Geo-Resilience 2023 Conference, Cardiff, Wales
D.G. Toll & M.G. Winter (Eds)
British Geotechnical Association, London. 2024
https://doi.org/10.53243/Geo-Resilience-2023-1-6

Protecting Critical Infrastructure through Georesilient Design: A Case Study from the A40 near Llanegwad

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Abstract

The UK's critical infrastructure is at greater risk of deterioration and failure under a changing climate. To build resilience into the design of mitigation solutions, a thorough understanding of the historical role of site-specific processes, geomorphological and geological conditions and possible future climate scenarios is needed. This paper presents a case study of an engineering scheme developed to protect a section of the A40 in Carmarthenshire from erosion by the River Towy. Due to rapid lateral erosion rates of up to 4.5 m/year, it was estimated that with no intervention the A40 would be undercut within 10 - 15 years. Hence, a mitigation solution was proposed that would provide both protection from imminent risk of failure but also consider resilience to future risk under a changing climate.

To provide a resilient solution, an optioneering exercise was undertaken to identify the constraints, risks and uncertainties of a range of options. A phased process of acquiring, analysing and integrating site-specific information was undertaken to arrive at a design that would provide long-term resilience for the A40, through which the preferred solution of an anchored embedded sheet pile retaining wall was determined. This process included: a) a desk study of historical mapping, aerial imagery and LiDAR to appraise the changes in the river planform over time, b) consideration of the benefits and limitations of different approaches based on site constraints, river morphology and geological information, and c) integrating all the information gathered through a geomorphological assessment of the options considering the future impact of climate change.

The design had to account for significant constraints, including a very tight working width at the pinch-point to the road, and a large theoretical retained height to account for worse-case future scour events. Utilising the geomorphological understanding of the site and presence of existing palaeochannels, the required length and alignment of the wall was designed and optimised to maximise the protection afforded to the A40. As infrastructure such as this is placed at greater risk of failure due to extreme weather events linked to climate change, this case study highlights the necessary multi-disciplinary, risk-based decision-making process that is required to develop resilient solutions.

Keywords: Highway Assets, River Erosion, Scour, Geomorphology, Sheet Pile Retaining Wall

1. Introduction

The River Towy is a large, geomorphologically active river that flows from the Cambrian Mountains in a south-westerly direction through Carmarthenshire to the Bristol Channel. It is one of the longest rivers flowing entirely within Wales at a length of 120km and is of ecological importance due to its native flora and fauna. The banks of the river between Llandovery and Pembrey coast are protected as a Site of Special Scientific Interest (SSSI) and a Special Area of Conservation (SAC). The footprint of these areas is in a constant state of flux as the river erodes and deposits materials over time. The river flows past several key pieces of public transportation infrastructure including the A40, which is a principal trunk road connecting London with Fishguard, and a regionally and nationally important transport corridor.

The A40, which is managed by the South Wales Trunk Road Agent (SWTRA), has been identified as being at risk of undercutting from the River Towy between Llandeilo and Carmarthen specifically at a site located approximately 500 m to the east of the village of Llanegwad (Ordnance Survey (OS) Grid Reference 252567, 221432). At this site, the A40 is located along the northern flank of the floodplain, which is also the location of a significant meander in the river.

The floodplain width from the toe of the embankment supporting the westbound lane of the A40 to the crest of the riverbank at the point of the meander closest to the road was 24.6 m in June 2020. At the site, the river is between 40 and 90 m wide, with a typical depth of 2 to 4 m under normal flow conditions. It has previously been estimated that the meander has been eroding at a rate of approximately 0.9 m/year between 1988 to 2010, indicating that the A40 would be undercut within 38 years. However, erosion rates have appeared to accelerate recently with an increase to a maximum rate of approximately 4.5 m/year between 2005 and 2010. Without any preventative measures, the River Towy was projected to erode the embankment supporting the A40 within 10 to 15 years. Atkins were commissioned by SWTRA to assess the risk associated with the River Towy undercutting the A40 and propose a resilient solution to protect this critical section the A40 from river erosion.

