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Quantifying beach variability along the Teignmouth-Dawlish seawall

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Abstract

An investigation into the variation of beach sediment levels fronting a seawall was conducted for both Teignmouth and Dawlish, on the south coast of Devon, UK. The aim was to quantify the levels of beach variability along the length of the seawall and discuss this in line with plans to re-develop sections of the existing structure. It was predicted that Sprey Point, a section of the seawall that protrudes into the surf-zone, would interrupt the littoral transport of sediment at Teignmouth. At Dawlish, it was expected that the presence of groynes positioned along the beach would also influence the transport of sediment in the longshore direction.

Plymouth Coastal Observatory offers bi-annual topographic beach profile surveys using RTK GPS, as well as a catalogue of wave data measured using a Directional Waverider MK III Buoy. This data was used to create historic profiles that show how the cross-shore beach profile has varied over the 7-year survey period (2013-2019). Historic profiles were analysed alongside local wave data plots showing the significant wave height, H_s, peak wave period, T_p, and wave direction, Dirp, in order to understand how the wave conditions have influenced the sediment levels on the beach over the years.

The vertical variability in front of Teignmouth town was found to range between 0.85 – 1.35 m for the survey lines in this section of the beach. In Addition, Sprey Point appears to function as a barrier to the longshore drift of sediment along the coastline. To the south-west of this protrusion the beach displayed its largest vertical variability of 3.52 m, positioned approximately 310 m upcoast of Sprey Point. To the north-west of this obstruction Teignmouth beach experienced a depletion of sediment levels and a reduction in vertical variability. Here, the beach displayed its lowest vertical variability of 0.62 m, located 80 m downcoast of Sprey Point.

In front of Dawlish town, the vertical variability ranged between 1.03 – 1.32 m in a 400 m section of the beach lying between the two groynes known locally as the Colonnade breakwater and the Coastguard breakwater. To the north-east of these groynes, the beach displayed a depletion in sediment levels. Central to the location of the seawall failure (335 m from the Coastguard breakwater) the beach exhibited a minimum sediment level of -1.2 m, and the lowest vertical variation of 0.9 m. The historic profiles showed a general movement in the longshore direction towards the north-eastern end of the beach near Langstone Rock, where the vertical variability was measured to be 1.78 m. The results confirmed that the presence of coastal structures has interrupted the longshore transport of sediment and consequently influence the acceleration of erosional processes.

Keywords: Sediment variation, sediment transport, beach variability, cross-shore profile, coastal defence, coastal erosion, erosional hotspots, topography, overtopping, beach morphology

Introduction

Several storms throughout February 2014 caused considerable damage to the coastline in Teignmouth and Dawlish on the south coast of Devon, UK. A major railway route was damaged in two locations, causing Southwest lines to be cut off from the rest of the country. In Holcombe, a landslip caused thousands of tonnes of material from the cliff faces above to fall on the railway line (Network Rail, 2020). Similarly, in Dawlish, the storms caused a major breach in the seawall, exposing the railway line to the sea (Figure 1.1).

The events caused a 6-week railway closure, prompting Network Rail's Southwest Rail Resilience Programme. The proposed new solutions (Network Rail, 2020) include a 1.8 km railway realignment from Parson's tunnel to Teignmouth, in order to stabilise the cliffs and protect the railway from future seawall breaches. Likewise, plans are in place to construct a larger sea wall in Dawlish, designed to protect the town from the sea for 100 years (Network Rail, 2020).

Figure 1.1: Emergency Repairs on Dawlish Seawall. Photograph provided with permission from Metcalfe (2015).

There is a direct link between seawall failure and the change in sediment levels of the beaches fronting them. Coastal defence structures can also speed up erosional processes. For example, seawalls can reduce surf zone dissipation which in turn leads to higher wave impact upon the wall. Beaches fronting a seawall with lowered sediment levels increase the risk of failure of the structure, including an increased likelihood of failure through scour (Fowler, 1992) and wave overtopping (Besley 1999).

Plans to re-develop these sections of seawall have indicated a need for a detailed understanding of the morphological variability of the beach (Network Rail, 2014).

This report aims to identify and predict areas of the beach with low sediment levels and areas indicating a large variability of sediment levels. To do so, 7 years of historical sediment profiles along the Teignmouth-Dawlish seawall have been examined using topographic survey data from Plymouth Coastal Observatory (PCO). This was analysed alongside the local wave data from a nearby Directional Waverider Buoy. The outcome of this analysis has allowed for the identification of any erosional and accretional hotspots (McNinch, 2004) as well as evidence indicative of whether the beaches are rotational or fluctuating in the cross-shore direction. This was then discussed in line with the plans laid out for the new railway developments.

Figure 1.2: Google Maps (2021), Teignmouth and Dawlish.

The two areas of interest are naturally divided into two sections: Teignmouth to Parson's Tunnel and Dawlish beach to Langstone Rock (Figure 1.2). It is anticipated that the new development at Teignmouth has the potential to reduce the longshore transport at Sprey Point, which is a section of the seawall that protrudes further into the sea and is not fronted by a beach.

Literature Review

Before constructing a seawall, it is important for engineers to understand how beaches behave naturally to not only maintain the structure, but also to maintain the beach fronting the wall (McDougal et al. 1996). Beaches undergo morphological changes when subject to changing wave conditions. A model by Short (1999, as cited in Masselink & Hughes, 2003) displays different beach formations in their accretionary and erosional states, ranging between typical dissipative, intermediate and reflective beaches. The model outlines how calm wave conditions result in onshore sediment transport, and storm conditions cause offshore sediment transport. In more detail, calm wave conditions are determined by a low wave steepness, $H_o/L_o < 0.02$, where small wave heights and long wavelengths give rise to this onshore berm formation (Masselink & Hughes, 2003). Storm conditions display a higher wave steepness, $H_o/L_o > 0.02$, where wave heights are larger, and the wavelengths and wave periods are shorter. These steeper waves give rise to offshore transport and generally lead to the formation of bar-type beach profiles

(Masselink & Hughes, 2003). Coarse grained beaches such as Teignmouth and Dawlish tend to require a larger wave steepness to produce a barred beach profile when compared to beaches with finer grained sediment, as mentioned by Masselink and Hughes (2003).

The morphological changes of beaches are not only a result of incident wave action, but factors such as sediment size, tidal cycles and groundwater levels also have an influence. Arcadis (2018) state in their Teignmouth grab sample report the median sediment grain size to be 0.2 mm at the foreshore and 0.4 mm at the backshore of the beach. This corresponds well with Niedoroda et al. (1985, as cited in Masselink & Hughes, 2003), where it is said beach sediments tend to display a seaward-fining trend. The sediment grain size affects the morphology of the shoreline as coarse-grained beaches require steeper waves to form bar-like profiles (Masselink & Hughes, 2003). The grain size can also impact the beach groundwater table; Masselink and Hughes (2003) discuss how steep, macrotidal beaches with coarse grained sediment (D > 0.3mm) drain well. Therefore, beaches such as Teignmouth are likely to have a narrow seepage face, as decoupling occurs closer to low tide. The decoupling of the groundwater table and the tide can result in offshore transportation of sediment (Masselink and Hughes, 2003). This could be somewhat responsible for the formation of the steep upper beach and low tide terrace at Teignmouth. Miles and Russell (2004) explain in a report on Teignmouth that the beach behaves as both reflective on the steep upper beach, and dissipative on the lower tide terrace; this is due to both sections of the beach engaging in the surf zone at different stages of the tide.

The depth of closure of a beach can be defined as the seaward limit to any significant change in the elevation of the beach profile for a given time interval. At this point of the cross-shore profile, any incident waves upon the beach have no significant effect on the sediment levels. This boundary was first defined by Hallermeier (1981) who suggested that the depth of closure, h_c, could be approximated using the formula

$$h_c = 2.28H_e - 68.5\left(\frac{{h_e}^2}{g{T_e}^2}\right) \qquad (2.1)$$

where H_e is the nearshore storm wave height that is exceeded only 12 hours per year, and T_e is the associated wave period. Birkemeier (1985, as cited in Komar, 1998) noted that from this equation the simple relationship $h_c = 1.57H_e$ provides a reasonable prediction of the closure depth.

Hallermeier (1981) also found that the depth of closure can be predicted with the simplified wave-based formulation

$$\overline{\overset{\approx}{d_1}} \approx 2\overline{H}_s + 11\sigma \qquad (2.2)$$

where $\overline{H}_s$ is the mean annual significant wave height and σ is the standard deviation of $\overline{H}_s$. This equation is suitable for sandy beaches with a common annual wave climate (Hallermeier, 1981). The depth of closure can also be identified relatively easily if there are high-quality repetitive surveys of the shoreface available (Masselink & Hughes, 2003). Creating a plot of all of the available cross-shore surveys creates a historical profile bundle, where the envelope of movement can be characterized as the area between the maximum and minimum elevations of the profile bundle (Masselink & Hughes, 2003). For cases where high-quality survey data is unavailable, Equations 2.1 and 2.2 are more suited for an approximation of the cross-shore profile's depth of closure. The morphological variability of a beach is greatest over the surf zone, and this envelope of vertical movement decreases in the seaward direction as the waves have less of an effect on sediment transport (Masselink & Hughes, 2003).

This study aims to identify certain areas along the Teignmouth-Dawlish seawall as erosional hotspots. Erosional hotspots were defined by Bridges (1995) as areas that behave atypically to adjacent shorelines, with unexpected levels of sediment deficit typical for the morphological processes occurring at these sites. Identifying these hotspots is beneficial for engineers to consider in the design or maintenance of coastal defence structures. Bridges (1995) suggests an understanding of erosional hotspots could help to improve coastal engineers' local scale predictions of profile variability. In a study comparable to this, an erosional hotspot is separately considered by McNinch (2004) as areas of the shoreline that undergo high net erosion, exhibiting high variance relative to adjacent areas of the shoreline. To do this, McNinch (2004) measured the thickness of the sand, the surface sediment distribution, and the shoreface morphology along 56 km of the Virginia-North Carolina shoreline, USA. The study also introduces the idea of accretional hotspots as areas of the shoreline with high net accretion that can also exhibit high variance relative to adjacent areas of the shoreline. High sediment level variation along the shoreline is seen often during storm events. McNinch (2004) explains how these hotspots tend to shift from storm to storm and there are cases where these hotspots occur ephemerally.

Quite often, beaches such as Teignmouth and Dawlish with a seawall at the backshore will have other methods to protect the coastline from erosion. For both of these sites, photos show the presence of groynes along the shoreline (See Figure 1.1 and later Figures 4.1.1 and 4.2.0). Groynes tend to be constructed approximately perpendicular to the shoreline, in order to interrupt the littoral drift and trap a finite quantity of sediment on the upcoast side of the structure. This method of shoreline protection is generally known to transfer the erosion problem downcoast of the structure, and in certain cases accelerate erosion downcoast (Komar, 1998). To prevent this transfer of erosion downcoast, Komar (1998) explains that groynes are often constructed in series with one another in what is known as a groyne field, designed to protect larger areas of the beach. Komar (1998) writes that the segment of the beach between two adjacent groynes acts like a small pocket beach and the sediment between the two will form a different shoreline than the one that existed prior the construction of the structures. The beach between two groynes, however, is known to oscillate with the changing directions of the incident waves.

Through the analysis of beach profiles for Teignmouth and Dawlish, this report aims to establish whether either of the beaches display trends of seasonal or decadal rotation in a longshore direction, or rotational changes in the cross-shore direction. A study by Klein et al. (2002) examines short-term beach rotations in headland bay beach systems. Short and Masselink (1999, as cited in Klein et al., 2002) explain that the rotation of beaches is attributed to periodic or long-term changes in wave climate, in particular the direction of incident waves. Additional studies of beach rotation by Short et al. (2000, as cited in Klein et al., 2002) determine a pivotal point along the beach with minimal variation in sediment levels, it was found that the rest of the beach rotates about this point. The study by Klein et al. (2002), however, did not locate an exact pivotal point along the shoreline but instead found a transitional zone. It is well known that headlands function as a barrier to the littoral drift of sediment along the shoreline, often creating a closed beach system within two headlands.

A study of nearshore processes in the presence of a seawall (Plant & Griggs, 1992) outlines how the morphological response to seawalls depends largely on the individual site. However, the study mentions that seawalls can cause downcoast erosion if the structure protrudes far enough into the surf zone (Tait & Griggs, 1990. As cited in Plant & Griggs, 1992). The study also discusses how impermeable structures can elevate beach groundwater levels, increasing the mobility of the fronting beach (Walton & Sensbaugh, 1979, as cited in Plant & Griggs, 1992). Both statements could hint towards post-construction morphological changes that could arise at Sprey Point.

Infragravity waves are low frequency waves that are generated directly or indirectly by incoming waves and the energy associated with these waves is proportional to the incident wave energy level (Masselink & Hughes, 2003). Guza and Thornton (1985, as cited in Masselink & Hughes, 2003) found that the height of Infragravity waves in the surf zone is 20-60% of the offshore wave height. Because Infragravity wave heights are proportional to offshore wave heights, it is considered that these waves may dominate the water motion in the inner surf zone during storm conditions (Masselink & Hughes, 2003). If this is the case, sediment is expected to respond to the energy levels generated by these lower-frequency waves.

The presence of a seawall can also alter the wave conditions incident on the beach, which in turn reduces the surf zone dissipation of wave energy and subjects the wall to higher wave impacts. A study by McDougal et al. (1996) into the effect of seawalls on beaches explores how the structures can influence wave-induced currents and therefore have an effect on sediment transport. As the sea wall protrudes into the surf zone, waves are reflected off the structure, affecting processes such as shoaling and breaking; the resulting energy dissipation subsequently occurs over a more limited extent of the surf zone (McDougal et al., 1996). This study found that wave reflection off the wall was not a significant contributor to the variability of the beach profile, however the reflection of waves caused more sand to be suspended (McDougal et al., 1996) The study by McDougal et al. (1996) was conducted in a wave tank, there was no longshore current present. In reality, these longshore currents have the potential to carry this suspended sediment along the shore. Miles et al. (2001) also found that a presence of a seawall can affect the amount of sediment suspended and how this is transported. The study focused on Teignmouth and compared the sediment dynamics of the beach backed by the seawall to the adjacent natural beach. It was found that the mean suspended sediment concentrations were up to three times larger in front of the seawall compared to the natural beach; this was attributed to an increase in wave reflection at the wall (Miles et al., 2001). Unlike the study conducted by McDougal et al. (1996) in a wave tank, the field study by Miles et al. (2001) was able to observe a stronger longshore current at the base of the seawall when compared to the natural beach. It should also be noted that on natural beaches the profile variability reduces closer to the high water line (Komar, 1998). This is because of the natural dispersion of wave energy through wave breaking processes incident on a beach face. The presence of the Teignmouth-Dawlish seawall, however, can interrupt the surf zone at times of high tide and disrupt this natural variability of the cross-shore profiles.

A common failure mechanism for coastal structures is due to a phenomenon known as scour occurring at the toe of the structure. Typically, the structure's foundations are undermined due to scouring, which leads to an increased risk of collapse or breaching (Wallis et al. 2009). This process has been studied for sandy beaches under normal incidence waves in multiple reports (Xie 1981; Fowler 1992; Sutherland et al. 2008; Wallis et al. 2009). Fowler (1992) derived a dimensionless equation for the prediction of wave-induced scour depth in front of vertical seawalls, where (S_{max}/H_o) is the dimensionless scour depth.

$$\frac{S_{max}}{H_o} = \sqrt{\frac{22.72 d_w}{L_o} + 0.25} \qquad (2.3)$$

where $-0.011 \leq d_w/L_o \leq 0.045$ and $0.015 \leq H_o/L_o \leq 0.040$.

where d_w is the pre-scour depth of water at the base of the wall and L_o is the deepwater wavelength. The use of Equation 2.3 is also constrained by the wave steepness (H_o/L_o) which restricts the equation to wave conditions typical of a storm (Fowler, 1992).

McDougal et al. (1996) reported that steeper beaches have more scour occurring at the seawall, due to the concentration of wave energy in a narrower surf zone. This could be relevant in Teignmouth, where the beach backed by the seawall is reflective with a low tide terrace (Miles & Russell, 2004). Network Rail commissioned ARUP to produce an option selection report in February 2020 to consider different approaches to protecting the railway line for the design life of the Southwest Rail Resilience Programme (ARUP, 2020). In this report, ARUP (2020) predict an erosion rate of 0.02 m/year for the levels of the beach and bedrock geology of the beach fronting the Dawlish section of the new sea defence. This estimate is uncertain and so the report explains that the programme has opted for some allowance of scour with the expectation that additional scour protection measures may be needed in the future (ARUP, 2020). This method hopes to prove to be more economical, as additional scour prediction may not be needed at all throughout the full design life of the structure.

