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SALHOUSE SPIT RESTORATION WITH DREDGED SEDIMENT IN GEOTEXTILE TUBES

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Abstract. The Broads Authority is responsible for the maintenance of navigation in the Norfolk and Suffolk Broads. Annually 50,000m^3 of sediment is removed from the rivers to keep up with the accumulating sediment and deal with the backlog of sediment. How to deal with this volume of sediment each year is a challenge as large parts of the Broads are protected habitats, in agricultural stewardship or urbanised. Alternative forms of sediment re-use are therefore sought with the aid of the European funded PRISMA project. The restoration of Salhouse spit is one of the pilot projects of PRISMA and focusses on the re-use of dredged sediment as part of a retaining structure made with geotextile tubes. The potentially unstable spit of land is strengthened by the application of 12,000m3 sediment dredged from the River Bure. The project area of 7,000m^2 is designed to develop into a reed-bed (BAP wetland habitat), that is of international importance. The geotextile tube retaining structure was carefully designed and calculated, in order to predict the consolidation, settlements, deformation and potential failure mechanisms. The execution was based on dredging with traditional means (mechanical grab) and the sediment was transported by barge. The barges were emptied at the project site by long-reach excavator and the sediment pumped into the geotextile tubes and backfill area by piston pump (concrete pump). The project has demonstrated successful use of dredged sediment in a bank strengthening project with the use of geotextile tubes. The restoration site has shown promising signs of wetland vegetation and we hope to see a successful reed-bed habitat develop within the next two years.

Keywords: Working with nature, building with nature, beneficial reuse, dredging, dredged sediment, habitat creation, geotextile tubes, retaining structures, vegetation transplant.

1. Introduction

The Broads Authority is responsible for the integrated management of the waterways in the Norfolk and Suffolk Broads, UK. This includes maintaining navigation while conserving and enhancing Broads wildlife. The Broads consists of 200 km of navigable waterways including around 60 shallow lakes. It is a delicate balance between conservation and enhancing the environmental value, while sustaining adequate water depths for navigation. The Broads Authority dredges approximately 50,000m^3 of sediment every year to keep up with the accumulating sediment and reduce a backlog which has built up over decades. This vast amount of sediment mostly consists of organic matter, silts, clay and sand. Historically, it was placed on the riverbanks to become part of the rivers' flood defences – a process known as side casting. Today side casting is not always an option: large parts of the Broads are protected for wildlife, urbanised or in agricultural stewardships and recent re-alignment of floodbanks. For this reason the Broads Authority is actively looking for alternative purposes for sediment, such as agricultural soil improvement, flood defence works, general earth works, land raising and restoration of habitat and eroded areas/banks.

The change in disposal practices created a need for knowhow and knowledge of re-using sediments. For this reason The Broads Authority became involved in the PRISMA Partnership; Promoting Integrated Sediment Management. PRISMA is a European funded project with four partners organisations; Waterwegen en Zeekanaal (BE), Water Board of Schieland and Krimpenerwaard (NL) and Armines acting through the

Centre de Douai (FR). PRISMA is aimed at obtaining sustainable sediment management practices that are feasible in the 2seas region. The project commenced officially in June 2011 and comes to an end in June 2014. This paper describes one of the individual pilots carried out by the Broads Authority.

2. Setup of the pilot at Salhouse Broad

The project at Salhouse Broad is centred on the restoration of a narrow spit of land between Salhouse Broad and the River Bure. The river side of the spit is protected by sheet piling, but during the last 60 years the broad-side has progressively eroded away to the extent that anchor piles were beginning to be exposed potentially destabilising the spit of land. The effect of the erosion can be seen when a comparison is made between the 2010 and 1946 MOD aerial photographic records.

The River Bure is also in need of maintenance dredging as part of the Broads Authority's responsibility. How to deal with the dredged sediments in this valley is a substantial issue as large parts are Sites of Special Scientific Interest (SSSI) or protected by status of Special Protected Area (SPA), Special Area of Conservation (SAC), National Nature Reserve (NNR) and Ramsar wetlands of international importance.

Fig 1. Salhouse Broad situated in the Bure valley 2010, Getmapping plc.

Fig 2. Salhouse Broad historic photograph RAF 1946, Norfolk County Council.