2. Fluvial Erosion Risk Assessment

The River Towy is a highly active river system, with the river planform in a constant state of flux as it migrates across its floodplain. Analysis of historical OS mapping from 1888 to the present day, and more recent aerial imagery and open-source LiDAR *(Natural Resources Wales (NRW), 2022)* demonstrated the dynamic nature of the Towy's planform. The analysis indicated that the meander is progressing towards the road at an average rate of 0.75 m/year. However, as rivers are complex non-linear systems that are unlikely to respond in a predictable manner *(Schumm, 1973)*, the rates and patterns of river erosion are difficult to forecast. River channels can move hundreds of metres within a few decades and, in some instances, tens of metres or more during a large flood event. Rivers can also scour or fill channels with sediment, commonly to a depth of 1-2 m, but sometimes to greater depths *(Macklin & Harrison, 2012)*. In 1888 the distance between the riverbank and the road was 112 m, however by 2019, a topographic survey measured this distance as just over 24 m. Analysis showing the dynamic nature of the River Towy is illustrated in Figure 1.

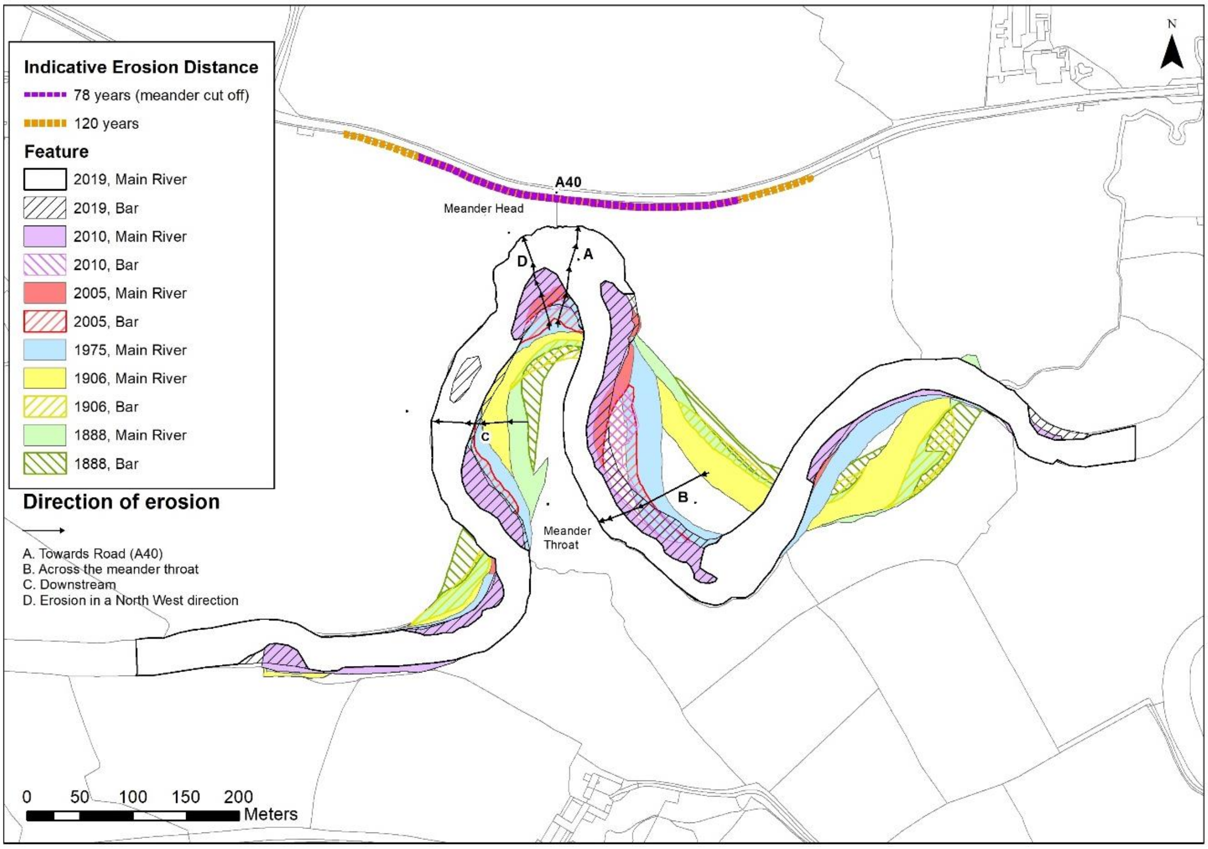

Figure 1: Historical migration of the River Towy near Llanegwad (1888-2019).