Sutherland et al. (2008) comment in a report on lowering of beaches fronting a coastal defence that lowered sediment levels at the base of a seawall can increase the chance of wave overtopping. Overtopping can occur in several forms, which are outlined in the EurOtop (2018) manual of wave overtopping for coastal engineering. The manual explains the concept of non-impulsive 'green water' overtopping where waves run directly up the coastal structure and over the crest with a relatively constant flow (EurOtop, 2018). In contrast, 'white water' overtopping occurs when waves break seaward of a coastal structure, or they break directly onto the structure resulting in non-continuous overtopping and sometimes significant amounts of sea spray (EurOtop, 2018). This form of overtopping can also be referred to as impulsive, as it tends to cause more violent overtopping conditions, as described in a study by

Bruce et al. (2009). The sea spray generated from impulsive overtopping is often not of concern unless there is substantial wind which can bring debris onshore. For Coastal Engineers, it is important to consider the mean overtopping discharge when designing a coastal defence in order to manage any health and safety risks that may arise in wave conditions resulting in overtopping. In the case of Teignmouth and Dawlish, the mean equations for overtopping discharge are arguable as the wall varies in nature along the length of the structure. In storm events, the varying sediment levels at the base of the seawall can lead to an increased value for the toe depth, in which case it is important to consider the effect of increased wave heights when calculating the overtopping discharge (EurOtop, 2018). When beaches are backed by a seawall it is likely that waves measured in deep water will break before reaching the base of the wall; this must be considered in calculations for overtopping discharge at sites of this nature. It has been widely acknowledged that depth-limited breaking of waves in shallow water tends to occur near $H_b = 0.78h_b$, where H_b is the breaking wave height and h_b is the water depth at breaking (McCowan, 1894; Sverdrup & Munk, 1946; Komar, 1998). EurOtop (2018) provides several equations for the dimensionless overtopping discharge, $\frac{q}{\sqrt{gH_{m0}^3}}$

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.0011\left(\frac{H_{m0}}{hs_{m-1,0}}\right)^{0.5} \exp\left(-2.2\frac{R_c}{H_{m0}}\right) \qquad \text{Valid for } 0 < R_c/H_{m0} < 1.35 \qquad (2.4)$$

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.0014\left(\frac{H_{m0}}{hs_{m-1,0}}\right)^{0.5}\left(\frac{R_c}{H_{m0}}\right)^{-3} \qquad \text{Valid for } R_c/H_{m0} \geq 1.35 \qquad (2.5)$$

where H_{m0} is the wave height at the toe of the structure, R_c is the crest freeboard of the structure, h is the water depth at the toe of the structure and $s_{m-1,0}$ is the wave steepness with L_o, based on $T_{m-1,0} = H_{m0}/L_{m-1,0} = 2\pi H_{mo}/(gT^2_{m-1,0})$. Both Equations 2.4 and 2.5 relate to a mean value approach. Equation 2.4 is more suited to situations where the lowered promenade at Teignmouth and Dawlish can be considered to be the seawall, and Equation 2.5 can be related to the seawall if the sediment levels reach the top of the lowered promenade, resulting in a large crest freeboard. A different approach could be to consider the seawall as a composite structure at times of high tide, where the toe of the structure is fully submerged (EurOtop, 2018)

$$\frac{q}{\sqrt{gH_{m0}^3}} = 1.3\left(\frac{d}{h}\right)^{0.5} 0.0014\left(\frac{H_{m0}}{hs_{m-1,0}}\right)^{0.5}\left(\frac{R_c}{H_{m0}}\right)^{-3} \qquad \text{Valid for } R_c/H_{m0} \geq 1.35 \qquad (2.6)$$

Equation 2.6 uses the depth of water at the toe of the structure, h, and the depth of water, d, at the ‘composite’ section of the structure, namely the lowered promenade at times of high tide.

A study by Allsop et al. (2005) investigated wave overtopping at vertical and steep sloped seawalls; the paper discusses how vertical walls fronted by steep slopes in combination with plunging waves may lead to large waves plunging directly onto the wall. With this in mind, it is often unfeasible to completely eradicate overtopping at a seawall and therefore overtopping is implicit in the design of seawalls in the UK and Europe (Allsop et al., 2005). The crest height of a seawall is designed for a permissible rate of overtopping. If this permissible rate is exceeded, there is potential for the seawall to fail as the pressure of the waves becomes too great (Mase et al., 2015). Overtopping is common in storm events, however, alongside other damages incident on the wall the chances of failure are greater (Mase et al., 2015). In Dawlish, the failure of the sea wall could be liable to a depletion in sediment levels which in turn worsens the effects of wave overtopping in storms.

The primary purpose of this paper is to quantify the levels of sediment variation along the Teignmouth-Dawlish seawall in order to see how this may affect the new railway development at the two sites. The literature that has been analysed will help to reinforce any findings from the study and highlight any differences between the results and the literature sources.

Methodology

Site Information

Teignmouth and Dawlish are situated on the south coast of Devon, UK The two beaches are generally south-east facing and are backed by a seawall supporting the railway that runs along the coastline. Both beaches have timber groynes located at several points along the shoreline which may impact the movement of sediment along the beach. The condition of these groynes appears to be fairly old and porous and so their effect on sediment transport can be uncertain in places. Maps of Dawlish show four larger groynes positioned along the beach, which appear to be constructed from concrete. Two of these groynes are placed at opposing ends of the beach, one at Langstone Rock and one at the south-western end. These are likely to be ‘terminal groynes,’ which are used in an attempt to close the beach system and prevent sediment from drifting to areas where sediment is not considered to be kept consistent. The other two are positioned in front of the town, approximately 400 m apart, and have been referred to in previous literature as the Colonnade Breakwater and the Coastguard’s Breakwater (ARUP, 2020). Although these structures are often referred to as breakwaters, their perpendicular orientation to the shoreline suggests that they effectively act in the same way as groynes, but also have secondary purposes such as a slipway for boats.

Figure 3.1.1 shows the locations of both sites of interest and the topographic survey lines at both ends of the sites. More detailed maps are included alongside the plotted profiles for each survey line later in the report in Section 4.0.

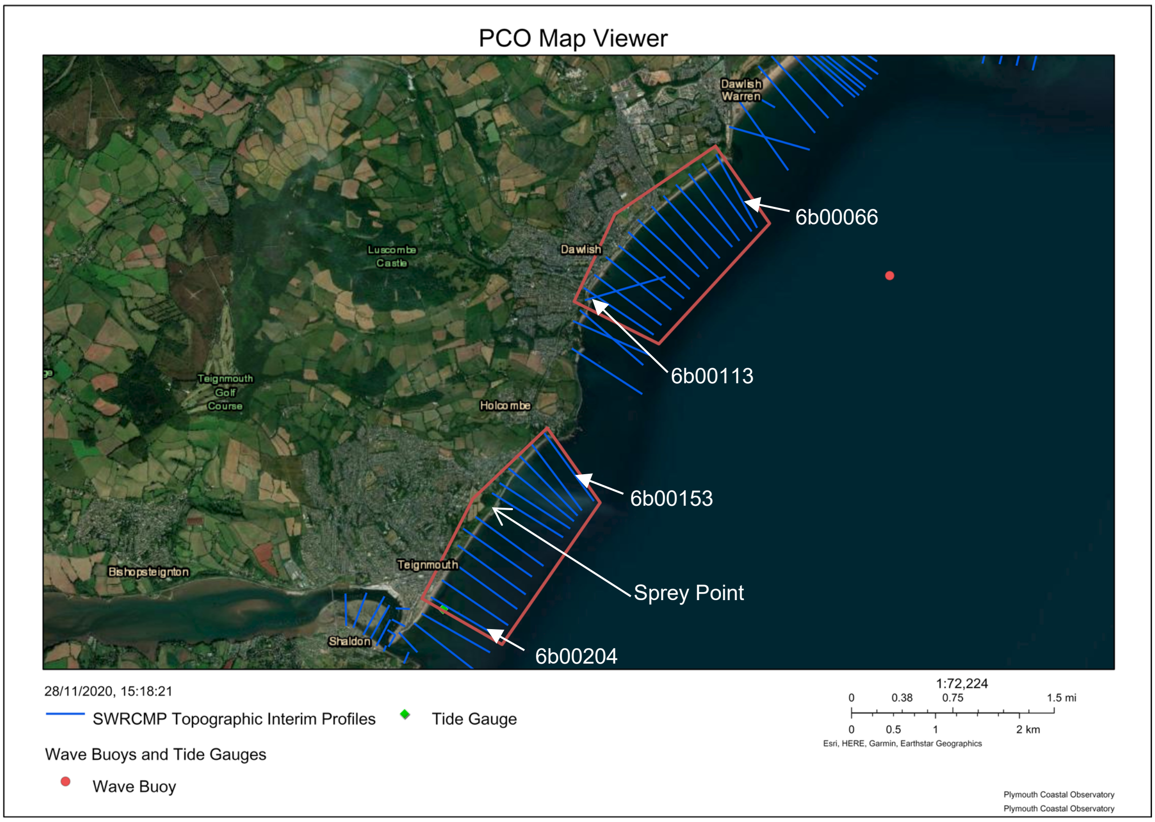

Figure 3.1.1: Map created by the Plymouth Coastal Observatory (2020), showing site locations (outlined in red) with their corresponding SWRCMP Topographic Interim Profiles.

The beaches are likely to operate in their individual beach systems and sediment is likely to move in a system bound by any local headlands. At Dawlish, the sediment is considered to move between the headland at Holcombe and Langstone Rock (Figure 1.2). For Teignmouth, the barriers of the beach system can be considered to be the Ness at the southwestern end and the headland at Holcombe at the north-eastern end (Figure 1.2). The Teign estuary also is a key influence on the beach system at Teignmouth, studied over a 10-year period by Robinson (1975) who monitored the cyclical pattern of change at the mouth of the estuary. After 10 years of observations, Robinson (1975) found the cyclical patterns of the spit to be complex and irregular. However, it was discovered that Teignmouth operates as a closed system from The Ness to the Headland at Holcombe, with little contribution of sediment to Spratt Sand by longshore drift from the direction of The Ness (Robinson, 1975). The study also established an accelerated shoreward sand bank migration at the mouth of the Teign during winter storm conditions (Robinson 1975).

The mean sea level has been measured to be +2.44 m ODN in Dawlish (EDINA, 2020) and it is reasonable to assume the same for Teignmouth as the sites are in close proximity. The mean spring tide range for the sites is +4.1 m ODN, which has been used to classify the beaches (EDINA, 2020). The wave climate is similar at both sites, with little local bathymetric evidence to suggest that waves would approach either of the beaches from differing directions. Wave rose diagrams have been included in Figure 3.1.2, which have been downloaded from Plymouth Coastal Observatory (2021). The wave roses have been plotted using data over an 11 year period (2010 – 2021) to show the direction of waves propagating towards the beaches. These diagrams (PCO, 2021) illustrate how the waves predominantly approach Teignmouth and Dawlish from the south-south-east in January, July and October. The wave rose for April, however, shows a dominating wave direction from the east-south-east with 98% of waves approaching from this direction. The direction of wave propagation is likely to be a key influence on the morphology of the two beaches, as the wave direction can affect nearshore currents, the direction of sediment transport and the means by which coastal structures are designed. The wave rose diagrams in Figure 3.1.2 also indicate the line of shore-normal to take the orientation of the sites into consideration. This illustrates how waves approaching from the east-south-east have the potential to drive sediment transport to the southern end of the beaches. Likewise, waves approaching from the south-south-east are likely to influence sediment transport to the north.

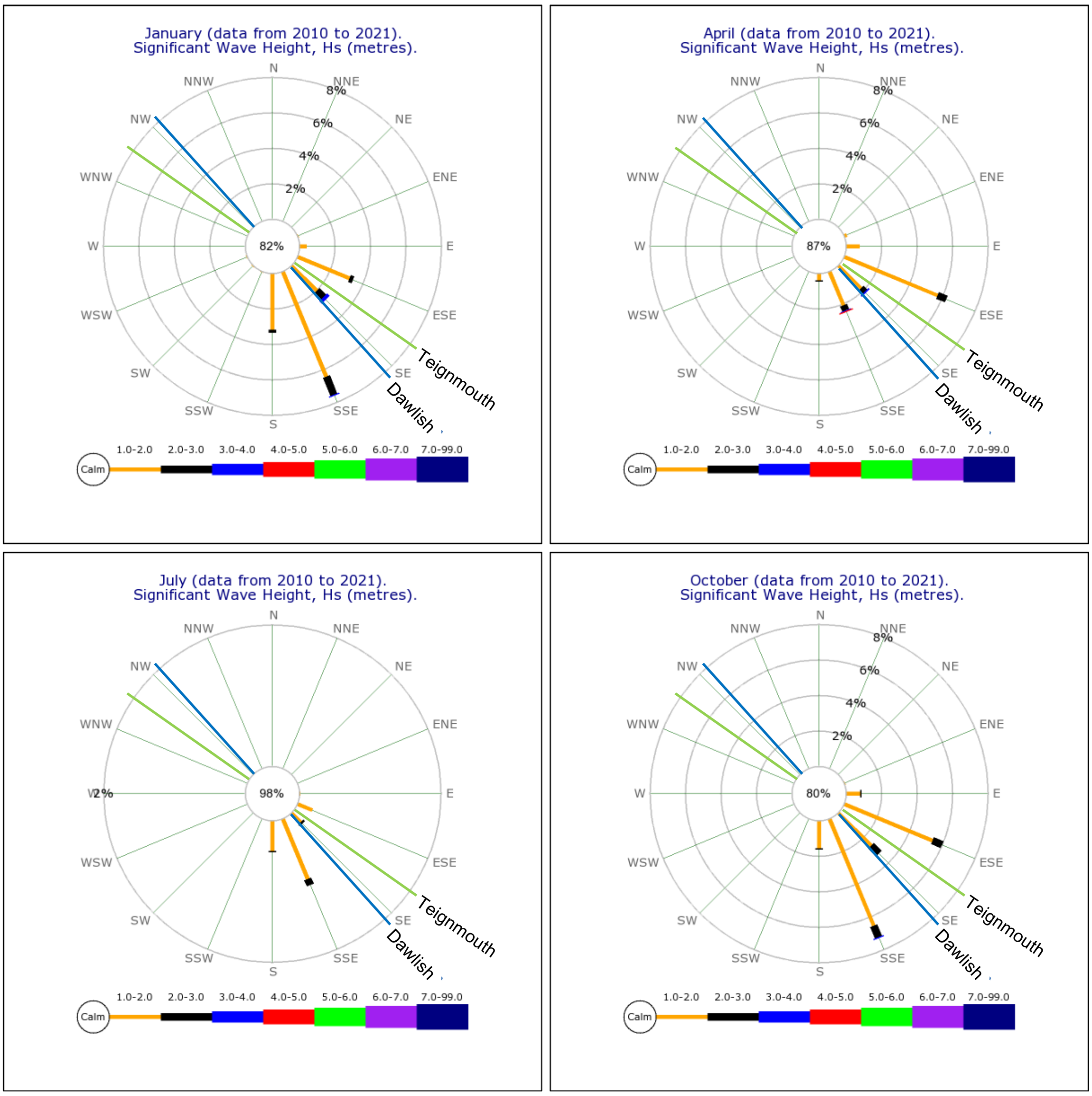

Figure 3.1.2: Wave Roses collected from Plymouth Coastal Observatory (2021) showing the significant wave height and their corresponding direction, measured between 2010–2021. Includes shore-normal lines for Teignmouth (125˚) in green and Dawlish (138˚) in blue.

Table 3.1.1 is a summary of the wave climate collected from the Dawlish wave buoy. Although the data has been collected over a longer period of time (2010-2021), it provides a general idea of the wave characteristics at both sites. The maximum significant wave height documented within the 7-year survey period was measured to be 5.62 m, recorded in February 2014 (PCO, 2021). Looking at the mean values for significant wave heights, it can be seen that the calmest conditions occur between the months of May and September. November appears to be the month with the highest average significant wave height at 0.73 m, however, the two largest waves recorded were in February 2014 and April 2012 (5.34 m). Because the maximum significant wave height in April occurred before the start of the survey period of this study, it will not be used in any calculations for this report. The value does still hold a significance, however, as this particular storm event possibly affected the sediment levels prior to the 2013 surveys. Consequently, the reasons for generally lowered sediment levels in 2013 could be attributed to this storm in April 2012. Similar to the maximum significant wave height, the mean peak wave period, T_p, has been recorded to be highest in February, with a value of 8.26 s. Table 3.1.1 also displays the average wave direction numerically, supporting the wave roses shown in Figure 3.1.2.

Table 3.1.1: Summary of the wave climate collected by the Dawlish wave buoy, with monthly wave data collected from Plymouth Coastal Observatory (2021). The shore-normal line for Teignmouth and Dawlish is 125° and 138° respectively.

