BENEFICIAL REUSE OF DREDGED MATERIAL IN A BREAKWATER OF GEOTEXTILE BAGS

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ABSTRACT

The Waterside Marina in Brightlingsea, Essex, UK, required the removal of approximately 11,000 m^3 of sediment in order to maintain the designed, functional water depth of the marina. Exo Environmental, together with long standing associates from Netics, engineered a bespoke breakwater design, consisting of a series of overlain geotextile bags, that was able to contain the entire volume of dredged sediment whilst also providing shelter to the marina. The design employed the 'Working with Nature' philosophy of PIANC, incorporating habitat conditions for saltmarsh, mudflat and the local oyster populations. Local topographical, hydrographical and geomorphological data was obtained and used in predictive models to assess the resultant effect of the construction. Changes to the hydrology were variable, depending on model detail, location and tidal state whilst morphological changes were deemed to be insignificant. This project is a unique example of how theoretical infrastructure can be successfully designed whilst incorporating wider environmental benefits in its engineering, maximising the opportunities and working with natural processes.

Keywords: Working with Nature, Sediment Engineering, Saltmarsh, Geotextile Bags, Coastal Breakwater.

INTRODUCTION

The Waterside Marina is located on the north bank of Brightlingsea Creek, Essex, UK, close to the mouth of the Colne Estuary, at a confluence with the River Blackwater. The Waterside Marina has significantly silted up over the last six years. This has resulted in an excess of 11,000 cubic meters (m^3) of silty CLAY and clayey SILT that requires dredging in order to maintain the designed, functional water depth of the marina.

Exo Environmental was approached by the client to engineer a geotextile breakwater that would be able to contain the entire volume of dredged sediment, whilst also providing shelter to the marina. Together with long standing associates from Netics, a design was developed, consisting of a series of overlain geotextile bags that permanently store the sediment. Additionally to the requirements, the structure featured habitat conditions for saltmarsh, mudflat and the local oyster population. The design was underpinned by the 'Working with Nature' philosophy that encourages going beyond merely avoiding impacts and aims to make a positive contribution to the built and natural environment.

This project required extensive research into the characteristics of the site, including hydrographic and geotechnical surveys, sediment analysis, flow modeling, wave calculations and specialist structural design of the geotextile bags, filled with sediment.

Ecology

The estuary is predominantly comprised of extensive intertidal mudflats and saltmarshes. As a result of the extent and quality of these habitats, they support a highly diverse community. This includes many scarce plants such as; golden samphire (*Inula crithmoides*) and small cordgrass (*Spartina maritima*), as well as rare, vulnerable and endangered invertebrate species, such as the scarce emerald damselfly (*Lestes dryas*) and marine species, such as the native flat oyster (*Ostrea edulis*).

They also provide an important habitat for many overwintering and summer breeding bird species.

Due to the importance of these habitats and the species they support, the environment surrounding the site is protected under several national and international designations. These include; Colne Estuary (Mid Essex Phase 2) Ramsar Site, Colne Estuary (Mid Essex Phase 2) Special Protected Area (SPA), Essex Estuaries Special Area of Conservation (SAC), Colne Estuary Site of Special Scientific Interest (SSSI) and the Blackwater, Crouch, Roach and Colne Estuaries Marine Conservation Zone (MCZ). The site lies adjacent to these designations and is included within the MCZ.

Hydrographic Survey

A pre-dredge single-beam hydrographic survey of the site was conducted. This provided a detailed description of sediment depths, allowed an estimate of the volume of sediment required to be dredged and highlighted bed undulations. Based on the survey and an extrapolation of the data, a sediment volume in excess of 11,180 m^3 was calculated.

Geotechnical Survey

Marina

A geotechnical survey was carried out to investigate and sample marina sediment, to examine geotechnical characteristics and for chemical analysis. Three Dynamic Continuous Sampling Boreholes were used to investigate the marina sediment to depths of up to 4.37 m using a detached Archway Competitor Dart Rig. The samples obtained were used for chemical analysis by the Centre for Environment, Fisheries and Aquaculture Science (Cefas).

Within the marina, the upper layer was comprised of recently deposited very soft, slightly sandy, very silty CLAY. The lower layer is made of more granular silty, sandy, slightly gravelly CLAY or silty, sandy GRAVEL with frequent shell fragments. The moisture content of these soils ranged between 75 – 193 % and had a bulk density of 1.26 – 1.28 Mgm^{-3}.

Action levels are used by Cefas in conjunction with other assessment methods, to assess dredged sediments and their suitability for disposal at sea or reuse. Action levels for individual chemical contaminants are based on toxicity levels and given threshold concentrations, which if exceeded, require further investigation prior to disposal at sea or reuse.