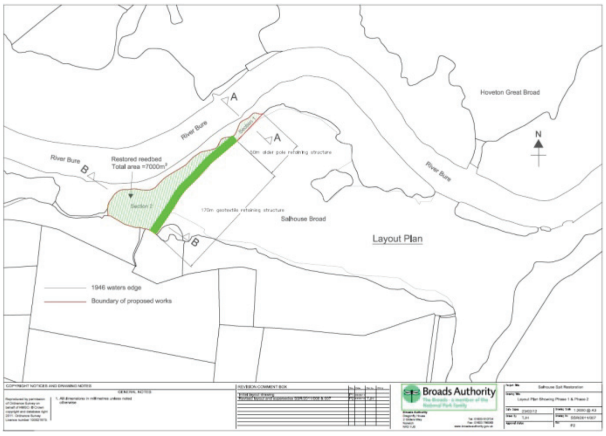

Fig 3. Outline based on superimposed 1946 waterline.

The aspiration of the Broads Authority was to reuse a considerable amount of dredged sediment to restore the spit and create a wetland habitat. The new habitat would become a corridor that links nearby sites. The Broads Authority produced a concept design and then entered a procurement process inviting tenders for detailed designs. A condition however was to utilise the Broads Authority's in-house construction and dredging teams to execute this ambitious project.

2.1 Design phase

Based on the aerial photographs of 2010 and 1946 the outline of the project was established. The project area is over 7000m^2 in size, with aim to restore the 1946 shoreline and create a wetland habitat.

As part of the PRISMA trialling, two forms of retaining structure were constructed (Ekkelenkamp, 2012). Section 1 is a 50m alder pole piling structure and Section 2 is a 170m gravity structure constructed with geotextile tubes. The focus of this paper is the use of the geotextile tubes.

The geotextile tubes and the area between the bank and the retaining structure had to be filled with sediment (PIANC, 2011, CUR, 2009, CUR, 2010). In order to achieve this, the sediment had to be pumped. The following chapters describe how this was achieved by piston (concrete pump).

As part of the project preparation public and landowner consultation was carried out. Also a detailed ecological and flood risk assessment was undertaken to support applications for a waste management licence, flood defence consent, planning permission, felling licence and the water framework directive. Following from the studies various mitigation measures were agreed upon.

2.2 Site investigation and sediment characterisation

In preparation for the detailed design a site investigation was carried out, including sampling and coring. The investigation was undertaken in accordance with a detailed plan at both the construction site as well as the dredging sites.

The sediments at both the dredge location and the Broad were analysed on a standard suite of parameters to determine the chemical composition. The results of the analysis indicated that the sediments were of suitable quality for re-use and posed no risk to the environment. From a risk based point of view, the sediments were used locally within the same waterbody, thus limiting environmental risk.

The sediment at Salhouse Broad consisted mainly of soft organic silts from 1.2 m below mean water level up to 6.0 m below mean water level. At the south side of the broad soft sediments were less thick, this is the natural boundary of the valley and crag deposits (sand and gravel) are closer to the surface. The very thick layer of soft sediments made the design of an adequate and economic piled retaining structure difficult. For this reason, a gravity structure exploiting relative densities was seen as the preferred option (Adel, 1986, Baker, 1988, Blot and Pye, 2001, Cox and Budhu, 2008).

The sediment available from maintenance dredging for the construction was similar organic soft silts, but with occasional localised dominance of peat or clay. The River Bure was dredged to the specification set out by the Broads Authority's Sediment Management Strategy (Wakelin and Kelly, 2007).

Table 1. Characteristics of the sediments at the broad

Parameter	Value	Unit
Moisture content	298	%
Organic matter	32.4	%
Bulk density	1160	kg/m^3
Dry density	295	kg/m^3
Dry solids	25.42	%
Liquid limit	212.3	
Plastic limit	121	
Plasticity index	91.5	
Liquidity index	2.04	
Undrained shear strength	0	kPa
Particle size distribution		
Sand (63 μm– 2mm)	5	%
Silt (2 μm - 63 μm)	83	%
Clay (<2 μm)	12	%

Table 2. Characteristics of the dredged sediments

Parameter	Value	Unit
Moisture content	493	%
Organic matter	42.2	%
Bulk density	1060	kg/m^3
Dry density	190	kg/m^3
Dry solids	17.92	%
Undrained shear strength	0	kPa
Particle size distribution		
Sand (63 μm– 2mm)	12.5	%
Silt (2 μm - 63 μm)	71.5	%
Clay (<2 μm)	16	%

The high level of organic matter increases the water content considerably and this reduces the geomechanical strength of the sediment. The use of geotextile tubes filled under pressure increases consolidation and therefore the strength of the material it contains. On average the dredged sediment had a lower natural density than the sediment within the Broad that would form the base layer: offering a great natural benefit to the structural stability. Geotechnical calculations were carried out on the results of the site investigation to theoretically prove a stable structure.