2010-2021 Data From PCO	Max H_s (m)	Mean H_s (m)	H_s Standard Deviation	Mean T_p (s)	T_p Standard Deviation	Average Wave Direction (Degrees)
Jan	3.99	0.66	0.48	7.80	4.08	167.47
Feb	5.62	0.57	0.57	8.26	4.27	162.36
Mar	3.48	0.62	0.44	7.34	3.91	157.24
Apr	5.34	0.53	0.44	3.93	3.93	156.59
May	2.71	0.43	0.32	6.02	3.51	162.30
Jun	2.76	0.40	0.28	5.39	2.87	160.86
Jul	2.36	0.34	0.24	4.90	2.69	167.97
Aug	2.19	0.39	0.28	5.16	2.70	170.21
Sep	2.38	0.46	0.32	5.79	3.23	163.58
Oct	3.46	0.65	0.48	6.40	3.29	158.76
Nov	4.16	0.73	0.53	6.92	3.44	160.08
Dec	3.71	0.70	0.51	7.81	3.93	167.42

Sediment surveys for both Teignmouth (Arcadis, 2018) and Dawlish (ADAS, 2019) classify the sediment for both sites to be predominantly slightly gravelly sand on the Udden-Wentworth scale. In Teignmouth, the median sediment particle size (D50) has been measured previously as 0.4 mm at the backshore and 0.2 mm at the foreshore (Arcadis, 2018). This supports a statement made by Miles and Russell (2004) where it is said that a fundamental property of Teignmouth beach is that the sediment grain size changes suddenly at the slope of the beach. At the Dawlish site the median sediment particle size (D_{50}) has been calculated from a survey report of the beach (ADAS, 2019) to be 0.71 mm; certain samples from the report showed values for D_{50} to range between 0.25 mm (medium sand) to 9.6 mm (medium gravel). Using the values of D_{50} for both of the beaches allows the dimensionless fall velocity, Ω, to be calculated and the beaches to be classified in conjunction with a model proposed by Masselink and Short (1993, as cited in Masselink & Hughes, 2003). The dimensionless fall velocity accounts for the effects of both wave steepness and sediment size for the occurrence cross-shore sediment transport (Gourlay, 1968: Dean, 1973, as cited in Masselink & Hughes, 2003). The dimensionless fall velocity can be calculated using the equation

$$\Omega = \frac{H_b}{w_s T} \tag{3.1}$$

where H_b is the breaker height, w_s is the sediment fall velocity and T is the wave period (Masselink & Short, 1993, as cited in Masselink & Hughes, 2003). Before the dimensionless fall velocity was able to be calculated, the breaker height was calculated using the deep water wave data collected from Plymouth Coastal Observatory (2020) using an equation derived by Komar and Gaughan (1972, as cited in Komar, 1998)

$$H_b = 0.39 g^{\frac{1}{5}} \left(T H_\infty{}^2\right)^{\frac{2}{5}} \tag{3.2}$$

where H_∞has been considered as the mean of the maximum wave heights from the wave data (PCO, 2020), and T has been considered to be the mean of the peak wave periods from the wave data (PCO, 2020). The sediment fall velocity must also be determined before the dimensionless fall velocity can be calculated, using an equation derived by Soulsby (1997)

$$w_s = \frac{v}{d}\left[\left(10.36^2 + 1.049 D_*{}^3\right)^{\frac{1}{2}} - 10.36\right] \tag{3.3}$$

Equation 3.1 then gives values of the dimensionless fall velocity for both sites, using the breaker height, Hb, the sediment fall velocity, ws and the wave period, T (Masselink & Short, 1993, as cited in Masselink & Hughes, 2003):

Teignmouth, Ω = 3.45
Dawlish, Ω = 2.04

Alongside the relative tide range parameter RTR, the beach can then be classified according to Masselink and short's model (1993, as cited in Masselink & Hughes, 2003). The relative tide range for Teignmouth and Dawlish has been calculated to be

RTR = MSR/H_b = 4.1/1.15 = 3.57

This allows both beaches to be classified as a combination between a low tide terrace beach and a low tide bar/rip according to the model (Masselink & Short, 1993, as cited in Masselink & Hughes, 2003). The dimensionless fall velocity, Ω, values for both beaches exceeds Ω = 2 and so because of this they both fall into the low tide bar/rip classification. This does, however, differ from what was written by Miles and Russell (2004), where it is said that Teignmouth is a reflective beach with a low tide terrace. The difference between findings by Miles and Russel (2004) and the model by Masselink and Short (1993, as cites in Masselink & Hughes, 2003) is likely to be due to which parameters have been applied, such as a differing grain size, wave height or wave period.

Data Collection

Quantitative data has been collected in the form of topographic and wave data from Plymouth Coastal Observatory (PCO). Plymouth Coastal Observatory (2020) aims to survey beaches around the South West Coast twice a year in Spring and Autumn using RTK GPS (Real-Time Kinematics Global Positioning System). The beach profiles are surveyed from the backshore to mean low water. If a site is considered to be of low risk from erosion, the programme will only survey the site once a year in the spring (PCO, 2020). A minimum of 2 GPS receivers are used for the surveys: one is used as a base station to provide corrections, and the other is a mobile station used to collect the data (PCO, 2020). There is a ground control network of Environment Agency Bench Markers (EABMs) positioned in hard structures along the coastline, which are used as reference points for the beach profile surveys (PCO, 2020). Every 5 years, baselines are established by measuring spot heights along the beach at 5 m intervals, and beach profile surveys are measured at 50 m intervals (PCO, 2020). Using PCO's online map-viewer (2020), the site locations are shown in Figure 3.1.1 along with the topographic survey lines, which can be identified and compared to the plans laid out by Network Rail. In doing so, potential erosional hotspots for beach erosion can be detected.

The wave data provided by PCO is collected from a Directional Waverider MK III buoy situated just off the coast at Dawlish and is part of a network of wave and tidal gauges recording wave height, wave direction, wave period and sea temperature (Plymouth Coastal Observatory, 2020). The wave buoy takes a live measurement of these wave parameters every 30 minutes. The location of the wave buoy can be seen in Figure 3.1.1 with coordinates 50° 34.78' N, 003° 25.03' W. Occasionally, there are spikes within the wave dataset, which can be regarded as errors; these spikes occur in situations whereby the wave buoy snags on its mooring, resulting in a jolt of the accelerometer inside the buoy, for example. These outliers were removed from the wave climate data by coding MATLAB to remove any values of wave height that exceed three times the standard deviation of the dataset. The programme then plots a graph by removing these outliers and interpolating between the adjacent data points.

All data collected for this study has been used in accordance with the relevant ethical conduct expected from the individual sources. The available data collected from Plymouth Coastal Observatory (2020) is well suited to this study. A study conducted by Komar (1998) in Duck, North Carolina, USA, shows comparable sources of data over a similar time scale. Komar analysed beach profiles at Duck over a 7-year survey period from June 1981 to December 1988 (Komar, 1998). However, the surveys took place more frequently than those by Plymouth Coastal Observatory, with a total of 214 surveys over the 7-year study. The identification of erosional hotspots could prove challenging in this study, due to the random nature of these areas of high sediment variance. The beach surveys are conducted just twice a year by Plymouth Coastal Observatory. A more definite detection of erosional or accretional hotspots would require looking at more than two incidences of time each year, which may not be enough to fully examine the presence of these hotspots. However, with the presence of the Teignmouth-Dawlish seawall the shoreward movement of the sea is limited, so areas where there is a large variance in sediment levels at the base of the seawall could be an indication of these hotspots.

Data Analysis Method

Wave Climate Data

Wave data gathered from Plymouth Coastal Observatory was analysed using MATLAB. This allowed the general climate of the waves to be studied and compared to the cross-shore profiles, to investigate how the wave conditions contributed to any morphological change at the two sites.

Figure 3.3.1 has been included as an example of the wave data analysed from the Dawlish wave buoy. Wave data has been analysed two weeks prior to each of the surveys at Teignmouth and Dawlish, and the remainder of the plots can be seen in Appendix A and C. The wave direction sub-plot shows that any waves plotted above the shore-normal line will be approaching the beaches from a southern direction and any waves plotted below the shore-normal line will be approaching the beaches from a northern direction.

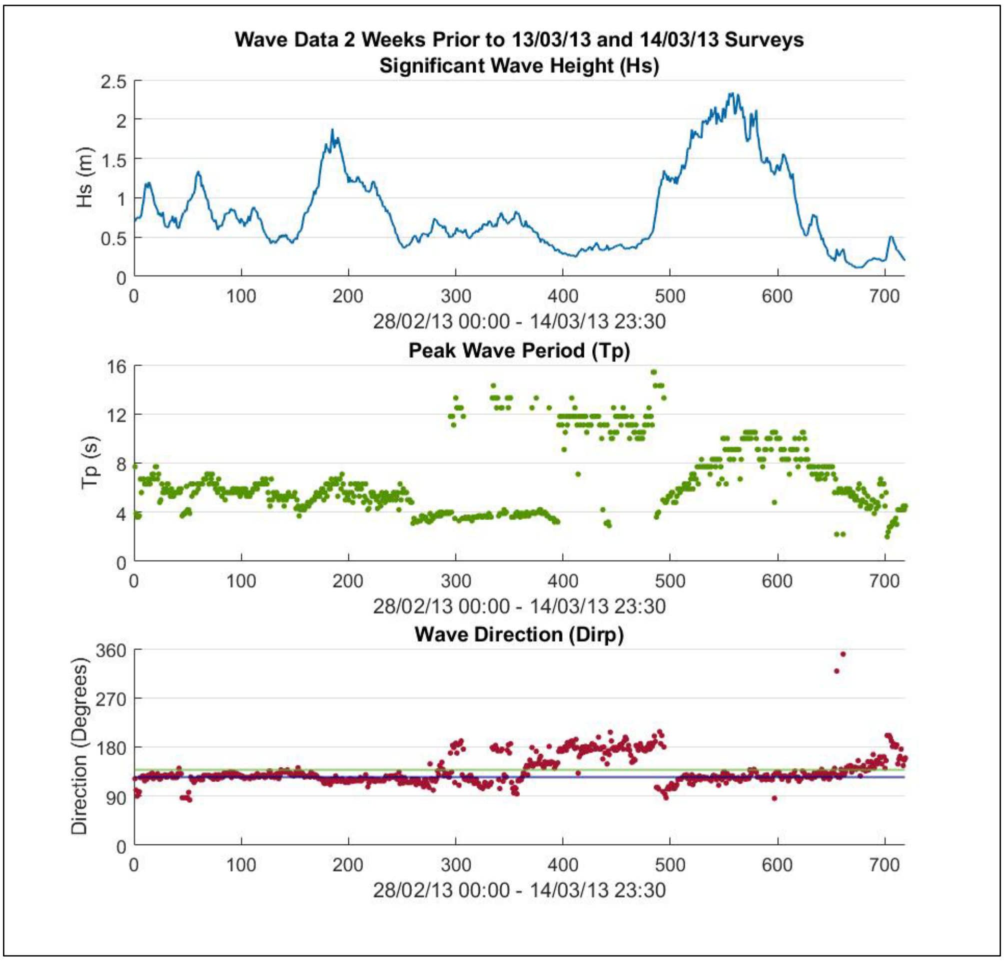

Figure 3.3.1: Plot showing significant wave height (H_s), peak wave period (T_p) and wave direction (Dirp), two weeks prior to the surveys on 13th (Dawlish) and 14th (Teignmouth) March 2013. The wave direction sub-plot shows the shore-normal line for Dawlish (138°) in blue, as well as the shore-normal line for Teignmouth (125°) indicated in green.

Beach Profiles

The beach profiles have been plotted using Microsoft Excel, by combining individual surveys conducted by Plymouth Coastal Observatory into single graphs for each survey line. Plotting the range of vertical movement required some careful interpolation of the individual profiles; this is because although the surveys ran along the same survey lines each year, the chainage of each data point would vary from survey to survey. The profiles were interpolated in 5 m intervals along the chainage axis in order to get an accurate representation of the range of vertical movement. Extra care was taken when interpolating the profiles at the base of the seawall, as the toe of the structure can easily be mistaken for the elevation of sediment at that location. In some profiles such as profile 6b00179 (See later Figure 4.1.6), the base of the seawall is clearly visible. It is worth bearing in mind that the visibility of the toe of the structure as seen in certain profiles can influence which equations are to be used to calculate the overtopping at the wall. The standard deviation of the profiles was obtained using an excel function that calculated the standard deviation for those 5 m intervals that had been previously interpolated from the original profiles.

Elevation Against Seawall

The elevation against the base of the seawall has been analysed for each survey line by taking the width of the profile against the base of the structure and plotting this in Excel to produce scatter line graphs along the length of the coastline. With these plots, the general movement of the beaches can be seen, and erosional hotspots can be identified.

Results and Data Analysis

Teignmouth

In Figure 4.1.1 the location of topographic interim profiles surveyed by Plymouth Coastal Observatory (2021) can be seen, starting with profile line 6b00153 at the north-easterly side of the beach. The survey lines are spaced approximately 200 m apart in general, with a 350 m spacing between survey line 6b00172 and 6b00179. The location of Sprey Point between survey lines 6b00172 and 6b00179 is noteworthy, as the variation in the profiles either side of this point is significant. This is evident in Figures 4.1.4 and 4.1.5 displayed further in the results section of the report.

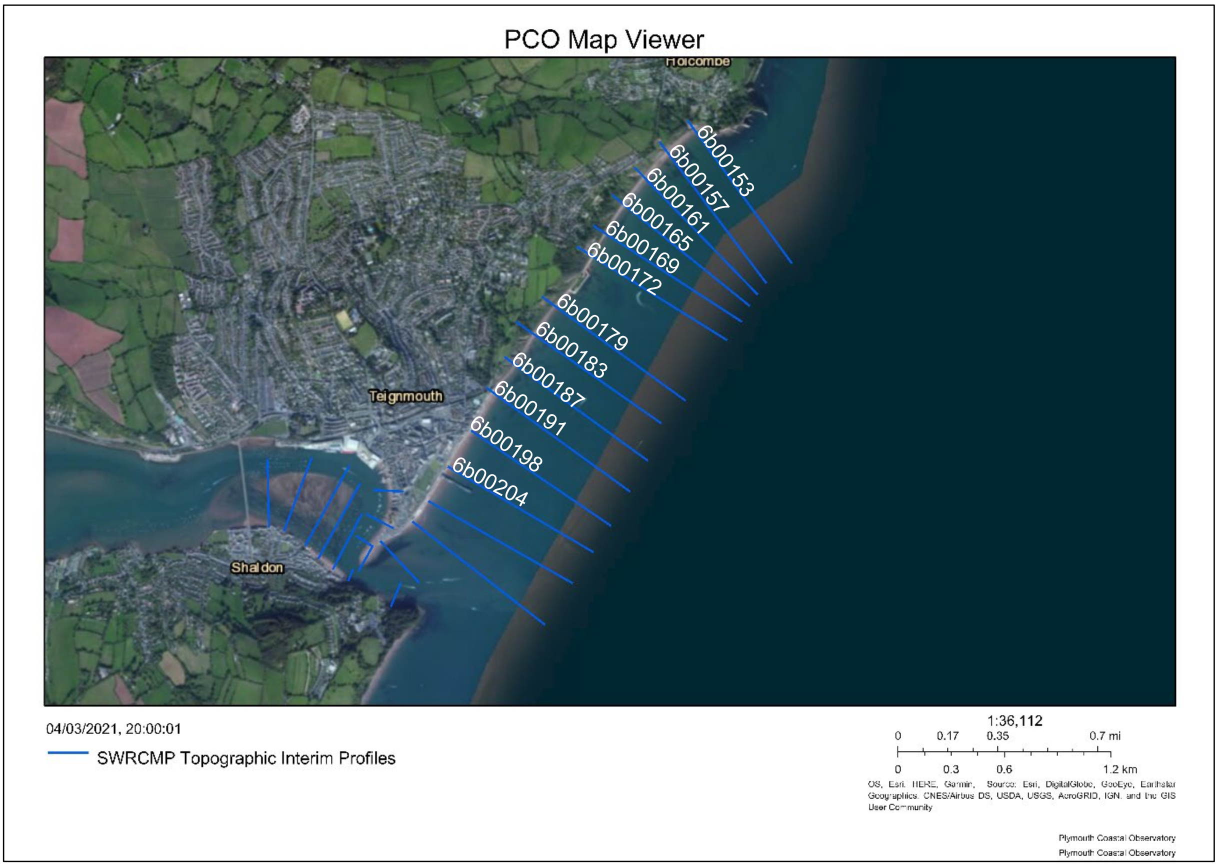

Figure 4.1.1: Map created by the Plymouth Coastal Observatory (2021) of Teignmouth beach, including topographic interim profiles corresponding to the cross-shore profiles for each survey line.

Teignmouth Beach Profiles

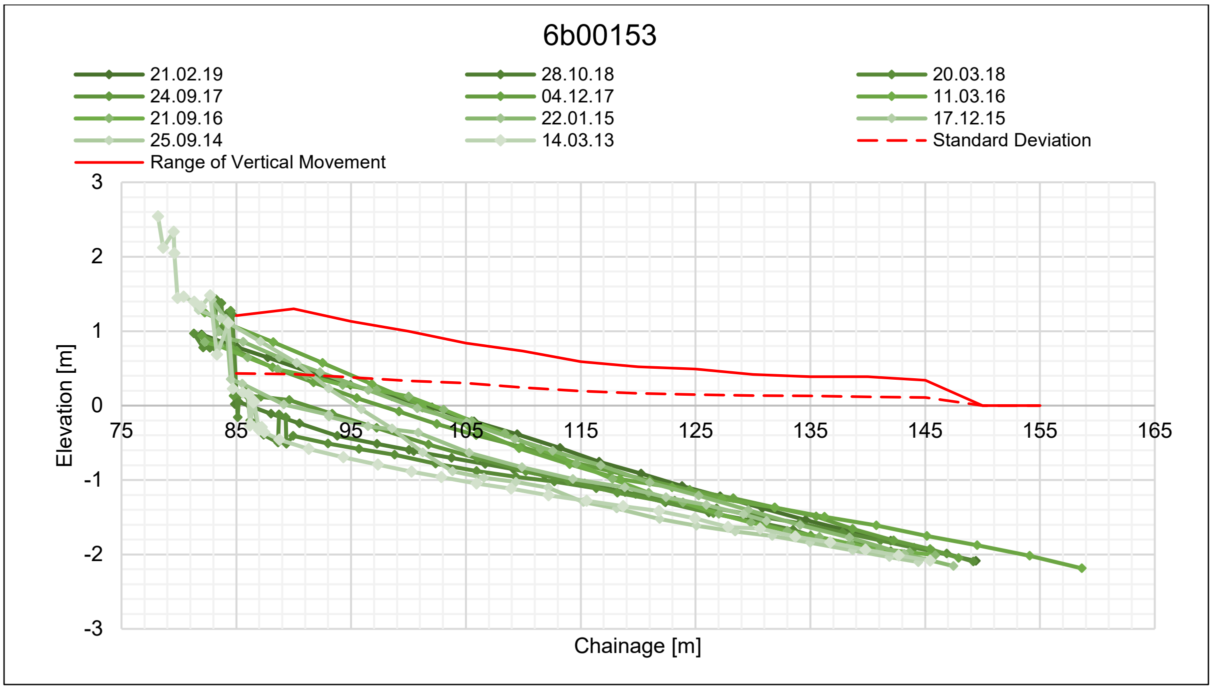

Figure 4.1.2: Historical Profile of survey line 6b00153 at Teignmouth. Including the range of envelope movement in the vertical, and the standard deviation of the vertical variations. The colour gradient shows the more recent surveys in darker shades of green.