The majority of chemical contaminants tested were found to be at levels below Action Level 1. Although arsenic (As), chromium (Cr), nickel (Ni) and zinc (Zn) levels were all on average, slightly above Action Level 1, the exceedance was marginal and the dredged sediment was deemed suitable by Cefas for local reuse.

Breakwater footprint

Outside of the marina, seven Dyanmic Cone Penetrometer Tests up to a depth of 1.72 m (using a CNS Farnell DCP, Model: A2456) and Hand Dug Trial Pits up to a depth of 1.10 m, were used to assess sediment characteristics of the intertidal area within the footprint of the proposed breakwater.

The surface of the intertidal area outside the marina was underlain by Tidal Flat Deposits. These were shown to consist of various sediment types (deposits of variable energy environments) including very soft, sandy, silty CLAY / clayey SILT and silty, sandy, clayey GRAVEL found to the west of the site. The shallow soils became less consolidated toward the marina boat access channel and to the east of the channel. The moisture content of these soils ranged between 9 – 67 % and had a bulk density of 1.65 – 2.12 Mgm^{-3}.

For the consolidation and settlement rates of the geotextile bags and soil the Atterberg limits were studied. It was found that these limits were well within a suitable range as well as the moisture content and organic matter.

Fig. 1 Breakwater footprint and overview.

Response Modeling

Although the accretion rate within the marina can be as high as 0.5 myr^{-1}, across Brightlingsea Creek the accretion rate is regarded low. Consequently, the morphology can be considered to be stable in the short term. A modeling study was conducted by Svasek Hydraulics [1] to examine the current morphological and hydrological characteristics of the site and to investigate how these could change following dredging of the sediment and installation of the geotextile breakwater.

Waves

The wave climate around the Brightlingsea area is governed by locally generated waves. The erosive forces of waves directly impacts on the design of a breakwater and so a study was conducted to examine the wind and subsequent wave direction and height in the area. The Bretschenider formula [2] was used to calculate the significant wave height and period, based on fetch length, water depth and wind speed.

Larger wind fetch length promotes the development of larger waves. Due to the sheltered position of Brightlingsea, potential wave building is inhibited. The Saville method [3] was applied to determine realistic fetch length while taking into account the local shoreline irregularities.

Wave height can also be greater in deeper water, which locally depends on bottom level and water level. Bottom was assumed constant at 2.6 m below chart datum, equal to the maximum channel depth within Brightlingsea Creek, whilst the tidal range in the area was conservatively presumed at 5 m above chart datum, resulting in a total water depth of 7.6 m.

Three year wind data was available from two stations approximately 25 km northeast of Brightlingsea. The highest wind speed and general wind direction was from the south to west sector. Both datasets were correlated to a Climate Forecast System Reanalysis (CFSR) monitoring station with data from 1979 to 2011. Conservative estimates of wave height were calculated to be 0.82, 1.10 and 1.18 m, with a return period of 1, 30 and 100 years.

Climate change could potentially result in greater wave height, through increased wind speed or greater water depth as a result of sea level rise. The influence of increased wind speed was expected to be in the order of centimeters according to UKCIP02, whereas modeling proved wave height to be seemingly insensitive to water depth and consequently, sea level rise was expected to have a minor effect on wave height in future.

Model design

Tides are the dominant force driving the currents within Brightlingsea Creek. A monitoring survey was conducted to measure the variation in current velocity over a full astronomical tidal cycle. Around the marina, spring and neap tides were found to induce a current velocity that ranged from approximately 0.7 – 0.3 ms^{-1} respectively. Current velocities were greater during the flood tide than the ebb tide. As a conservative prediction, the model was calibrated to the present maximum water velocity measured in the centre of the creek, approximately 2 knots (approximately 1 ms^{-1}).

Bathymetry of the creek was comprised of data from several sources; a hydrographic survey of Brightlingsea Harbour, a survey plan of the area, LIDAR Data, Google Earth and admiralty charts.

Three different model outlays were calculated based on differing layouts and was run over a five day period.

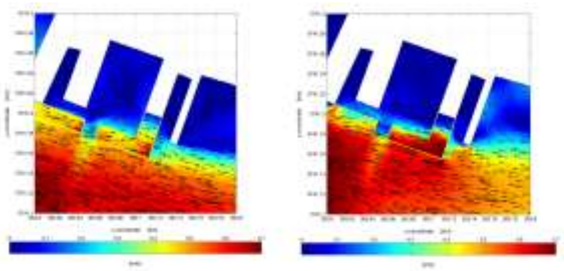


Fig. 2 Hydrodynamic and morphological response.