3. Geotechnical engineering and calculations

During the preparation phase a number of risks were identified in relation to the failure of the construction. Various destabilising forces and failure mechanisms were assessed such as wave impact, overtopping, liquefaction, micro instability, drifting ice and vessel impacts.

Although at first glance large forces such as ice and vessels might seem of major importance, the micro instability and potential liquefaction was of greatest concern. For this reason the geotextile building materials were selected with great care. The geotextile tubes selected were the TenCate Geotube® GT500D units, the tubes were covered with a non-woven geotextile fabric; TenCate Polyfelt TS70 to act as armour against hydrodynamic loads, specifically to reduce the disturbance of fine grained particles.

In order to determine the shape and dimensions of the retaining structure the geomechanical behaviour of the soil body and subsoil had to be described and calculated. The total settlement of the retaining structure during filling equals the sum of the subsidence of the subsoil and consolidation settlement of the sediment contained in the geotextile tube (see Fig 4). The deformation of the subsoil and the settlement of the geotextile tubes themselves (consolidation process) were predicted by using the method of Koppejan (Koppejan, 1948, Lambe and Whitman, 1969, Van 2002). This method combines the theory of Terzaghi (Terzaghi, 1925) for primary settlement and the theory of Keverling Buisman (Keverling Buisman, 1940, Verruijt, 1999) for secular subsidence. Together with these theoretical formulations the measured geotechnical properties were used to define the coefficients and to calculate the expected settlements.

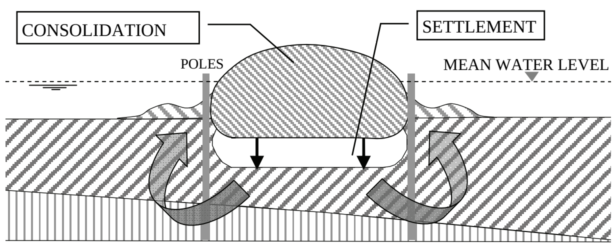

Fig 4. Consolidation and settlement of the geotextile tubes.

Thereby it was possible to anticipate settlements during the filling process of the geotextile tubes and afterwards. In order to level the crest with the mean waterline, the subsidence of the subsoil and consolidation of the geotextile tubes were compensated by the chosen filling height. The method of Koppejan is described by:

$$\frac{\Delta h}{h} = \left[\frac{1}{C_p} + \frac{1}{C_s}\log(t)\right]\ln\left(\frac{p_g - \sigma_0}{\sigma_0}\right) + \left[\frac{1}{C_p''} + \frac{1}{C_s''}\log(t)\right]\ln\left(\frac{\sigma_i - p_g}{p_g}\right)$$

With:

Δh = settlement of the geotextile tube
h = layer thickness underneath the tube
C_p = primary compression constant
C_s = secondary compression constant
C'_p = primary compression after threshold tension
C'_s = secondary compression after threshold tension
t = duration period
σ_i = grain tension after load
σ_0 = initial grain tension
p_g = boundary tension

The applied compression coefficients followed from the NEN6740 1990 standards. The tension stresses were related to the calculated pressures at the geotextile tube. Both depended on the sedimentological properties of the fill material and subsoil which were studied during the site investigations and laboratory analyses. Because the sediment was dredged and pumped mechanically (i.e. with no increase in water content) the geomechanical strength remained intact. In addition, the geotechnical behaviour of the sediment and geotextile tubes could be predicted more accurately. The calculation of the coefficients, soil stresses and total settlements take into account that the retaining structure is submerged (NEN, 1991b, NEN, 1991c).