Analysing the past planform migration of the River Towy allowed prediction of future river alignments. These predictions relied on two significant assumptions: a) that the river could move from the current alignment in any direction (upstream or downstream) and b) that the river will continue to move at an average rate of 0.75 m/year towards the A40 (see direction of erosion 'A' in Figure 1). From these assumptions, a buffer of the 2019 alignment of the river was produced for two time periods: a) 78 years and b) 120 years. The 78 year time period is the anticipated timeframe in which the Llanegwad meander will be cut off. This would result in the river shifting away from the A40 , therefore removing the risk of undercutting at the northern riverbank. The longer time period of 120 years is the desired design life of an engineering scheme to protect the A40. From the fluvial erosion risk assessment, the predicted length of the A40 at risk of being undercut by the River Towy was determined to be 164 m over 78 years and 241 m over 120 years (Figure 1).

3. Informed Optioneering Assessment

Following the fluvial erosion risk, a multi-disciplinary optioneering assessment was undertaken to advise on the most appropriate solution considering: a) existing constraints (primarily ecological, environmental and spatial constraints), b) the inherent uncertainty in the fluvial erosion risk, and c) the ground conditions of the site. Early discussions with Natural Resources Wales (NRW) identified that planning permission would be required for work within 8 m of the riverbank due to the SSSI and SAC designations placed upon the site.

The first stage in the optioneering assessment was to undertake a preliminary ground investigation (GI) to characterise the ground conditions. The initial GI phases were completed in 2017 and 2018 and comprised five dynamic sampled boreholes with rotary core follow on to a maximum depth of 17.5 m below ground level (bgl). The GI identified cohesive Alluvium (of 1 to 2 m typical thickness) overlying granular Alluvium. Mudstone was recorded in only one borehole located within the A40 from 11.90 m bgl, indicating that rockhead may drop significantly towards the river channel. Based on the available information on the local ground conditions derived from the GI and existing site constraints, four high-level solutions were considered: 1) working with natural processes, 2) realignment of the highway, 3) a set-back retaining wall and 4) a buried rock revetment.

3.1 Working with natural processes

Accelerated meander cut off was proposed increasing the rate in which the meander neck is cut off thereby realigning the flow of the River Towy away from the A40. This was considered a highly uncertain option due to the variability of processes involved. Encouraging meander cut-off was predicted to increase the gradient of the channel bed leading to accelerated local bank and bed erosion to force planform adjustment to recover the natural slope gradient. This could result in loss of agricultural land and habitat types associated with a dynamic river system, thereby threatening the SAC and SSSI designation of the river.

3.2 Highway realignment

The highway realignment option proposed relocating the A40 further north, cutting into an existing slope and on an alignment where the bedrock (Nantmel Mudstones Formation) is shallow enough to limit northward migration of the River Towy. The final alignment of the A40 would be highly dependent on the depth of competent bedrock. This option required the most extensive third-party land purchase.

3.3 Set-back retaining wall

Various retaining wall solutions were considered with the primary options including: a) a sheet pile wall supported with deadman anchors, b) a sheet pile wall supported with inclined ground anchors, and c) a bored pile wall solution. In these options, the embedded retaining wall would be constructed set-back from the river and would be fully buried post-construction on both the active and passive sides of the wall. As the river erodes and progresses towards the wall, the retained height would be progressively increased, causing differential lateral earth pressure and the initiation of the retaining wall carrying load.