Profile 6b00153 above shows a vertical variability of 1.21 m against the seawall at the most north-easterly point of Teignmouth's beach, close to Parson's Tunnel. The range of vertical movement for this profile is greatest near the sea wall. The plot validates how the variability of the beach profile tends to be greatest over the surf zone and decreases in the seaward direction (Masselink & Hughes, 2003). The standard deviation and width of the profile envelope has been plotted to show how the beach profile has evolved over time. Over the 7-year survey period, the general accretion of sediment at this point on the beach can be seen by the colour gradient of the graph. Although, in 2018, the sediment levels visibly drop, almost reaching levels as low as those recorded in 2013. This particular profile seems to have since recovered from these lowered sediment levels in 2018, and there is little evidence of a storm in the wave data two weeks prior to the surveys for 2018 (See Appendix A) to suggest any reasoning for the sudden drop in the elevation against the seawall. This could mean that the sediment levels dropped steadily throughout 2017.

Figure 4.1.3 shows the protrusion of Sprey Point in the seaward direction, making it a feasible obstacle preventing the movement of sediment along the beach as a whole. Profiles 6b00169 and 6b00172 (Figures 4.1.4 and 4.1.5) are both located to the north-east of Sprey Point. Both survey lines show a clear deficit in sediment levels at the base of the seawall. Profile 6b00172 shows an approximate overall loss of 0.618 m of sediment between 2013 and 2019.

Figure 4.1.3: Aerial View of Teignmouth Beach to Parson's Tunnel. Photograph provided with permission from Metcalfe (2015).

Profile 6b00169 however, displays a loss of sediment near the seawall but an overall increase in sediment in the seaward direction. The lowering of sediment levels at these locations indicate a possible reduction in longshore transport downcoast of Sprey Point.

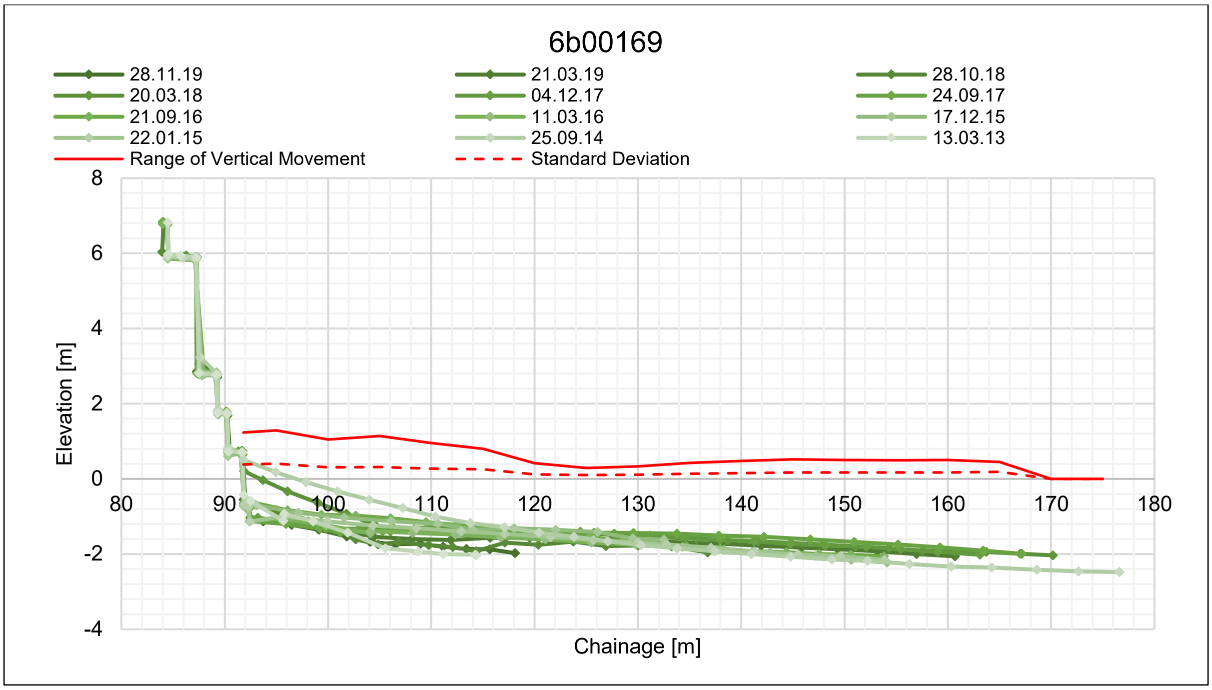

Figure 4.1.4: Historical Profile of survey line 6b00169 at Teignmouth, located 280 m north-east (downcoast) of Sprey Point.

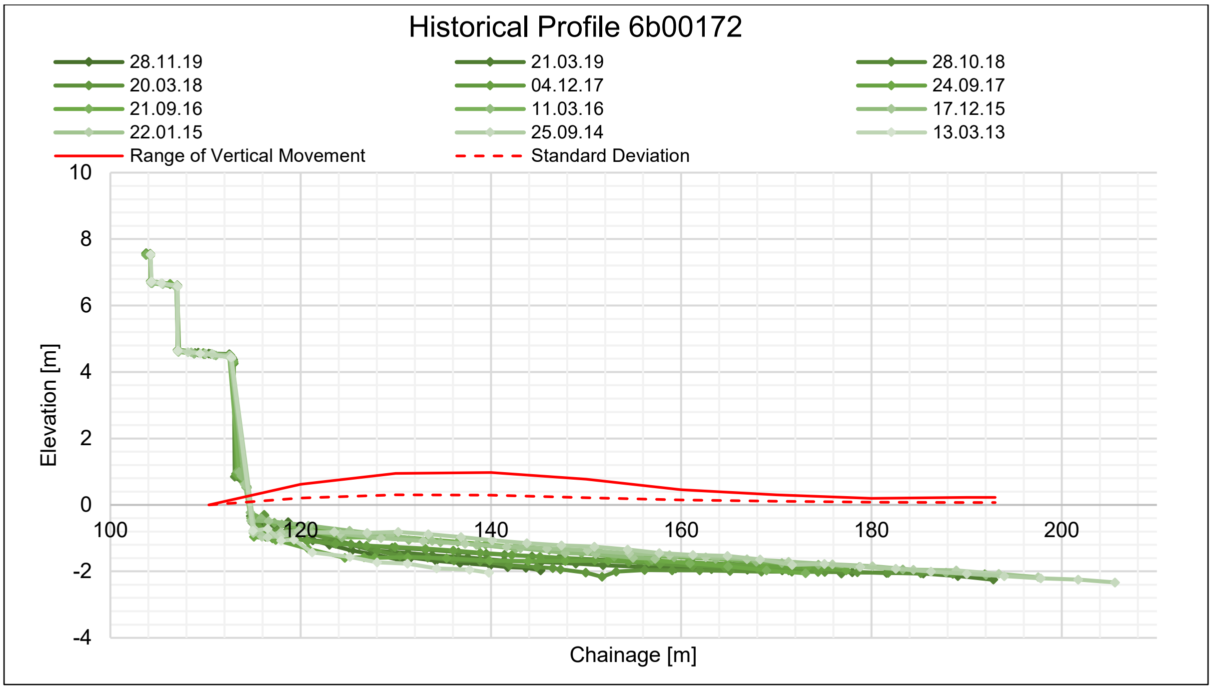

Figure 4.1.5: Historical Profile of survey line 6b00172 at Teignmouth, located 80 m north-east (downcoast) of Sprey Point.

Figures 4.1.6 and 4.1.7 illustrates two survey lines to the south-west of Sprey Point. For these profiles, the sediment levels have increased over the survey period, with as much as 3.52 m of variation at the base of the seawall for profile 6b00183.

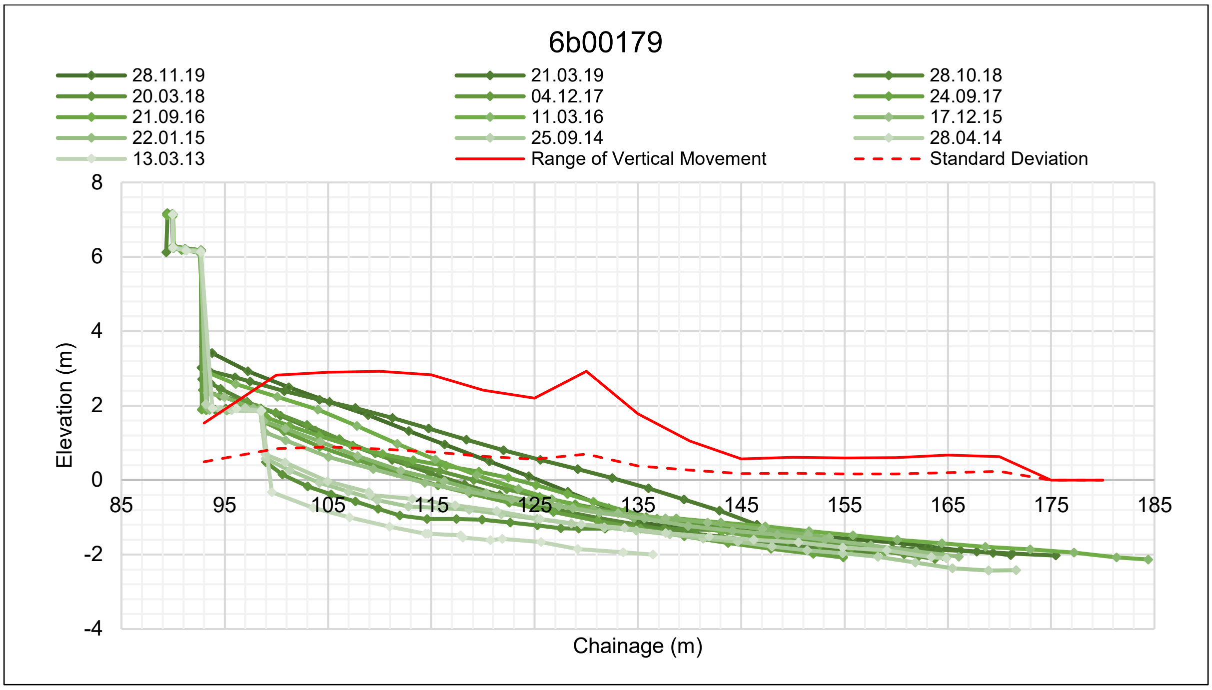

Figure 4.1.6: Historical Profile of survey line 6b00179 at Teignmouth, located 110 m south-west (upcoast) of Sprey Point.

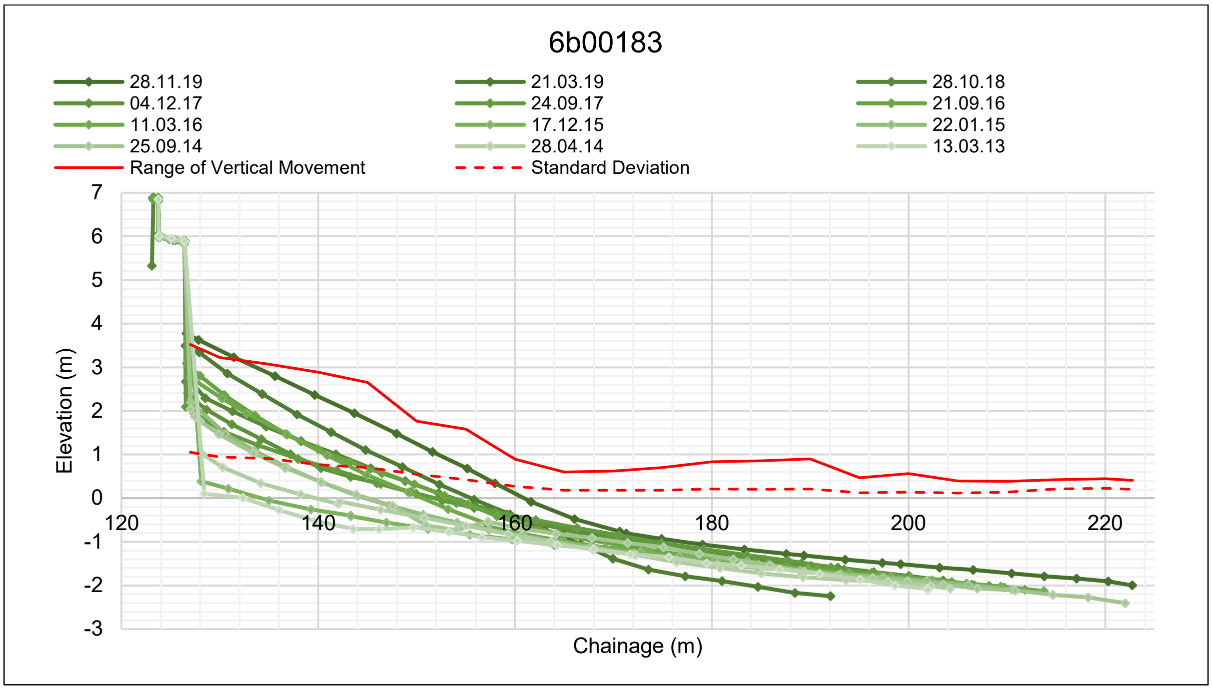

Figure 4.1.7: Historical Profile of survey line 6b00183 at Teignmouth, located 310 m south-west (upcoast) of Sprey Point.

Profile 6b00179 (Figure 4.1.6) also shows a sudden drop in sediment levels in March 2018, similar to profile 6b00153 (Figure 4.1.2). This profile displays the most vertical variation at the base of the seawall for the whole beach.

In Figure 4.1.8, it can be seen that survey line 6b00198 has experienced an accretion of sediment at the base of the seawall in recent years, but a depletion in sediment levels towards the tail of the profile. The profile has shifted from a shallower slope to a steeper slope, as sediment has been pushed towards the backshore.

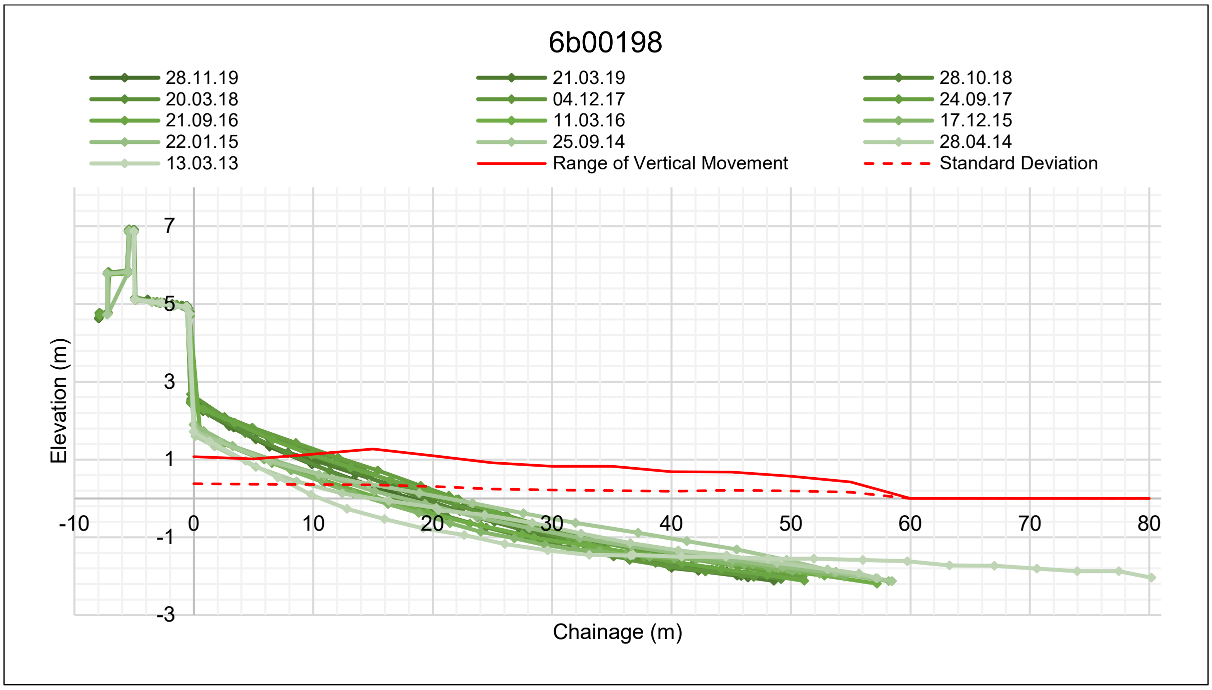

Figure 4.1.8: Historical profile of survey line 6b00198, located in front of Teignmouth town.