The subsidence of the subsoil depends on the load (by the filled geotextile tubes) and the properties of the subsoil. These properties are often called the deformation characteristics. By the spreading of the load the settlements will be uneven. The primary or first phase settlement results from the deformation of the subsoil. The geotextile tubes exert a downward force on the subsoil. The grain structure will deform by normal and shear stresses. If the shear stresses become too big, the grain structure will have to reorient which means that the amount of space between particles will decrease. At a certain moment the number of contact points between the grains will increase in such a way that a state of equilibrium is reached. The secondary settlements occur more gradually with time and result from soil creep. This means that the soil deforms due to the changed circumstance caused by the geotextile tubes. The soil particles rearrange after the pore size is considerably decreased. This is part of the consolidation process. The same applies for the consolidation of the fill material in and behind the tube (Bisschop et al. 2003, Den Haan 1991, Douwes Dekker, 1991, Dykstra and Joling, 2001, Ekkelenkamp, 2011, CROW, 2003).

The permeability of the soil is important for the subsidence and consolidation process. Water is gradually pressed from the pores as a result of the load by the geotextile tubes. The consolidation period increases as the permeability of the subsoil decreases. This period is called the hydrodynamic consolidation period. The clayey soil has a relatively low permeability. Therefore the period of the total settlement takes a long time.

Also the thickness of the sediment layer at the bed of Salhouse Broad played an important role in the duration of the consolidation period. It was estimated that the subsoil, consisting of a homogeneous sediment layer, had a thickness of 5m measured from the bed level downwards. This meant that the settlement period could be substantial (100 to 300 days, or longer, see Figure 5). Indications were found along Salhouse Broad which suggested the presence of a permeable gravel layer. This layer could speed up the consolidation process by a factor 4 (CUR report 162, 1991 and 1993). Figure 5 shows that the major part of the total settlement is reached after the first 10 to 20 days. This initial primary settlement results from the decreasing pore volume and consolidation of the subsoil. The so called "settlement speed" was determined by a number of parameters. The most important parameter was the permeability of the soil. Other soil properties were used in the calculation including the consolidation coefficient and coefficient of compressibility. The calculations predicted that the primary settlements would end just before the completion of the filling phase. This could be very beneficial for the execution of a number of filling cycles. In theory, the initial settlement would be almost 0.50m. After 15 days the transition to the secondary settlement starts. During this stage the total settlement of the tube would increase to 0.70m. Depending on the permeability of the clayey subsoil the settlement would vary between 0.60 and 0.90m. After completion of the filling phase the tubes exerted their maximum load onto the subsoil. This could eventually (after approx. 3 months) result in a total settlement of 0.90 to 1.10m, depending on the local soil properties (permeability, pore volumes, specific density) and stratification of the subsoil. The long term subsidence

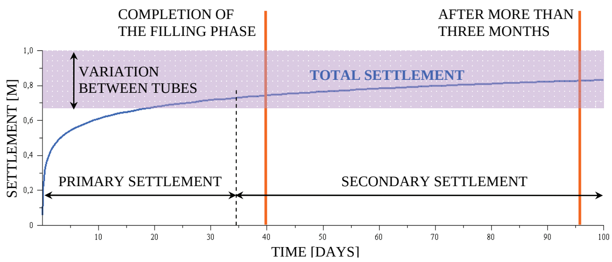

Fig 5. Relation of the extent and duration of settlement.

of the subsoil, which depends on the creep factor of the subsoil, was estimated at 1.10 to 1.30m (after approx. 12 months or more).

The crest height of the retaining structure made of geotextile tubes depends on the consolidation of the geotextile tube fill and was designed to be at the same height as MWL (Mean Water Level) 0.3m ODN. During high water the structure would be flooded while during low water the crest would stay above water. The consolidation depends on the specific density and effective stresses of the filling material and on the geometric dimensions of the geotextile tube. From the effective stress the consolidated undrained shear stress was calculated. Eventually the total decrease in height of the retaining structure caused by consolidation of the filling material was calculated by the use of Skempton's 1957 correlation formula (Verruijt 1999):

$$\frac{c_u}{\sigma'} = 0.11 + 0.37 \cdot \mathrm{PI}$$

With:
cu = consolidated undrained shear strength
σ' = effective stress
PI = plasticity index

With the relation introduced by Winterwerp & Van Kesteren, 2004, the moisture content after consolidation was calculated (Bezuijen en Vastenburg 2012). The calculated consolidation height of the tube was h=0.5029m. An extra height of 0.5m after the filling stage was needed in order to level the geotextile tubes crest with the mean water level. The height of the structure was adjusted by adding sediment to the geotextile tubes during a number of filling cycles. In this way the consolidation process (and, of course, the subsidence of the retaining structure) was controlled.