In the proposed sheet pile wall supported with deadman anchors solution, it was determined that the required deadman anchor size would be unfeasibly large in size to provide sufficient resistance, and was therefore deemed too difficult to accommodate within the spatial constraints of the site.

In the proposed sheet pile wall supported by inclined ground anchors solution, this option could be set further back from the riverbank with the inclined anchors able to extend towards and beneath the A40. Although the anchor forces would still be significant, the required resistance could be provided from grouted anchors. Compared to other anchorage systems, larger horizontal restraining forces could be generated using the angled anchors in the available space. For construction of the anchor arrangement, excavation and the installation of a suitable working platform would be required in front of the wall. Ongoing maintenance of the anchors would also need to be considered to ensure sufficient design life.

The final proposed bored pile wall option would bore deep enough to work in cantilever and remove the need for an anchor system entirely, saving construction time and cost, as well as eliminating the need for a maintenance programme for ground anchors. However, it was identified early on that although the wall could satisfy the ultimate limit state of the design retained height, large deflections would likely be experienced in the serviceability limit state consequently deeming it unsuitable without anchorage. On the basis that some form of anchorage would be required, it was decided a sheet pile solution would be a more cost-efficient solution.

3.4 Buried rock revetment

Due to the 8 m exclusion zone and spatial constraint of the embankment supporting the A40, there was insufficient space to consider a completely buried rock revetment. However, a revetment could form part of a hybrid design where an anchored sheet pile would be required at the pinch point of the meander head, with a buried rock revetment constructed up and downstream either side. This option required many components and interfaces, large excavations and the disposal of large volumes of material. It also required a complex maintenance regime and contained uncertainties on the dynamic operation of the apron in response the river.

3.5 Conclusions of the optioneering exercise

The optioneering exercise identified the optimum solution by balancing cost, risk and programme. This concluded a) realignment of the A40, b) an embedded sheet pile wall with inclined ground anchors, and c) hybrid buried rock revetment and embedded sheet pile wall with inclined ground anchors were preferred choices in the absence of more detailed GI information. The A40 realignment solution was heavily dependent on the presence of bedrock being encountered at shallower depths, which required confirmation by further GI. In contrast, the embedded sheet pile wall solutions (including buried revetment) required bedrock to be confirmed as sufficiently deep so as not impact the driveability of the sheets.

4. Detailed Development of Resilient Geotechnical Solution

4.1 Ground model

Following the completion of the informed optioneering assessment, a third phase of targeted GI was specified and completed in March 2021. This comprised five dynamic sampled boreholes with rotary core follow on to a maximum depth of 30 m bgl and a seismic refraction tomography and electrical resistivity tomography geophysical survey. The geophysical survey was deemed critical for confirming the depth to bedrock across the site, as it was not consistently encountered in the earlier phases of intrusive-only GI. From GI information from all phases, a ground model was developed (Figure 2**Error! Reference source not found.**).