Teignmouth Profile Variation

A summary of the sediment elevation at the base of the seawall at Teignmouth can be seen in Figures 4.1.9 – 4.1.11 There is a large variability against the seawall for profile lines 6b00179 and 6b00183 (south-west of Sprey Point) where sediment has generally accrued over the survey period; this can be clearly seen in Figure 4.1.9. between each of the surveys. For these two profiles in particular, there seems to be evidence of a decadal trend in the accretion of sediment against the seawall (Figure 4.1.9). Figure 4.1.11 shows that profile 6b00183 is also the location of the largest maximum sediment elevation against the seawall, when compared to the beach as a whole. Figure 4.1.11 displays the lowest minimum sediment elevation against the seawall, occurring at profile 6b00172 to the north-east of Sprey Point at -1.32 m. This minimum elevation was measured in September 2017 and the wave data plotted two weeks prior to this survey in Appendix A shows that wave conditions were calm over this period, with the majority of waves approaching from the south. Although in Figure 4.1.10 it appears sediment levels vary less towards the town of Teignmouth, Figure 4.1.9. shows that sediment levels for the rest of the beach south-west of Sprey Point have generally risen over the survey period.

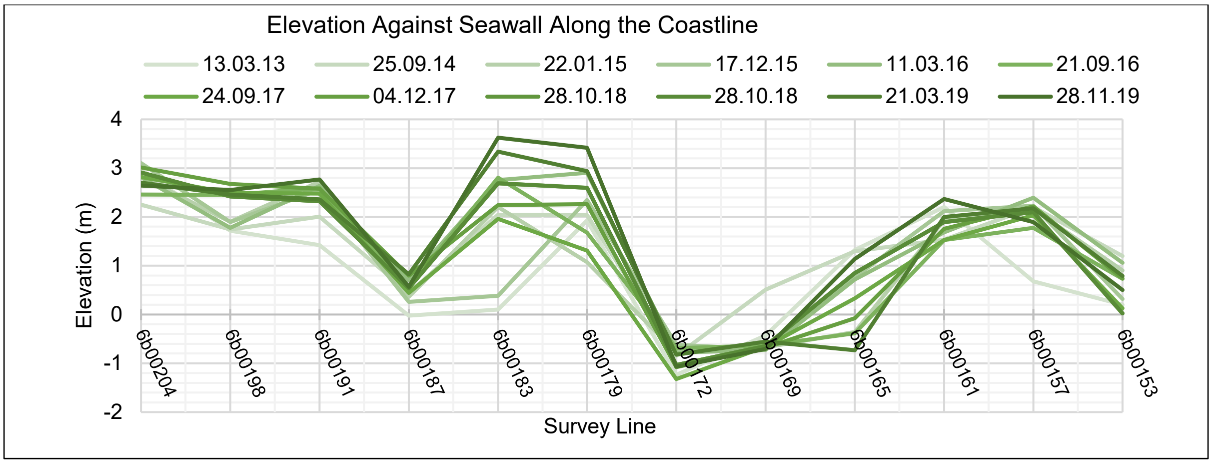

Figure 4.1.9: Sediment elevation relative to ODN, plotted against the corresponding survey lines (Spaced approximately 200 m apart) for each of the individual surveys.

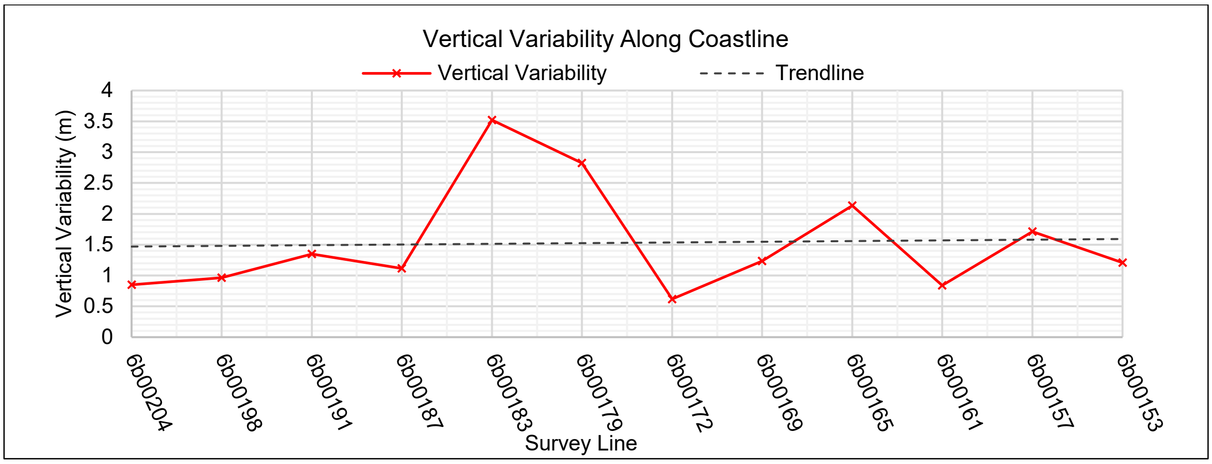

Figure 4.1.10: Vertical variability relative to ODN, plotted against the corresponding survey lines (Spaced approximately 200 m apart) for the full survey period 2013-2019.

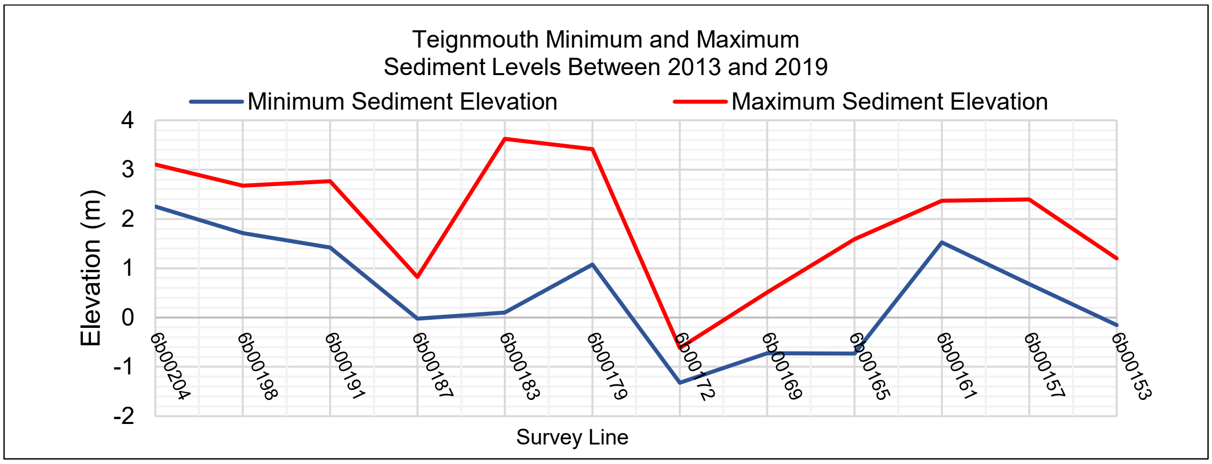

Figure 4.1.11: Minimum and maximum sediment levels relative to ODN, plotted against the corresponding survey lines (Spaced approximately 200 m apart) for the full survey period 2013-2019.

Dawlish

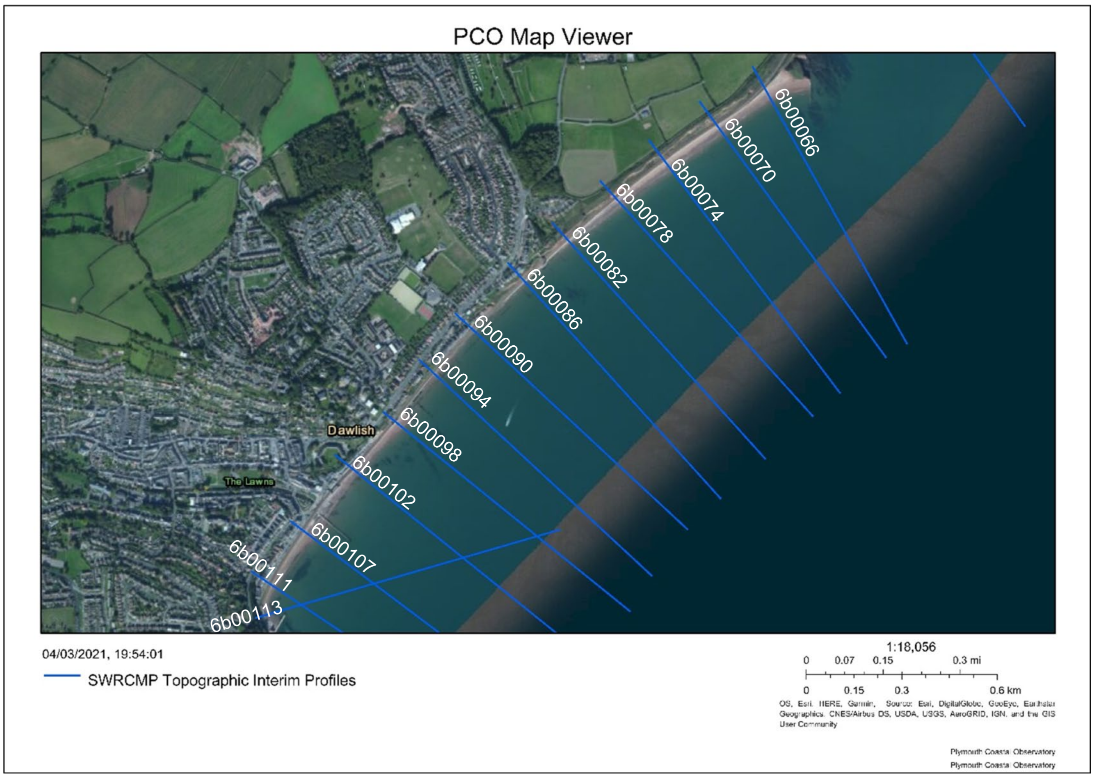

Figure 4.2.1: Map of Dawlish Beach created by Plymouth Coastal Observatory (2020), including topographic interim profiles relating to the cross-shore profiles for each survey line.

The topographic interim survey profiles are drawn in Figure 4.2.1 along the Dawlish shoreline. The survey lines are spaced approximately 200 m apart, with 100 m between profiles 6b00111 and 6b00113 when measured along the perimeter of the seawall. It is worth mentioning that survey line 6b00090 is located almost exactly in the centre of the site of seawall failure that occurred in 2014. It can also be seen that there is a large groyne just above profile line 6b00107 (Colonnade breakwater) and as well as another in between profiles 6b00094 and 6b00098 (Coastguard's breakwater). These larger groynes are likely to have a greater impact on the amount of sediment movement along the beach. The location of these could also be responsible for the lack of sediment fronting the seawall in survey line 6b00090 and consequently the failure of the wall at this location. There are also terminal groynes located at either end of the beach, perpendicular to the coastline near profile 6b00113 at the south-western end and following profile 6b00066 at the north-eastern end.

Dawlish Beach Profiles

In profile 6b00066 (Figure 4.2.2) the maximum variance in the sediment levels is 2.1 m, occurring at a chainage of 125 m. This change in elevation is not overly alarming as it has occurred further away from the base of the seawall. The maximum sediment elevation at the seawall for this profile was measured in December 2014 to be 4.5 m. For this profile, it seems the steep upper terrace of the beach has advanced and retreated over the years in a uniform way.

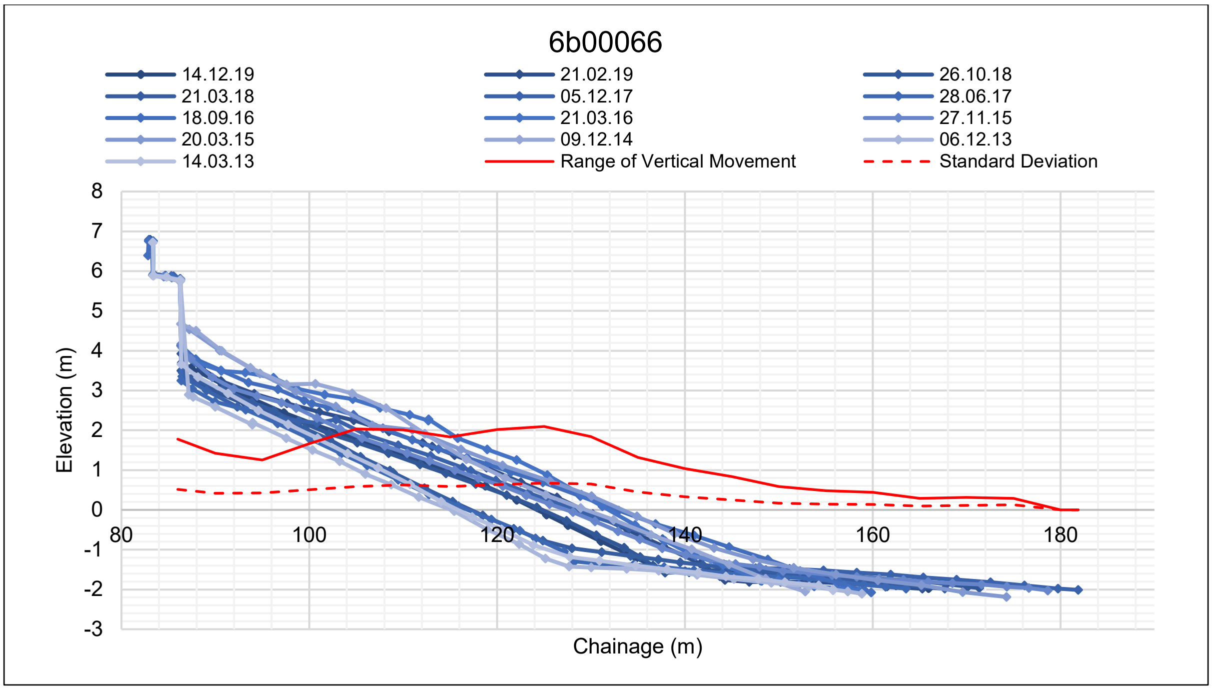

Figure 4.2.2: Historical Profile of survey line 6b00066 at Dawlish, near Langstone Rock.

The historical profile of survey line 6b00078 is shown in Figure 4.2.3 At this point along the beach there is little evidence for an overall accretion or depletion of the cross-shore profile. Nonetheless, it is important to note a variation in sediment levels of 1.57 m at the toe of the structure.

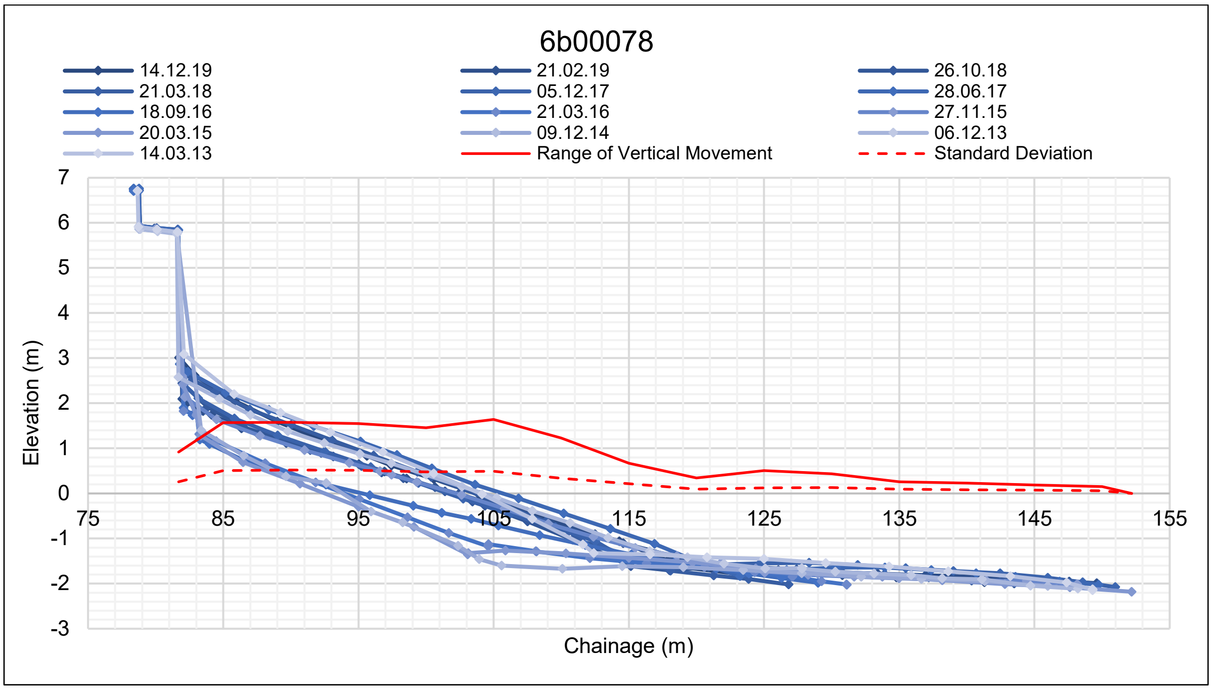

Figure 4.2.3: Historical Profile of survey line 6b00078 at Dawlish, downcoast to the location of the 2014 breach (See Figure 1.1)

In Figure 4.2.4, a 0.71 m variance in sediment levels at the base of the seawall can be seen. Only a handful of the surveys reach a chainage of 135 m, which suggests that the lower tide terrace was often submerged at the times of surveys.