During the design stage the predicted settlements and consolidation of the geotextile tubes were used to determine the geometry of the tube. The strength calculations of the geotextile material are of great importance. The strength of the geotextile tubes is guaranteed by the manufacturer Tencate. The calculation of the geometry of the geotextile tubes was based on two different principles. The width and height of the tube had to be maximised and the filling volume had to be optimised. An important prerequisite for the filling of a geotextile tubes was to achieve a maximum degree of filling of 80% in the final condition. Due to the assumed circumference of the tube of 18.6m, a calculation was performed in which the shape of the tube for the final state was determined. An important parameter for the calculation of the tensile strength of the geotextile tubes was to maintain the water level depth.

An "overall" safety factor of 3.5 was used because of strength reducing factors, such as a very high pressure during the filling process, the occurrence of creep, insufficient strength of the sewing stitch and wear or tear of the geotextile during filling. Eventually the geometry of the geotextile tubes was modelled. The calculated height of 2.50m was suited for our requirements of the retaining structure.

Fig 6. Gauging rods placed into the geotextile tubes.

During the construction period field data was collected. The data concerns the subsidence of the retaining structure and consolidation process of the filling material. Both were recorded daily between the 26th of October 2012 and the 16th of November 2012. The gauging rods (see Fig 6) were placed into the Geoports® (filling points) along the geotextile tubes to measure the subsidence of the structures crest.

Every rod was numbered and marked. In addition to the measurements of the settlements, the average water levels were observed. The height of the structure crest was related to the surrounding water level. Also a number of depth measurements were made in order to study the behaviour of the bottom profile of the geotextile tubes.

For the evaluation of the geotechnical behaviour the theoretical predictions were compared with the field measurements. It was found that the sediment was evenly distributed within the tubes. The pump had enough power to pump the sediment sideways after entering the tube. The large forces on the inlet were guided by the geotextile of the inlet port. This configuration of tubes, ports, concrete pump and sediment resulted in an evenly distributed filling of the tubes. The number of filling cycles depended on the location of the tube, the settlement of the subsoil and the consolidation of the fill material. This method proved to be a powerful tool to get the correct height of the crest between 0 and 0.20m above the waterline.

The primary settlement of the geotextile tubes proved to be a significant part of the total subsidence. Then over a period following completion of the last filling cycle significant further secondary settlement was observed. The estimated value of 0.50m additional height was found to be a good approximation. The influence of the consolidation process of the filling material was linear. This was expected according to the theoretical predictions.

Table 3. Average settlement and displacement values

Cross section	**1 - 2**	**3 - 6**	**7 - 10**	**11 – 14**
Tube no	3	1	2	4
Tube height [m]	0.73	2.09	2.56	1.96
Crest height* [m]	0.12	0.17	0.09	0.11
Total settlement [m]	0.10	0.92	1.02	0.26
Difference bed level** [m]	-0.17	0.21	0.26	0.19

* Crest height above mean water level (0.33 ODN)

** Difference of bed level at the tube and 2 m out.

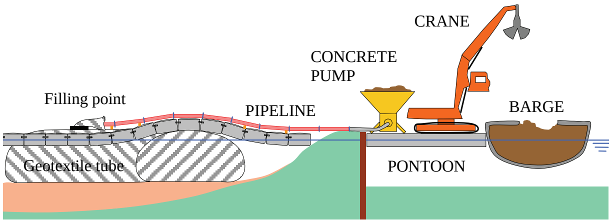

Fig 7. Schematisation of the execution phase (not to scale).

Fig 8. Filling of the geotextile tubes underway, November 2012 (Mike Page).

The calculated primary settlement of 0.50m and secondary settlement of 0.60 to 0.90m approached the reality. In practise it was found that the primary (or initial) settlement was on average 0.35m. Eventually, after consolidation of the subsoil (secular effect), the total settlement reached 0.73 to 1.39m. This indicates a smaller initial subsidence and longer secondary settlement period which means that the deformation of the subsoil was less than expected. In other words, the consolidation process of the subsoil (secondary settlement) had a larger share in the total settlement than the deformation of the soil (primary settlement). This could be the consequence of a heavier filling material (cohesive heavy clay) in combination with a high pore volume of the subsoil. For every geotextile tube project it is important to monitor the soil properties of the filling material throughout the process.

4.0 Execution

The project at Salhouse Broad was made more complex because of the absence of land access; everything had to be transported via water. This was a huge constraint on the operation and required the works on site, related deliveries and health & safety, to be highly organised.