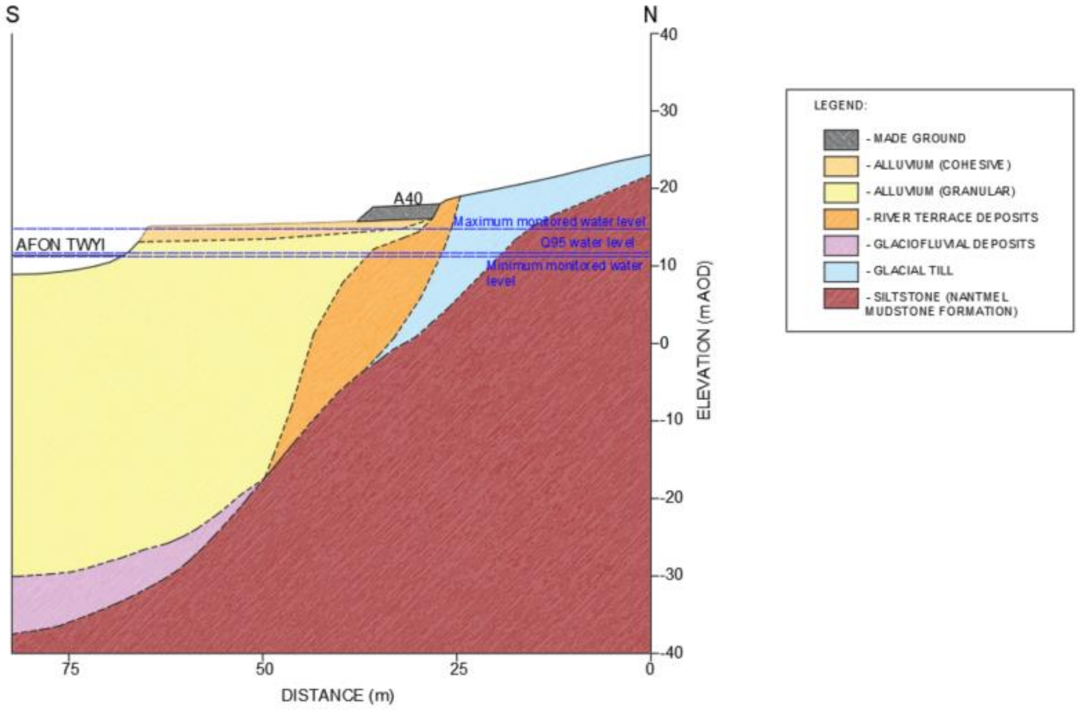

Figure 2: A40 Interpreted Ground Model.

Ground conditions generally comprised 2 m of cohesive Alluvium, overlying thick deposits of granular Alluvium. These were underlain by Glaciofluvial Deposits and Siltstone of the Nantmel Mudstones Formation. River Terrace deposits were recorded beneath the A40, and Glacial Till was anticipated to be present to the north.

Siltstone of the Nantmel Mudstones Formation was recorded at 17 m bgl beneath the A40, however, bedrock was not encountered in any of the boreholes located in the flood plain. Continuous cross-sections from the seismic refraction tomography and electrical resistivity tomography survey confirmed the presence of bedrock at approximately 17 m bgl beneath the A40 and also identified a steep increase in depth to bedrock towards the river, imaging bedrock depth >30 m bgl beneath the flood plain.

4.2 Determination of single option development

The additional GI information confirmed that realignment of the A40 could not be developed any further due to the significant depth to bedrock, coupled with potential land take issues. Both the embedded sheet pile option with inclined ground anchors and the hybrid rock revetment option with a sheet pile wall supported by inclined ground anchors were plausible based on the encountered ground conditions. However, the hybrid rock revetment option was considered to carry greater technical risk associated with the dynamic behaviours of the river channel and potential variability of the solutions' response to the erosion and therefore protection offered to the A40. Furthermore, it would require a more demanding maintenance regime and was anticipated to have similar construction costs to the sheet pile wall with inclined ground anchor support. Consequently, it was determined that a sole sheet pile wall with inclined ground anchors was the optimal solution to provide long-term resilience to the operation and usage of the A40.

4.3 Geomorphological assessment

With the proposed protection measure confirmed, a detailed assessment of the extent of A40 at risk from erosion was undertaken to determine the length of wall needed to protect the road. Identifying the at-risk section was largely determined by predictions of how the River Towy could migrate over the operational life of the structure, taking into consideration factors such as climate change, wall effect and erosion trajectory.

The assessment considered three assumption-based scenarios of the length of road at risk. These scenarios were determined from a buffer distance which was estimated using *erosion rate*, *period of operation,* a *wall effect factor*, an *erosion trajectory factor* and a *climate change factor*. Separate estimates were undertaken to determine the up and downstream buffer zone distances. The buffer zone was the distance applied as an offset to the right bank edge of the River Towy to predict the wall length required to protect an equivalent section of A40 carriageway associated with each scenario, with the transition between upstream and downstream progression taken as the apex of the bend.

Erosion rate is defined as the rate at which the River Towy erodes towards the A40. Three rates, based on analysis of historical rates of erosion, have been used in the scenario analysis.