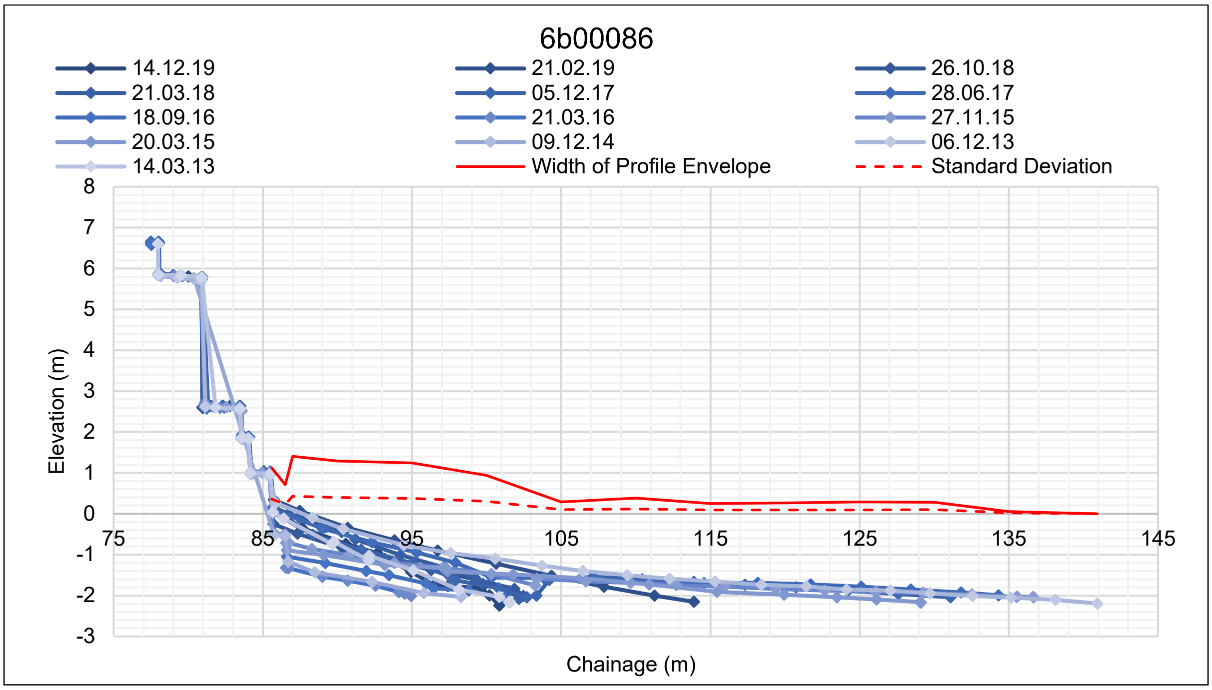

Figure 4.2.4: Historical Profile of survey line 6b00086 at Dawlish, adjacent to the profile at the centre of the 2014 breach (See Figure 1.1).

In Figure 4.2.5 the historical profile of survey line 6b00090 can be seen, which is located central to the point of seawall failure in February 2014. For this transect it is evident that the sediment levels cover up the toe of the seawall at these particular instances in time. Therefore, these surveys give no evidence to suggest that scour could have caused the breach of the structure. In March 2013, the levels at the base of the seawall fall to a low of -0.30 m, however, the elevation of sediment at the seawall seems to fluctuate throughout the rest of 2013 – 2014, where it reaches a high of 0.5 m at the base of the structure in December 2013. There was only one survey in 2014, measured well after the February storm; in December 2014, the sediment levels at the base of the seawall were measured to be 0.45 m. Only a handful of the surveys reach a chainage of 110 m which suggests that over 100 m from the seawall, there is a lack of unsubmerged beach available for surveying. This lack of sediment at the foreshore could have contributed to a higher proportion of wave energy reaching the base of the wall, resulting in its failure. Wave data has been analysed for 3-days over the course of the storm occurring on the 5th of February 2014, which can be seen in Figure 4.2.6.

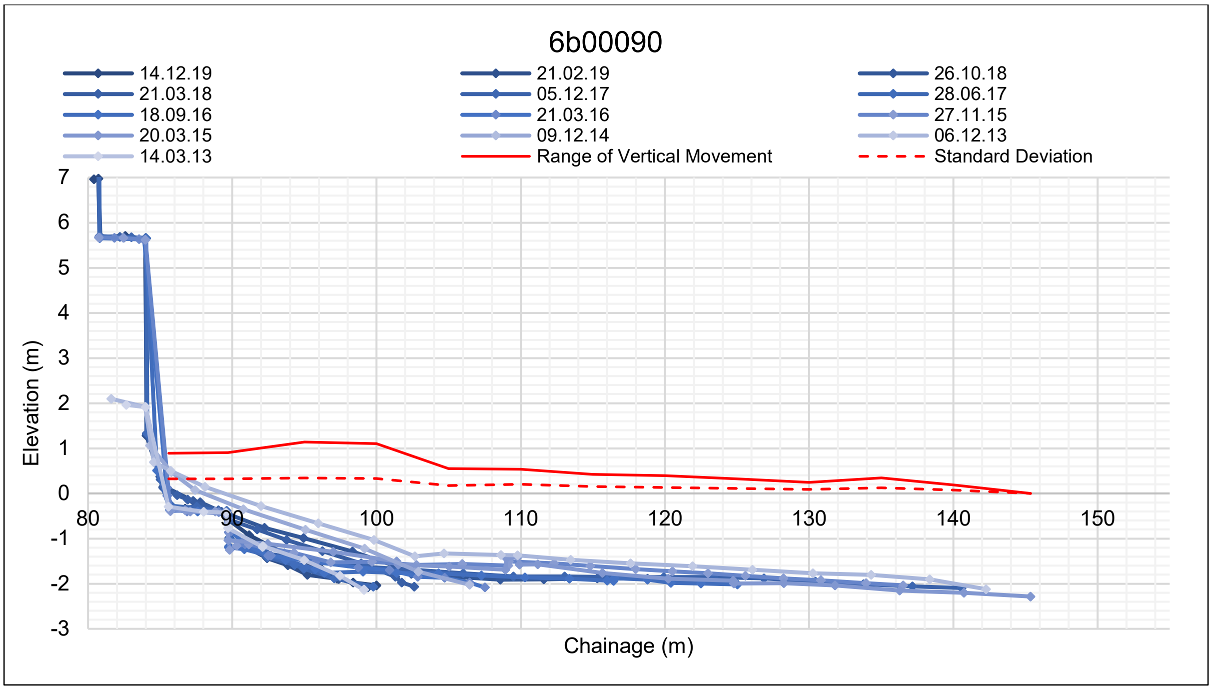

Figure 4.2.5: Historical Profile of survey line 6b00090, central to the site of the 2014 seawall breach.

The wave data graph in Figure 4.2.6 shows that over the course of the February 2014 storm, waves approached both Teignmouth and Dawlish predominantly from the south. The significant wave height also reached a high of 5.18 m during the storm, which is likely to give rise to offshore transport and an increase in the strength of littoral drift currents. The approach of waves from the south indicates that storm was therefore likely to influence sediment transport to the northern end of the beach over this period. This is evident in Figure 4.2.2 where it can be seen that the maximum elevation of sediment against the seawall was measured in the December 2014 survey at profile 6b00066.

Survey line 6b00094 is plotted in Figure 4.2.7. The variation of sediment at the base of the seawall for this profile is similar to that of profile 6b00090. The sediment levels here increase to their highest levels in June 2017 with a measurement of 0.65 m at the base of the structure. After this survey, however, levels begin to drop again and similarly to profile 6b00090, some surveys only reach a chainage of 105 m.

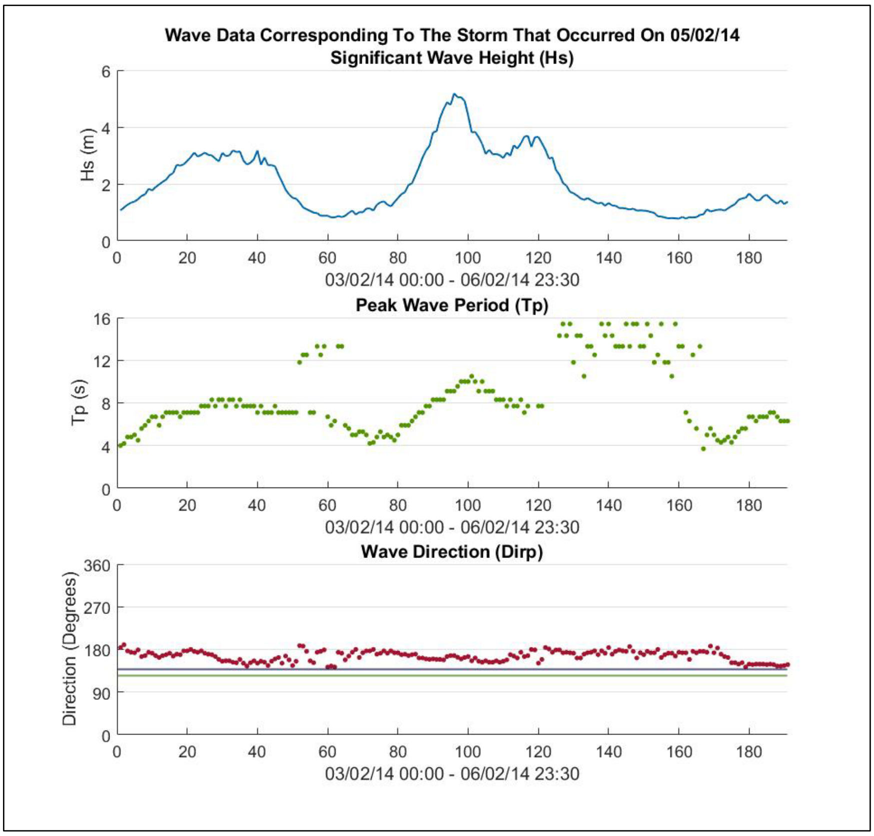

Figure 4.2.6: Plot showing significant wave height (H_s), peak wave period (T_p) and wave direction (Dirp) over a 3 day period of the February 2014 storm. The wave direction sub-plot shows the shore-normal line for Dawlish (138°) in blue, as well as the shore-normal line for Teignmouth (125°) indicated in green.

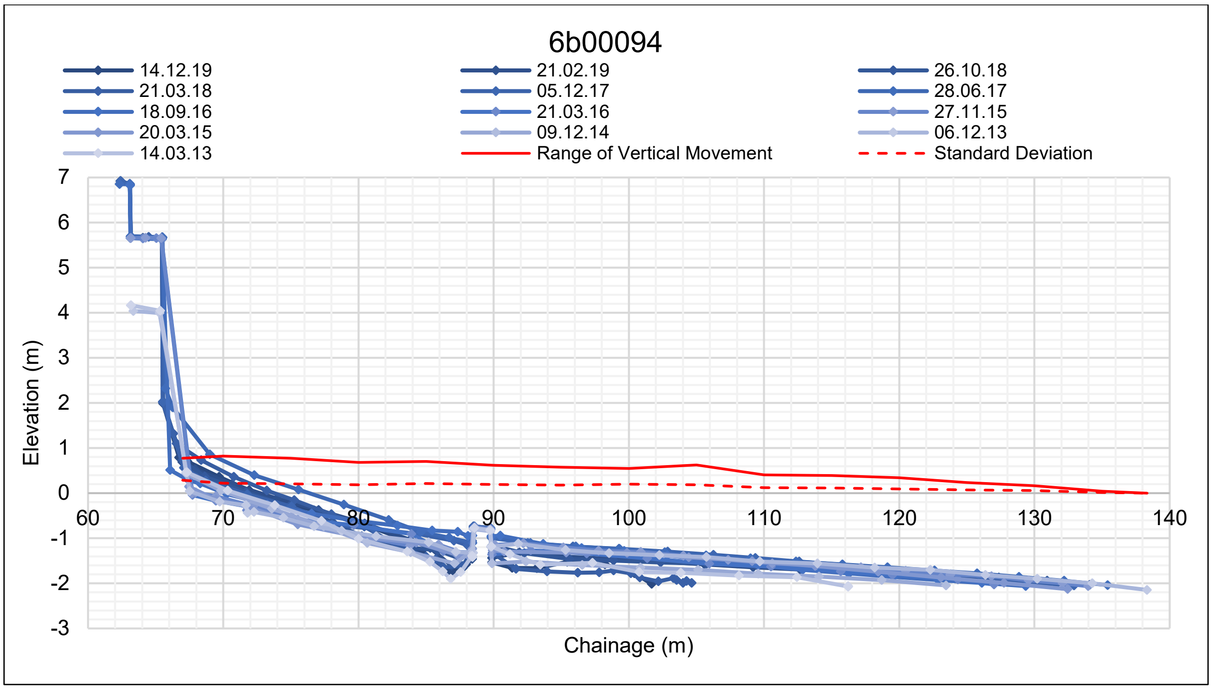

Figure 4.2.7: Historical Profile of survey line 6b00094, upcoast and adjacent to the site of the 2014 seawall breach.

Figure 4.2.8 displays a maximum sediment variation of approximately 2.2 m at a chainage of 68 m. Again, there seems to be no overall accretion or depletion of sediment levels close to the seawall overall, however, the seaward end of the profile shows a trend of sediment accretion over the years. Comparing profile 6b00098 (Figure 4.2.8) to profile 6b00086 (Figure 4.2.4), there seems to be something preventing the longshore transport between these two survey lines. This is likely to be the groyne positioned just 40 m downcoast of survey line 6b00098 which helps to trap sediment on the south-western side of the beach. Similar to the other profiles, the envelope of movement is greatest nearer to the seawall.

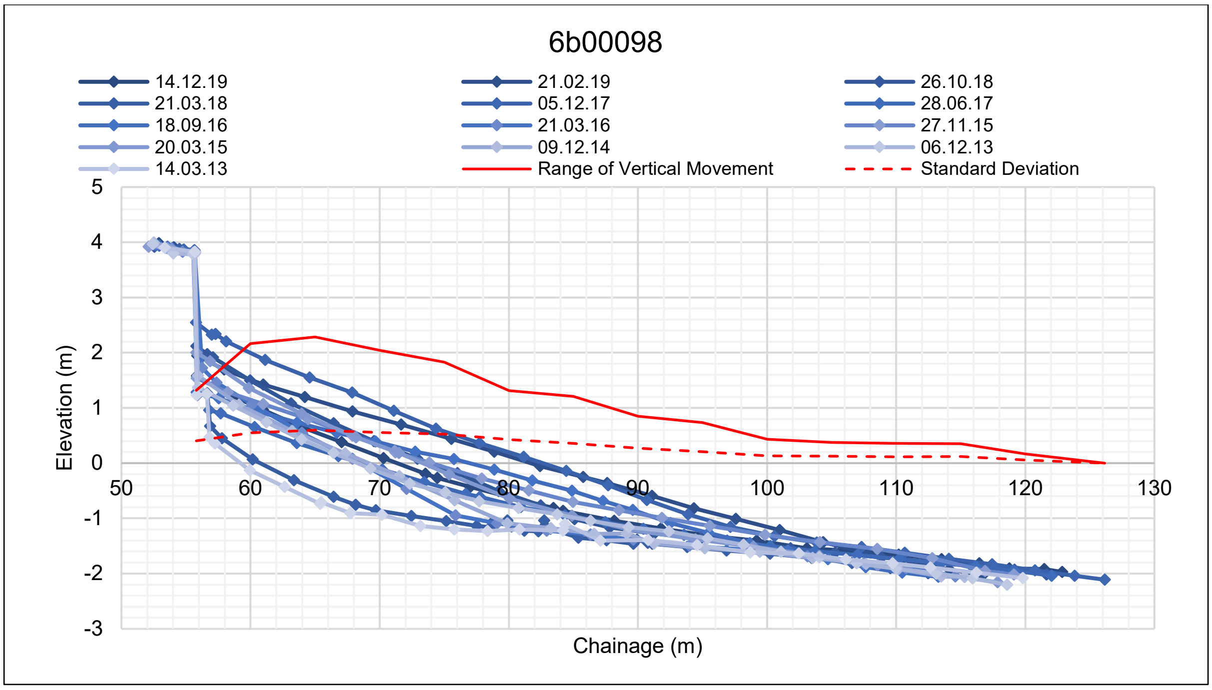

Figure 4.2.8: Historical Profile of survey line 6b00098 at Dawlish, upcoast of the location of the 2014 breach (See Figure 1.1).