Upon completion of the preparation stage the work commenced with the placement of alder poles based on GPS readings to temporarily hold the geotextile tubes in place. The alder poles (each approximately 6m long and 100mm diameter) were locally felled trees (Alnus glutinosa) and were pushed in the bed by hydraulic arm from a work boat. The geotextile tubes were attached to two parallel rows of poles, ready for filling.

Sediments were mechanically dredged by a NCK Rapier Pennine C34B crane, positioned in a barge. The mechanical dredging by clamshell grab allowed in-situ sediments to be removed from the bed and transported by barge. The 3 barges used on this project were generally loaded with 80 tonnes of sediment.

A long reach JCB360 18T excavator was positioned on a 9 float pontoon with spudlegs and situated on the river side moorings. On the pontoon a Putzmeister 1407 concrete pump (piston pump / displacement pump) and a McCloskey Mini Sizer (screener / vibrating screen) were also positioned.

The excavator unloaded the dredged sediment from the barges and placed it onto the vibrating screen in order to screen out any large objects. The screening size was 74mm and this was sufficient to remove any unwanted objects such as tyres, bricks, bottles and vegetation. From the vibrating screen the concrete pump was able to pump the in-situ sediment over a distance of 170m to the geotextile tubes through a 127mm diameter pipeline. Riding spars in front of the piled moorings at the unloading area allowed the fluctuating river level (0.3 – 1.0m) to be accommodated.

The geotextile tubes with an approximate circumference of 18.6m were filled with approximately 3,000m^3 sediment. The fill level was monitored by gauging rods in the centre of the tubes. All measurements were related to water level which in turn was assessed using two gauge boards marked relative to ODN. The filling process started with one of the central tubes, 'Tube 1, followed by tubes 2, 3 and 4. This method of filling allowed the use of the geotextile tubes as working platform during the filling stage. For the duration of the filling process Jetfloats (modular floating platforms) were used to allow access to the site.

Upon completion of filling all the geotextile tubes, specific sites measurements were taken. This was approximately 3 weeks after filling of tube 1. The primary consolidation had completed and some final fill adjustments were undertaken. Subsequently the tubes were covered with a non-woven geotextile in order to

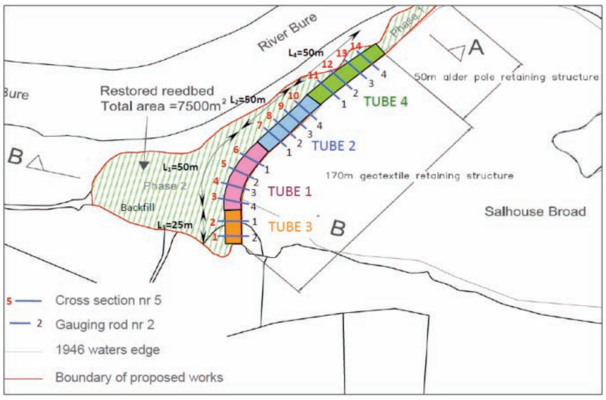

Fig 9. Schematisation of the geotextile tubes and cross sections.

Fig 10. Scraped vegetation placed on the geotextile tubes, March 2013.

protect the structure. With the non-woven geotextile in place, further filling was no longer possible. On average the completed fill level was approximately 0.53m ODN (0.2m above mean water level).

After the non-woven geotextile was placed, filling of the area behind the retaining structure commenced and completed over an intermittent period of 16 weeks. In total this project removed 12,000m^3 of accumulated sediment from the river Bure navigation and re-used it beneficially with a bespoke pump arrangement to restore the eroded spit and create a wetland habitat. Depending on the type of material the general capacity of the setup was between 750 and 1,200 m3 /week.

5.0 Vegetation

During the filling period sediment was also placed on the geotextile tubes to form a growing medium for vegetation. For the success of the structure, establishing wetland (reed-bed) vegetation was essential. It forms a protection against erosion as well as an important habitat. Reed-bed is a Biodiversity Action Plan (BAP) habitat and of international importance.

Vegetation was scraped from a donor site in the vicinity of the project location in March 2013. This timing was of importance as general mitigation and the vegetation was still dormant, ready for the new growing season of 2013.

Before the vegetation was placed on the geotextile tubes a pocket was created in the sediment were the vegetation could be placed. This pocket provided continuous damp conditions in order to avoid the vegetation drying out. It also provided protection from waves as the vegetation was not protruding the shape of the retaining structure.

