systems are available from construction or much earlier in the design life of a SSP wall. As such it is not possible to assess if cathodic protection would have aided extending the life expectancy of the SSP walls in this setting by comparing walls with and without such systems.

These findings are in line with what is typically expected and highlights that the strategic assumption made about only replacing these walls once within a 100 year period in Weymouth Harbour is questionable.

Having identified the experience of existing walls in Weymouth Harbour, this research has undertaken a high-level assessment of the whole-life technical, socio-environmental, economic cost, and carbon implications for future replacement of these walls assuming different wall construction types, in order to explore the challenges posed by long-term approach to FCERM using steel-sheet piles compared to other methods (i.e. masonry and concrete walls), in order to illustrate these challenges and to prompt discussion in the wider industry with reference to the Weymouth Harbour case study location, though the elements considered in this assessment could be applied to other locations along the SCOPAC area or beyond when exploring possible wall replacement options. The key findings of this high-level assessment for the case study site are:

- Based on EA costings data alone, SSP walls are a lower initial cost compared to concrete/masonry walls. They are also quicker to construct, but do not last as long so have a higher maintenance cost and require more frequent replacement incurring additional costs.
- Comparing EA costings data to actual costs for SSP wall construction in Weymouth Harbour in recent years draws into question the realism in the EA costings data, as actual costs are much higher than EA guidance. Whilst it is likely that a similar finding would be found if recent costs for concrete or masonry walls was available to compare to EA costings data, this highlights the importance at the strategic level of ensuring use of the same cost-estimating basis to allow comparison between options to the same baseline. Given the actual recent costs are much higher than EA costings data, it also highlights the importance of ensuring strategic option cost assumptions, and impact on economic case, are robustly sensitivity tested. It may even be worth seeking realistic cost estimates through early contractor involvement to provide greater confidence in viability of strategic options at the strategic study level.
- SSP walls appear to be more challenging to incorporate ecological enhancements into the design and/or retrospectively compared to concrete/masonry walls, so the potential to improve biodiversity in future wall replacements appears greater with concrete/masonry walls.
- The future construction of new walls in SSP, concrete or masonry are likely to encroach on the harbour channel area to similar extents if assuming a one-off replacement, though

with each round of SSP wall construction the encroachment will increase more than concrete/masonry walls over the longer-term appraisal period. No assessment of long-term encroachment on water flows in the harbour channel in the wider area has been made, but could be worth investigating further as part of future modelling to develop the design of any future tidal barrier in Weymouth Harbour.

- Depending on wall thickness assumed, concrete walls have a similar or higher carbon impact when using traditional concrete than SSP walls on a single construction in 100 years, but if a second (or potentially third) round of SSP construction is needed the whole-life carbon cost of concrete walls appears to become the better option in carbon terms, particularly if eco-friendly concrete is used during construction. Although only assessed at a high level using data in the Carbon Modelling Tool, this work demonstrates the case for thinking more deeply at the strategic level about whole-life CO2. It also causes further questions to be asked about the weight given to total whole life carbon in the decision-making process when put alongside other decision criteria to select a final preferred option to move forward with, particularly as Carbon is not yet given a monetised value to include in FCERM economic appraisal at this time.

5.1 Suggestions for future SCOPAC research

The findings of this research highlights a number of areas of potential for future research by SCOPAC (and/or others), as follows:

- Incorporation of carbon into the FCERM decision making process could be explored further, particularly how to apply a cost (£) value to carbon, to support decisions towards selection of lower carbon options even if they may be more expensive to construct compared to lower cost but higher whole-life carbon solutions. Additionally, greater transparency of the data used in the Carbon Modelling Tool would also assist with improving carbon assessment overall by making it clear what is and is not accounted for in calculating the carbon impacts of different material / construction methods.
- The difference in EA costing data to actual more recent costs in Weymouth Harbour is significant, and work to produce an updated, local (to SCOPAC region) costs database could be helpful to inform future projects and give greater confidence at earlier stages of project development (e.g. SOC stage) in the likely cost, and so partnership funding contributions, that are likely to be required.
- An objective of this research was to explore the actual performance of SSP corrosion protection systems in a common environment to assess if, and by how much, use of such systems has aided extending the life expectancy of the SSP walls by comparing walls with and without such systems. However, there has been limited use of such systems in the Weymouth Harbour case study area and so further research, utilising other locations across the SCOPAC area where such systems have been applied, could be helpful to understand actual experience of them versus manufacturers expectations to increase the understanding of the merits of such approaches in the environments found along the central south coast of England.
- There appears to be limited information about how to incorporate ecological enhancement in SSP walls, with research to date appearing to be more focussed on concrete and masonry walls. Exploring options for post-installation of ecological enhancement once SSP walls have been placed, and/or incorporating ecological enhancements the design stage to SSP walls could be another area for further research.

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