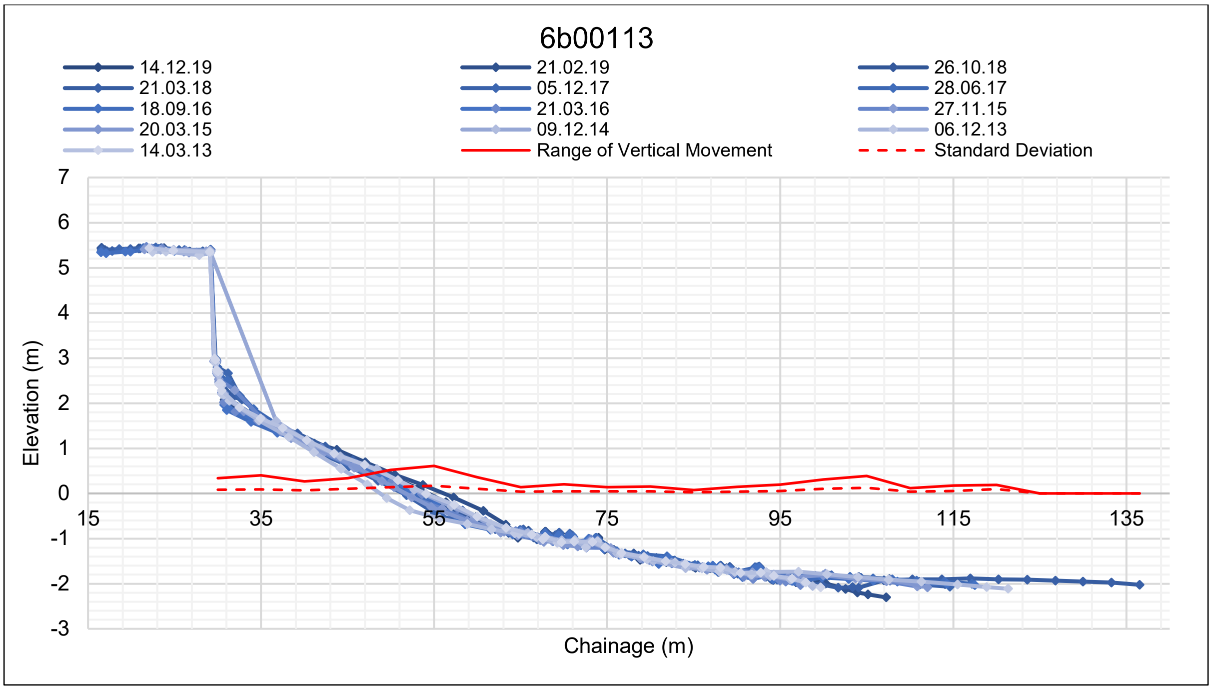

Figure 4.2.9: Historical Profile of survey line 6b00113 at Dawlish, the most south-westerly of the beach profiles.

Survey line 6b00113 is shown in Figure 4.2.9. Referring back to the map in Figure 4.2.1 it can be seen that this profile is located at the south-western side of the beach extending from a point where the seawall begins to curve as the beach approaches the headland at Holcombe. There is also a Groyne located 60 m to the south-west of this profile at the end of the beach. There is very little variation in sediment levels for this profile, the largest variation occurs at a chainage of 55 m with 0.61 m of variation in the profiles at this point.

Dawlish Profile Variation

A summary of the profile variations at Dawlish is shown in Figures 4.2.10 – 4.2.12. Figure 4.2.11 indicates that the profile with the least variation against the seawall (0.34 m) is survey line 6b00113, located where the seawall begins to curve towards the headland at Holcombe. Figure 4.2.10 shows that sediment levels between profiles 6b00086 and 6b00094 are lower when compared to the profiles along the rest of the beach. The three survey lines within this region occur after the large groyne located 40 m north-east of survey line 6b00098, which could be trapping sediment to the south-western end of the beach. The highest variability in sediment levels against the seawall occurs at profile 6b00066, at the north-east end of the beach with 1.78 m of variation over the 7-year survey period (Figure 4.2.11). Sediment levels at this point along the coast reached their highest in 2015 with an elevation of 4.67 m (Figure 4.2.12). The lowest elevation of sediment against the seawall was recorded at profile 6b00090 to be -1.20 m in September 2016.

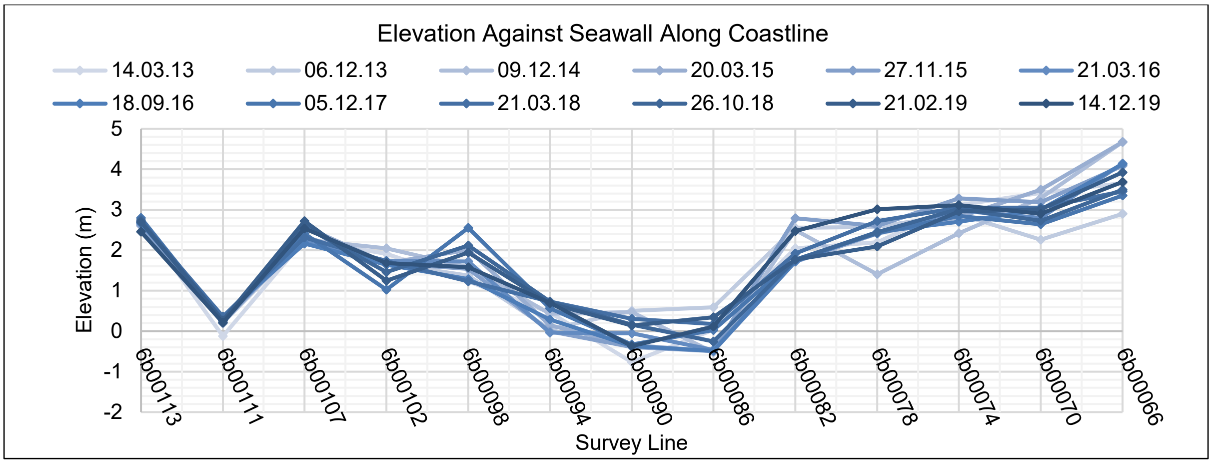

Figure 4.2.10: Sediment elevation plotted against the corresponding survey lines (Spaced approximately 200 m apart) for each of the individual surveys.

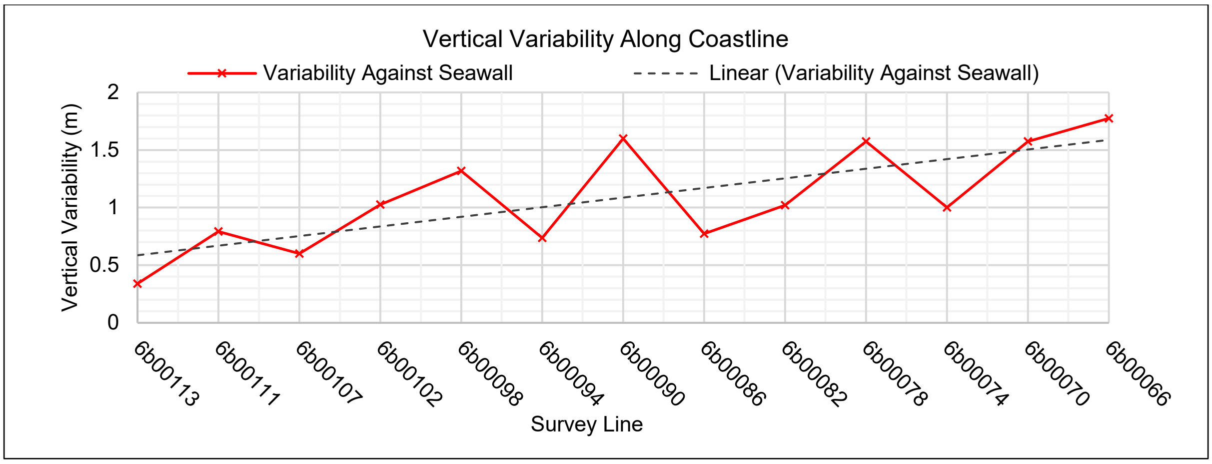

Figure 4.2.11: Vertical variability plotted against the corresponding survey lines (Spaced approximately 200 m apart) for the full survey period 2013-2019.

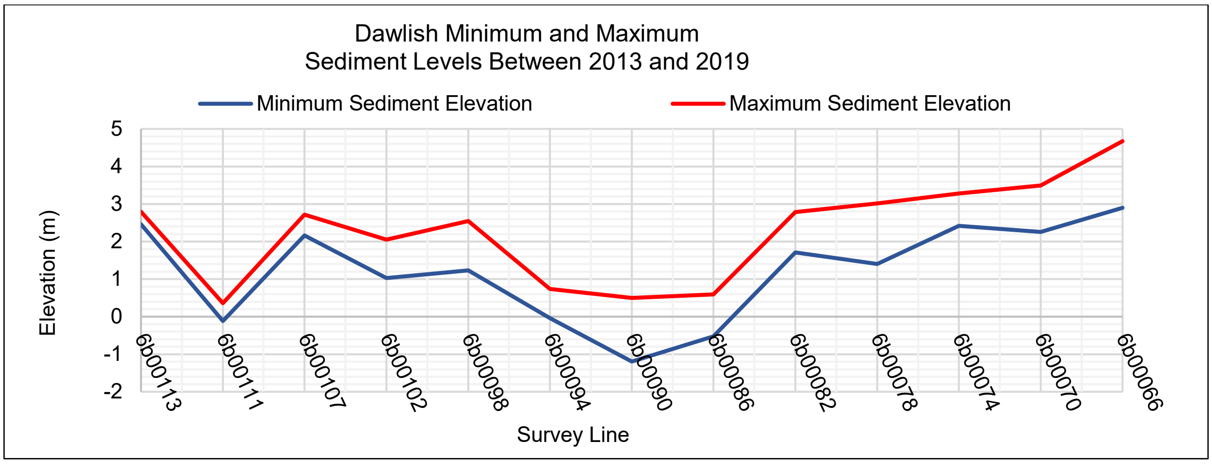

Figure 4.2.12: Minimum and maximum sediment levels relative to ODN, plotted against the corresponding survey lines (Spaced approximately 200 m apart) for the full survey period 2013-2019.

Further Analysis

Overtopping

The chainage of the profiles seen in Figure 4.3.1 has been adjusted slightly so that the base of the seawall can be considered from the same point in the horizontal direction. The previously discussed historical profiles in Section 4.1 and 4.2 vary in chainage due to the curvature of the coast and the seawall relative to the EABMs used for the surveys.

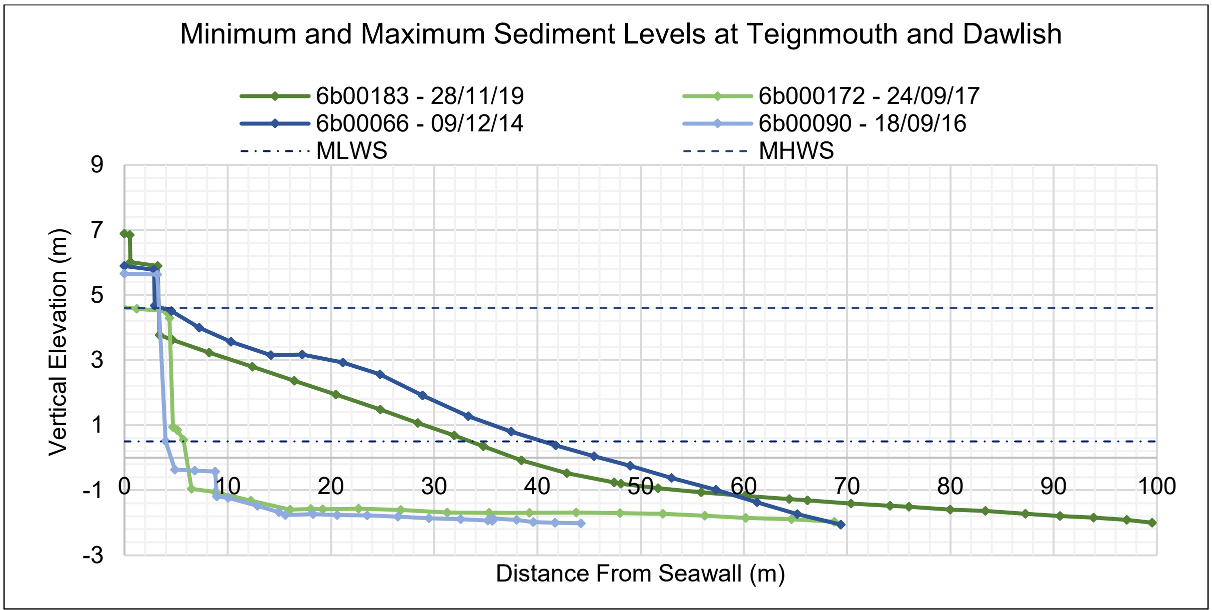

Figure 4.3.1: Minimum and maximum sediment levels measured at Teignmouth and Dawlish over the 7-year survey period, used to calculate overtopping at the seawall. Teignmouth sediment levels can be seen in green and Dawlish in blue.

To calculate the overtopping discharge at the seawall, the broken wave height at the base of the structure had to be calculated by considering a depth-limited wave height in shallow water. This was taken using the depth of the water at the base of the wall measured from the MHWS water level, 4.6 m, for the worst case scenario. The wave height at the base of the wall, as defined by the water depth was calculated using $H_b = 0.78h_b$, where H_b is the breaking wave height and h_b is the water depth at breaking (McCowan, 1894; Sverdrup & Munk, 1946; Komar, 1998). As mentioned earlier, the case at Teignmouth and Dawlish is complex as there is some variability in the nature of the seawall such as the lowered promenade and bullnose return wall at some points along the structure. For a first estimation, however, considering the structure as a vertical wall case with representative values of wave height and differing beach levels, the overtopping can be estimated using Equation 2.4 and rearranging for the overtopping discharge, q.

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.0011\left(\frac{H_{m0}}{hs_{m-1,0}}\right)^{0.5} exp\left(-2.2\frac{R_c}{H_{m0}}\right) \qquad \text{Valid for } 0 < R_c/H_{m0} < 1.35 \qquad (2.4)$$

where H_{m0} is the wave height at the toe of the structure, which has been substituted for the broken wave height H_b ($0.78 = H_b / h_b$). R_c is the crest freeboard of the structure, h is the water depth at the toe of the structure and $s_{m-1,0}$ is the wave steepness with L_o, based on $T_{m-1,0} = H_{m0}/L_{m-1,0} = 2\pi H_{mo}/(gT^2_{m-1,0})$. For this representative case, the wave steepness has not been considered in in Equation 2.4, and so the values for overtopping discharge will be a slight overestimate. Using the remaining parameters from the profiles shown in Figure 4.3.1, the following table gives the output of Equation 2.4.

Table 4.3.1: Differing parameters for overtopping Equation 2.4, using the minimum and maximum sediment levels at the sites as illustrated in Figure 4.3.1 and the corresponding estimation of mean overtopping discharge, q (l/s/m).

PROFILE:	**6b00183**	**6b00172**	**6b00066**	**6b00090**
Sediment Levels at Toe (m)	3.63	-1.32	4.50	-1.20
Broken Wave Height, H_b (m)	0.75	4.62	0.08	4.52
Crest Freeboard, R_c (m)	2.40	2.40	2.40	2.40
Water depth at Toe, h (m)	0.97	5.92	0.10	5.80
Overtopping Discharge, q (l/s/m)	0.002	3.61	0.00	3.52

The output from Equation 2.4 shows that for both of the maximum sediment level cases (Profiles 6b00183 and 6b00066), the resultant overtopping discharge is effectively zero. For the profiles with minimum sediment levels, however, the resulting overtopping is approximately 3.61 l/s/m for profile 6b00172 at Teignmouth and 3.52 l/s/m for profile 6b00090 at Dawlish.

Depth of Closure

The depth of closure has been defined by Hallermeier (1981) as the seaward limit to any significant change in the elevation of the beach profile for a given time interval. An estimate of the depth of closure, $\overline{\widetilde{\widetilde{d_1}}}$,has been calculated for Teignmouth and Dawlish using the mean annual significant wave height, $\overline{H}_s$, and σ as the standard deviation of $\overline{H}_s$, with Equation 2.2.

$$\overline{\widetilde{\widetilde{d_1}}} \approx 2\overline{H}_s + 11\sigma \qquad (2.2)$$

Using wave data from the Dawlish Waverider buoy, the annual significant wave height has been analysed between 2013 and 2019 to get the mean, $\overline{H}_s$ = 0.5389 m and the standard deviation, σ = 0.4078.

Inputting these values into Equation 2.2, the depth of closure has been calculated giving a water depth of $\overline{\widetilde{\widetilde{d_1}}}$ ≈ 5.56 m. To give this value context, the Dawlish wave buoy is positioned approximately 2.5 km offshore at a water depth of 11.5 m relative to ODN at mean low water springs (PCO, 2021). Assuming the seabed has a constant slope from MLWS to the wave buoy, this would mean that the depth of closure, $\overline{\widetilde{\widetilde{d_1}}}$ ≈ 5.56 m is approximately 1.21 km offshore when measured from the mean still water level relative to ODN.

Discussion

The beach profiles for Teignmouth show a general accretion of sediment at the base of the seawall south-west of Sprey Point. There is also an indication that sediment levels at the base of the seawall have generally increased in front of the town of Teignmouth between survey lines 6b00179 and 6b00204. Immediately upcoast of Sprey Point (6b00179) the elevation against the seawall has increased by as much as 3.27 m between the Spring 2018 and the Autumn 2019 surveys. The drop in elevation in March 2018 occurred for the majority of profiles (see Appendix B), however, profile 6b00169 (Figure 4.1.4) displays an increase in sediment levels in March 2018. Looking at the profiles since this drop in 2018, the beach looks to have recovered between 2018 and 2019. The profiles display evidence of the depletion of sediment levels against the seawall to the north-eastern side of Sprey Point. Survey line 6b00172 immediately north-east of Sprey Point has a low variation in sediment levels against the seawall (0.62 m). This confirms that Sprey Point does in fact interrupt the littoral drift along the beach, preventing the movement of sediment from the southern side to the northern side of the beach. This is surprising as the wave direction tends to predominantly range between south-south-easterly and east-south-easterly (See wave rose diagrams in Figure 3.1.2). The effect of Sprey Point on the profiles to the north-east of the structure support Tait and Grigg's claim that seawalls have the ability to cause erosion downcoast if the structure protrudes far enough into the surf zone (Tait & Griggs, 1990, as cited in Plant & Griggs, 1992).