During the creation of these pockets the front slope of the retaining structure was also profiled, this was aimed to create the maximum gradient possible. Although the design recommendations indicated a slope of 1:10, this was not practically feasible because of the space requirements. The profiling was carried out with a slope of approximate 1:5, a gradient that is still providing the desired wave force reducing qualities and marginal habitat conditions.

The vegetation was subsequently placed on the geotextile tubes and covered with TenCate GS20/20 Geogrid. The geotextile mesh holds the vegetation in place until it is sufficiently rooted. To ensure the success of a wetland habitat the correct site level in relation to the fluctuating water level was essential. Reed-bed related vegetation requires seasonal inundations, while other species are unable to tolerate these prolonged flood conditions. This design enables the desirable vegetation to flourish and an important habitat to get established (Barko et al 1991, Brix 1994 Brix 2003, Gries et al. 1990, Hawke and Jose 1996, Hammerl et al. 2004, Tornbjerg et al. 1994, Weisner and Ekstam 1993, White et al 2003, Worral et al. 1996.

The year 2013 had a cold spring and even in June 2013 there were some night frosts recorded. For this reason the vegetation growth had a late start but in July good signs of growth were recorded. In addition to the scraped vegetation, plug plants and seeds were also spread over the site to encourage wetland and reed-bed vegetation to establish. In total over 30 different species of vegetation were recorded in August, some of which are rare. Strong vegetation growth was recorded from the scraped vegetation, this is expected to spread over the site where growth is less robust during the next few years.

Fig 11. Completion of the site works, July 2013 (Mike Page).

Fig 12. Success of vegetation, September 2013.

4. Conclusions

1. The Broads Authority through the PRISMA project promoted the beneficial re-use of sediments by using sediments from maintenance dredging as a resource for a retaining structure in combination with geotextile tubes. The sediments formed an essential component in the protection of the spit between Salhouse Broad and the River Bure. This furthermore enabled the creation of an internationally important habitat.
2. Site investigations and subsequent sediment analysis allowed geotechnical calculations to be carried out to assess the stability, settlements, consolidation and overall feasibility of using the un-engineered sediment in a geotextile tube structure.
3. The dredging by mechanical means allowed the sediment to retain some of its resistance and strength (unlike hydraulic dredging). The filling of the geotextile tubes (under water) however required the sediment to be pumped via pipeline. The use of a piston pump (positive displacement pump) allowed the in-situ sediments to be pumped undiluted over a distance of 170m to the geotextile tubes and backfill.
4. Primary settlements were found to be smaller than predicted; however, following consolidation of the subsoil, the actual total settlements were very close to the calculated settlements.
5. Using settlement calculation and repeated filling cycles it was possible to achieve accurate final fill levels will be a critical factor in appropriate colonisation of vegetation.
6. Use of alder poles piles as temporary lateral restraint and ensuring reasonably level bed topography resulted in minimal lateral movement of the geotextile tubes, which was identified as a project risk.
7. The sediment filled geotextile tubes have provided an effective retaining structure supporting soft backfill material with up to 1.2m retained height.
8. The behaviour of the structure and local ground was predictable and manageable. Although at a higher financial cost than traditional side casting methods; this technique has potential for further use where sediment can be reused with multiple benefits.
9. The calculations and techniques applied during this project provide new opportunities for the re-use of sediments as a resource. Individual aspects of the geotechnical engineering as well as the habitat creation can be utilised in future projects in the Broads and internationally.

Nomenclature

%: percentage
C_p : primary compression constant
C_s : secondary compression constant
C'_p : primary compression after threshold tension
C'_s : secondary compression after threshold tension
Cu: consolidated undrained shear strength
Δh : settlement of the geotextile tube
h: layer thickness underneath the tube
kg: kilogram
kpa: kilopascal
m: metre
m^3: cubic metre
σ': effective stress
PI: plasticity index
p_g : boundary tension
t: duration period
σ_i : grain tension after load
σ_0 : initial grain tension

Broad: Shallow manmade lake
BAP: Biodiversity Action Plan
NNR: National Nature Reserve
ODN: Ordnance Datum Newlyn
PRISMA: Promoting Integrated Sediment Management
SAC: Special Area of Conservation
SPA: Special Projected Area
SSSI: Sites of Special Scientific Interest

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