Period of operation is defined as the number of years the wall will need to function. Two shorter periods (71 and 78 years) were based on trajectories leading to meander cut-offs. The longer period assumed the wall must continue to function for 120 years (the optimum structure design life).

A *wall effect factor* has been considered for the analysis depending on different scenarios, which considers how the introduction of a smooth hard surface, such as the proposed sheet pile wall, into a fluvial system can reduce friction associated with erosion. In turn this can result in an acceleration in erosion rates adjacent to and downstream of the hard surface.

The *erosion trajectory factor* considered the future impact of meanders. Meanders commonly migrate in a down valley direction. However, occasionally, and particularly in the presence of hard irregularities in the valley floor, meanders can (unexpectedly) migrate upstream.

The *climate change factor* assumed that erosion rates of the River Towy will increase over time and in proportion with an increase in river flows in west Wales as a consequence of climate change. Based on guidance provided by the Welsh Government, an allowance for an increase in peak flow of 30% was applied (Welsh Government, 2021). A summary of the variables used for the estimation and buffer distances estimated is shown in Table 1.

Table 1: Variables used to determine buffer distance.

Estimated length of road at risk	Erosion rate (m/yr)	Period of operation (yrs)	Wall effect factor	Erosion trajectory factor	Climate Change factor	Total Buffer distance (m)	Proposed wall length (m)
Longest	2.95	120	1.50	1.00 (downstream) 0.75 (upstream)	1.30	1208	1321
Medium	0.75	78	1.25	1.00 (downstream) 0.50 (upstream)	1.30	143	228
Shortest	0.67	71	1.00	1.00 (downstream) 0.75 (upstream)	1.30	77	128

Each buffer distance was then applied to the existing river course to determine the length of wall required for each scenario using a GIS analysis. This concluded that the longest section road at risk scenario required a 1321 m wall, the medium section scenario required a 228 m wall and the short section scenario required a 128 m wall. The results of this assessment were integrated with a review of the historic planform migration, which determined that a 228 m long wall length (medium length of road at risk scenario) was most appropriate. This was increased slightly in the final length to allow angled wall ends away from the road, directing the river's future erosional pattern towards an identified palaeochannel and guiding towards a more natural taper.

A separate assessment was undertaken to assess the maximum height of the retaining wall, to the base of the River Towy and any additional erosion associated with short term scour events. The assessment follows the United Stated Department of Agriculture (USDA) approach which considers total scour as a series of components that can be broadly grouped into event scour and long term bed elevation change. The gravel river bed at the site meant that bedform scour was not considered (as this is a sand bed river phenomenon), and the planform configuration and bed material at the meander preclude use of the USDA bend scour equation. Therefore, the event scour assessment at Llanegwad was limited to an empirical determination of general scour combined with an adjustment based on professional judgement for other scour processes including scour associated with a tight river bend and scour amplification due to the retaining wall. The empirical general scour equations of Lacey, Blench and Blodgett (*USDA, 2007*).

A maximum scour depth of 2.69 m was established the equation by Blodgett's method (*USDA, 2007*). From this, a total scour allowance up to 3.0 m was determined. This accounts primarily for event scour, but also recognises the risk of long term change in bed elevation during the lifetime of the scheme. Following the scour assessment, a maximum retaining wall height of 9.7 m was determined, comprising 6.7 m to the base of the riverbed and an additional 3.0 m below riverbed during scouring events.

4.4 Proposed design

From assessing the risk the River Towy poses, and how these will evolve over time, a detailed design for the embedded sheet pile wall with ground anchor support could now be undertaken. The final design comprised a 240 m long anchored sheet pile wall with a minimum embedment length of 14.7 m (Figure 3). 16 m long ground anchors which had an 8m fixed bond length were installed at alternating 30° to 35° angles from horizontal, with a 1.2 m spacing along the sheet pile wall.