Plans laid out by Network Rail (2020) include the extension of Sprey Point by 28.4 m from the existing seawall, in order to re-align the railway. Extending this structure's protrusion into the surf-zone has the potential to interrupt the longshore transport of sediment to a greater extent, worsening the sediment deficit on the north-eastern side. The plans, however, show that the seawall at Sprey Point will have a more gentle curve than the existing wall. This could allow for longshore transport currents to move sediment around the obstruction rather than entrain sediment on the south-western end. The distinct differences in sediment elevations in Figure 4.3.1 can be used as an ideal example of how sediment levels at the base of a seawall can affect the overtopping discharge. The EurOtop manual (2018) suggests the use of Equation 2.4 to calculate the dimensionless overtopping discharge at a vertical seawall.

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.0011\left(\frac{H_{m0}}{hs_{m-1,0}}\right)^{0.5} exp\left(-2.2\frac{R_c}{H_{m0}}\right) \qquad \text{Valid for } 0 < R_c/H_{m0} < 1.35 \qquad (2.4)$$

where H_{m0} is the wave height at the toe of the structure, which has been substituted for the broken wave height H_b ($0.78 = H_b/h_b$). R_c is the crest freeboard, h is the water depth at the toe of the structure and $s_{m-1,0}$ is the wave steepness with L_o, based on $T_{m-1,0} = H_{m0}/L_{m-1,0} = 2\pi H_{m0}/(gT^2_{m-1,0})$. The seawall at Teignmouth and Dawlish is more complex than this, however, so a simplified estimate of the overtopping discharge has been calculated from the minimum and maximum vertical elevations at both sites. This simplified representative case shows how sediment levels have an effect on the overtopping discharge when wave height is depth-limited in the surf zone. The overtopping discharge for profile 6b00183 at Teignmouth was calculated to be 0.002 l/s/m when the sediment levels were measured to be their highest when surveyed in November 2019. Similarly, the maximum sediment levels at Dawlish

(Profile 6b00066), surveyed in December 2014, gave an estimate of the overtopping discharge to be 0 l/s/m. Opposing this, lowered sediment levels at both sites resulted in an increase in the estimate of the mean overtopping discharge. Profile 6b00172 at Teignmouth, immediately north of Sprey Point exhibited a minimum sediment level when surveyed in September 2017, and a corresponding discharge of 3.61 l/s/m. Likewise, a mean overtopping discharge of 3.52 l/s/m was calculated for the minimum sediment level at Dawlish for profile 6b00090 (Surveyed in September 2016), central to the site of the seawall failure that occurred in 2014. The reasons for this increase of overtopping for the maximum sediment levels is purely down to how the sediment levels affect the wave height in the surf zone. Higher sediment levels give rise to smaller wave heights at the base of the structure, and a decreased chance of any overtopping. Lowered sediment levels and consequently larger water depth, h_s, at the base of the structure means the maximum shoreward travelling component of the wave height at the base of the wall, H_b, is also larger when disregarding reflection induced losses from the presence of the wall. The values calculated for the mean overtopping discharge therefore correlate with the theory that lowered sediment levels fronting a seawall increases the chance of wave overtopping, as outlined by Sutherland et al. (2008).

At Dawlish, there is evidence to suggest a few plausible explanations for the failure of the seawall in 2014. The locations of the larger groynes along the beach provide some justifications for this, positioned 70 m north-east of profile 6b00107 and 40 m north-east of profile 6b00098. It was expected that sediment may be confined to a certain extent within these two structures (Komar, 1998), and the historical profiles confirm this assumption. In Figures 4.2.10 - 4.2.12 it is apparent that sediment is building up on the south-western side of the groyne, with a difference of 0.58 m in variance of sediment levels between profile 6b00094 and 6b00098. The presence of these larger groynes may also be responsible for the deficit of sediment fronting the seawall between profiles 6b00086 and 6b00094. The historical profiles for this portion of the seawall show little evidence of an overall accretion or depletion of sediment. However, the three profiles within this 600 m length of the beach have much lower values for sediment elevation at the base of the seawall when compared to the rest of Dawlish beach. In Figure 4.1.7, the wave data shows that over the course of the February 2014 storm, all recorded waves approached Dawlish from a southern direction, with a mean angle of 171.4°. This validates the idea that waves from the south will drive sediment transportation towards the northern end of the beach and the likelihood of sediment becoming trapped on the south-western side of the groynes.

The location of the groynes at either end of the beach appear to have also contributed to the morphology of the shoreline over the survey period. There is evidence to show that the groyne near profile 6b00113 (Figure 4.2.9) could be the reason for the low variance of sediment levels at this point on the beach. This is because the profile is located on the downcoast side of the groyne, where it is common for erosion to be transferred (Komar 1998). There is little indication of any acceleration of erosion at survey 6b00113, as the sediment levels here have remained fairly constant. Another factor contributing to the consistent sediment levels at profile 6b00113 is the direction of waves approaching the beach. The wave rose diagrams (Figure 3.1.2) show that the waves predominantly approach from the south-south-east in January, July and October, which is virtually perpendicular to the edge of the groyne at this end of the beach. This means that the waves are unlikely to drastically affect the sediment elevation on the other side of the structure. The profile with the largest variation in sediment levels occurs at the most north-eastern of the survey lines on the beach at profile 6b00066 (Figure 4.2.2) with a variation of 1.78 m over the survey period. Survey line 6b00066 is in close proximity to the groyne at Langstone rock and is located near the upcoast edge of the structure. This means that the large variance at this point could be credited to the accumulation of sediment on the upcoast edge the groyne. Several surveys within this portion of the beach in particular show that the position of the lower tide terrace of the beach has shifted over the years, as the length of the profiles differ from survey to survey. Likewise, the surveys are undertaken on foot and so by time the beach surveys are completed, or if the tide is approaching the low water line, the surveys may not represent the full cross-shore profile. A change in the foreshore topography could affect the shoaling and breaking processes of the waves and cause more waves to break directly onto the seawall. In combination with the lower levels of sediment at profile 6b00090, an increase in wave energy at the wall has been shown to contribute to a higher volume of overtopping discharge at this point, which in turn can affect the structural integrity of the seawall.

There are some limitations to the data gathered from PCO; in particular, it can be difficult to identify the envelope of movement directly from the historical profiles of the sites due to the macrotidal nature of Teignmouth and Dawlish. The programme aims to survey beaches along the South West coast twice a year, however sometimes the effect of the tide can be seen in the data as the full cross-shore profile of the beach will not be fully exposed at times of high tide. The other possible cause for the difference in lengths of the profiles could be attributed to the erosion of the beaches. At low tide, less of the lower tide terrace may be exposed if this has been eroded over the years. The depth of closure is likely to be seaward of the profiles collected for this report, as the sites are intertidal. In this case, the depth of closure has been predicted using the wave-based Equation 2.2.

$$\widetilde{\widetilde{\overline{d_1}}} \approx 2\overline{H}_s + 11\sigma \tag{2.2}$$

where $\overline{H}_s$ is the mean annual significant wave height and σ is the standard deviation of $\overline{H}_s$.

Applying this equation to Teignmouth and Dawlish, the depth of closure was calculated to beat a water depth of 5.56 m, which is positioned approximately 1.21 km offshore from MLWS. This value is consistent with previous studies, lying between the depth of closure at Naples: Florida, USA., which was calculated to be 2.8 m and Nags Head: North Carolina, USA which was calculated as 7.5 m (Hallermeier, 1981: Cowell et al., 1999, as cited in Masselink & Hughes, 2003). The beach at Naples, Florida is west-facing into the Gulf of Mexico, meaning that the wave climate here is likely to be fetch-limited and so a shallow depth of closure is anticipated. At Nags Head, North Carolina, however, the beach is east-facing towards the Atlantic. The orientation of the beach here is less sheltered than Naples, therefore it would be expected that waves influence the beach further offshore. At Teignmouth and Dawlish, the beaches are both south-east facing and are slightly sheltered from waves approaching from the south-west, because of this both beaches tend not to experience any real long period swell. The complex nature of Teignmouth and Dawlish suggests that a value of $\widetilde{\widetilde{\overline{d_1}}}$ ≈ 5.56 m is coherent with the values obtained by Hallermeier and Cowell et al. (1981, 1999, as cited in Masselink & Hughes 2003). Nonetheless, it should be noted that the depth of closure for Naples and Nags Head were both calculated using Equation 2.1, which provides a more accurate approximation than the wave-based formula given by Equation 2.2. From the data gathered, it can be difficult to identify erosional hotspots along the length of the seawall due to the time interval between surveys. Other literature shows that Hotspots are variable in position, especially during storm events (List et al., 2004, as cited in McNinch, 2004). However, it can be seen in the data that at Teignmouth there is good evidence to suggest an accretional hotspot to the south of Sprey Point, with a decadal trend in sediment accretion for profiles 6b00179 and 6b00183 over the 7-year survey period. At Dawlish it appears that there is greater variability at the north-eastern end of the beach when compared to the south-western end. The reason for this could be the curvature of the coast and the relationship between this and the wave direction, for instance. The samples were gathered a year apart at times, and there clearly would have been some variability of the sediment levels within that period. Nevertheless, the profiles provide a snapshot of what is happening during that time and so the general movement of the beach is still captured because of the length of the survey period.

The vertical variation plots for both Teignmouth and Dawlish (Figures 4.1.10 and 4.2.11) show magnitudes of vertical variation similar to those recorded in Duck, North Carolina, USA (Komar, 1998). Komar (1998) recorded a maximum vertical variation of 4.0 m at the backshore of the beach at Duck, with this variation decreasing in the seaward direction to a value of approximately 0.25 m at the shoreline. At Teignmouth, the maximum variability against the seawall has been measured to be 3.52 m at profile 6b00183. Dawlish displays a maximum vertical variation of 1.78 m for profile 6b00066 at the north-eastern end of the beach. These values are consistent with those measured at Duck, although it is important to consider that Duck is a natural beach, whereas the seawall at Teignmouth and Dawlish is likely to have an influence on the sediment dynamics. This comparison is relevant as the wave climate at both locations has similarities, with a mean wave period of 8.4 s and a mean annual significant wave height of 2.9 m at Duck, North Carolina (Larson & Kraus, 1994). It can be seen in Table 3.1.1 that the wave climate at Teignmouth and Dawlish correlates well with the measurements at Duck, with a mean annual wave period of 6.31 s and a mean annual significant wave height of 3.51 m. This validates the plots of cross-shore profiles at Teignmouth and Dawlish. However, the longshore variability at the sites looks to be linked to a combination of longshore transport patterns interrupted by features along the shoreline and cross-shore transport, which makes it difficult to pinpoint the exact morphological processes present.

Wave data was analysed two weeks prior to each survey at both sites, in order to identify any potential reasons for a sudden depletion of sediment levels for the historical profiles. The analysis was achieved using MATLAB, and the corresponding wave graphs can be seen in Appendices A and C. From these graphs, it can be difficult to provide precise explanations for any loss of sediment at either site due to the complexity of the morphological processes present. Nevertheless, it is known that sediment responds to local currents and the strength of longshore currents increase with the offshore wave height (Masselink & Hughes, 2003). Infragravity waves form a significant part of the wave energy in the surf zone and are particularly energetic as the offshore wave height increases, which increases the erosive power of these low frequency waves (Guza & Thornton, 1985, as cited in Masselink & Hughes, 2003). Once again, the surveys tend to be carried out twice a year and so a drop in sediment levels could be attributed to storm conditions incident on the beaches at any other point in the time between surveys. Sometimes beaches can take a long time to recover from their storm profiles (Komar, 1998) and so a single storm can have a potentially deleterious impact on the sediment elevation on the beach. The largest significant wave height recorded in the wave data leading up to the surveys was measured to be 2.91 m (Appendix C), occurring in the two weeks leading up to the survey on the 26th October 2018 at Dawlish. This is above the storm alert threshold of 2.64 m set by PCO (2021). Waves above this threshold are therefore likely to have a significant impact on the movement of sediment. This particular storm could have potentially contributed to lowered sediment levels for profiles 6b00086 and 6b00082 at this point in time. The survey on the 26th of October 2018 also displayed higher levels of sediment at the base of the seawall at Dawlish for profiles 6b00107 and 6b00098, both located to the southern side of the groynes. Again, the storm prior to this survey could have influenced this build-up of this sediment. However, it is important to consider the effects of shoaling and breaking processes of the waves as they approach the shore, as the Dawlish wave buoy is measuring the waves in deep water. Table 3.1.1 shows a more comprehensive summary of the wave climate both sites, which has been produced from the analysis of waves measured by the Dawlish wave buoy between 2010 and 2021.

Tides can also have an effect on the morphology of the two beaches. At times of low tide, the waves are likely to dissipate on the lower tide terrace at Teignmouth (Miles & Russell, 2004). However, at high tides the upper slope of the beaches can reflect the waves back in the seaward direction (Masselink & Hughes, 2003). The classifications of the beaches calculated in Section 3.1. categorises both Teignmouth and Dawlish as low tide bar/ rip beaches, according to the model proposed by Masselink and Short (1993, as cited in Masselink & Hughes, 2003). This differs from the classification of Teignmouth as a low tide terrace beach by Miles and Russell (2004). The reasons for differences between these classifications is likely to be caused by the data that was used as well as the approach to the use of classifications. There are a range of grain sizes at Teignmouth, with the median grain size, D_{50}, ranging from between 0.2 mm at the foreshore to 0.4 mm at the backshore (Arcadis, 2018). At Dawlish, the median grain size, D_{50}, ranges between 0.25 mm and 9.6 mm (ADAS, 2019). This makes it difficult to identify which grain size is useful in the beach classification calculations. Furthermore, changing wave heights means that the beach at Teignmouth is always chasing a different equilibrium and therefore the beach classification model outlined by Masselink and Short (1991, as cited in Masselink & Hughes, 2003) is at most a broad indicator.

Conclusion

An investigation into the variability of sediment levels at the base of the Teignmouth-Dawlish seawall in south Devon, UK was conducted in order to identify areas of the beaches that may be affected by the re- development of the seawall. The data collected from Plymouth Coastal Observatory (2021) suggests that both of the beaches, subjected to similar wave conditions, have shown some significant variation in the sediment levels over the 7-year survey period. The vertical variability has been quantified in the order of metres, which is important in the design of future developments at the site. The range of movement for the majority of profiles at Teignmouth and Dawlish increases shoreward, which is consistent with previous work. In particular, results from the Teignmouth surveys show that Sprey Point acts as a barrier interrupting the littoral drift towards the north-eastern end of the beach. Sediment levels within a 600 m section of the beach in front of the town have generally increased over the length of the surveys, as a result of Sprey Point preventing the movement of this sediment. Within this 600 m section of the beach lies three profiles: 6b00204, 6b00198 and 6b00191, all spaced approximately 200 m apart. The range of movement in front of Teignmouth town has been found to be 0.851 m at profile 6b00204, the most south-westerly survey line. To the north-east of this, the range of movement gradually increased to 0.96 m for profile 6b00198 and 1.35 m for profile 6b00191. Sediment levels directly south-west of Sprey Point were also seen to increase at the base of the seawall over the 7-year survey period. A large vertical variability of 3.52 m was recorded for profile 6b00183 and 2.82 m for profile 6b00179, spaced 200 m apart. Opposing this, the sediment levels dropped immediately north-east of Sprey Point and the variance of the profiles against the base of the seawall has reduced on this side of the obstruction. The lowest value for vertical variability against the base of the seawall was observed for profile 6b00172, 80 m north-east of Sprey point, with a vertical range of 0.62 m.

From the results, some interesting observations can also be made for Dawlish beach. Here, the presence of groynes along the shore has affected the movement of sediment in the longshore direction. 70 m south of the groyne known locally as the Colonnade breakwater, profile 6b00107 displays a smaller range of movement observed at 0.67 m. In a 400 m section of the beach between the Colonnade breakwater and the Coastguard breakwater the sediment has been trapped to some degree, in an attempt to prevent the erosion of the main section of the beach fronting the town. Spaced 200 m apart, profiles 6b00102 and 6b00098 lie within this section, displaying a range of movement at the base of the seawall of 1.03 m and 1.32 m, respectively. The placement of these larger groynes, however, has caused a depletion of sediment levels to the north-eastern side of the structures. A significant deficit in sediment fronting the seawall was recorded within a 600 m section of the beach between profiles 6b00094:6b00086, to the north-east of the groynes. The minimum sediment level measured at the beach was recorded at profile 6b00090 to be -1.20 m. This profile is central to the location of the seawall breach that occurred in February 2014. Historic data shows that the beach level prior to the breach at this location was low, at a level of -0.77 m, compared to profile 6b00086 to the north where the level was recorded at 0.04 m. The range of movement at this location was recorded to be 0.90 m. This validates the idea that beaches backed by a seawall with lowered sediment levels increases the risk of seawall failure. The beach as a whole appears to be moving in the north-eastern direction towards Langstone rock. The range of movement increases from 1.03 m, at profile 6b00102 in front of the town to 1.78 m, at profile 6b00066 near Langstone Rock. The two groynes at either end of the beach also contribute to the morphology of the site. At the headland near Holcombe, the presence of the groyne has prevented the variation of sediment levels at survey line 6b00113. On the contrary, the groyne near Langstone rock at the north-eastern end has led to this larger range of movement at survey line 6b00066.

Although it is natural for beaches to rotate, the results confirm that coastal structures influence the acceleration of erosional processes. The implications of the findings suggest a need for further solutions to prevent potential future seawall breaches. Additional groynes at Dawlish may help to entrain more sediment between profiles 6b00094 and 6b00086, to provide additional protection of the new railway development. At Teignmouth, plans are in place to extend the protrusion of Sprey Point by 28.4 m from the existing seawall, in order to re-align the railway. However, the results show that reducing the protrusion of Sprey Point into the surf zone may help to limit the structure's interruption of longshore sediment transport.

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