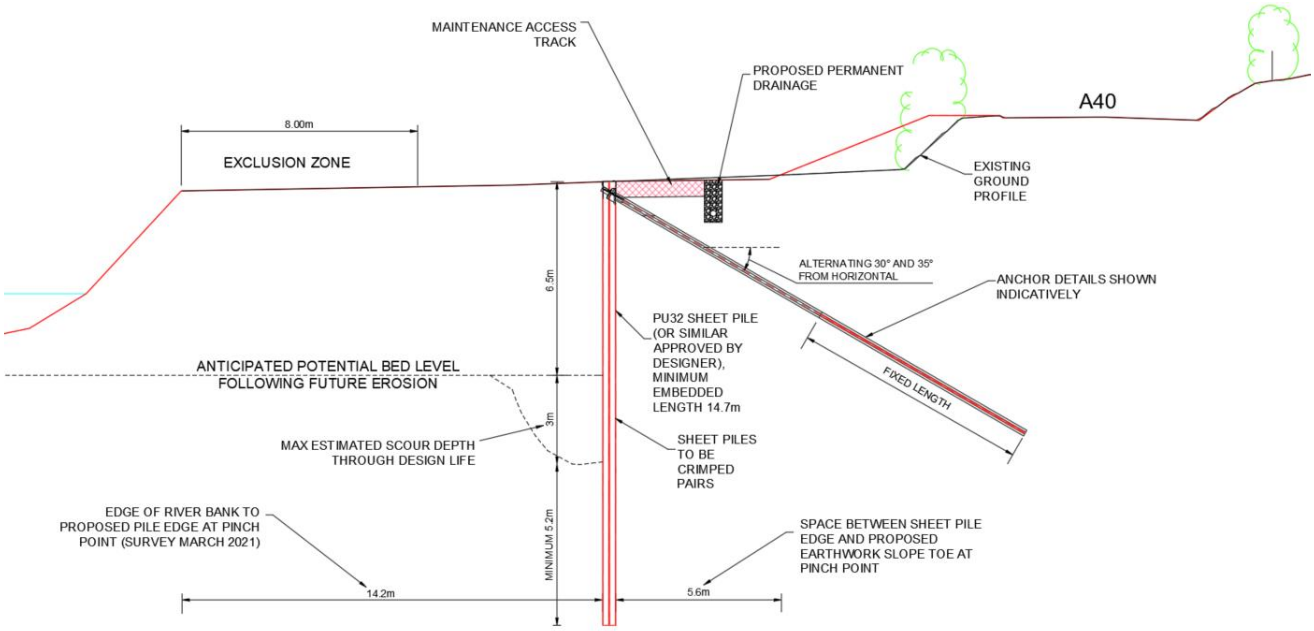

Figure 3: Anchored sheet pile wall arrangement.

The construction of the sheet pile wall was completed Summer 2022 without any significant issues. The benefit of the structure being a singular design (as opposed to a hybrid solution) allowed for a greater ease of construction and enabled the Contractor to quickly become familiar with the installation methodology and adapt it to suite the site conditions. This relatively simple method of construction also limited the impact to the surrounding landscape and the adjacent SSSI and SAC sites. Furthermore, this removed the potential complexity associated with the integration of the different design elements and likely associated delays, and construction was completed within the anticipated programme timescale. In the as-built design, the retaining wall was fully embedded with no visible signs of hard engineering except for the pile cap. The double corrosion protected anchors, in combination with the use of an inert backfill in front of the sheet piles in the zone of the anchor heads, allowed for a reduced maintenance frequency during the early years of the scheme. The material used in the construction and operation of the temporary piling platform was reclaimed post-construction and subsequently reused as fill to the A40 shoulder widening, allowing the area to be returned to grassland.

5. Conclusion

The constructed anchored sheet pile wall solution was identified as the optimal river erosion mitigation measure, providing a resilient design against future behaviours of the River Towy and taking into account a changing climate. This design was based on an intensive geomorphological assessment, which proved critical in determining the level of required resilience and spatial extent of the protection to the A40. The alignment of the wall was designed so that the flow of the River Towy would be redirected into existing palaeochannels, encouraging the river to flow in the path of least resistance, away from the critical A40. By gaining an understanding of the past movements of the River Towy, and anticipating how future changes in climate will influence the planform migration, an appropriate solution was determined to build resilience into the asset.

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