Morphological response

Changes to the present water velocity around the proposed breakwater were identified by the models (figure 1). Although spatially the velocity increased and decreated depending on the morphology, in general, the models predicted that eroded sediment would likely be deposited in areas adjacent to the breakwater. The locations of any deposition however would be material dependent, with sandy sediments staying in the deeper areas of the creek, whilst finer material could settle in the wake of the breakwater.

BREAKWATER DESIGN

The design of the geotextile breakwater was underpinned by the 'Working with Nature' philosophy by PIANC [4], to go beyond merely avoiding and minimising impacts, but to make a positive contribution to the environment. Exo Environmental and partners researched the colonisation potential of saltmarsh species iconic to Brightlingsea Creek, as well as the sediment trapping capabilities of several geotextile fabrics and their suitability to diatoms, critical to the sediment stabilisation of mudflats, concluding in general that non-woven fabric would best encourage microalgal growth and subsequent pioneering plant species.

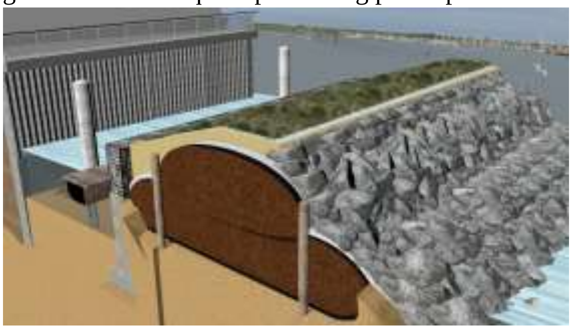


Fig. 3 3D artists impression of the final layout.

Slopes and shape of the structure

The geometric shape of the breakwater was inspired by the natural profile of saltmarsh and designed to encourage biodiversity. The design includes gentle slopes on which saltmarsh habitats could develop. The shape of the breakwater was also inspired by the large tidal differences which cause varying load combinations and water level situations. The strength of the slopes and structure basis was adapted to these requirements. The materials used were a determining factor for the strength of the structure and succes of saltmarsh developenment.

Geotextile bags

The structural basis of the breakwater consisted of large geotextile bags with a height of 3 m and lengths up to 56 m. The breakwater was formed of two layers of elliptical geotextile bags. The stability of the bags and stacked structure was calculated by the engineering model developed by NETICS. The dimensions of the structure depend on the governing hydrodynamic conditions, properties of the filling material, quality and properties of the fabric and the interaction of forces within the breakwater structure.

The geotextile bags were designed to be mechanically filled with locally dredged sediments to the desired height. During dredging works the sediment could be pumped directly into the bags without the use of expensive flocculants. By filling the bags under pressure they could be stacked up to get the necessary crest height. When the sediment is pumped into the bags the material will dewater and settle. By using local sediments the total settlement of the structure will be minimized which saves costs and the amount of building materials. The storage volume and height of the breakwater depend on the properties of the local subsoil and the dredged sediment. This will partially determine the consolidation and settling proces of the structure which is taken into account for the design process.

Auxiliary structures and building materials

Prior to the placement of the bags, a 0.5 m deep trench would be created to cradle the bags and increase their stability. Large wooden poles would be evenly spaced to further stabilise the bags and prevent lateral movement. Gabion baskets filled with local oyster shell would be placed on top of the existing wall to the north of the breakwater, thereby forming an inner wall. They would also encourage biodiversity and provide a link to the local heritage.

Once the first layer of bags are filled with dredged sediment, a second layer of bags would be placed perpendicularly to the first layer and covered by a non-woven, polyfelt fabric. The non-woven, polyfelt layer would act to; absorb loads caused by waves or other dynamic forces, prevent the loss of fine sediment from the geotextile bags, help to spread the load equally and retain the shape of the structure and protect the woven geotextile bags from mechanical damage which may result from the rock armour layer placed on the front slope.

On top of the polyfelt layer, dredged sediment from the stabilising trench would be used to backfill towards the gabion baskets to form an inner slope. A protective layer of open block armour would then be placed on top of the structure to reduce erosion, whilst simultaneously facilitating the microalgal growth and the subsequent colonisation of pioneering plant species, resulting in saltmarsh development.

The rock armour placed on the estuary side of the breakwater would protect the construction by creating a berm that would reduce erosion from wave impacts, currents and protect the structure from collisions with boats.

TECHNICAL SPECIFICATIONS

The technical specifications of the breakwater are based on a number of boundary conditions, loads and environmental properties. Several loads can be exerted; macro and micro instability, wave run-up, overtopping, liquefaction, scouring and failure of the structure, with a combination of loads leading to an enhanced negative impact.

Macro stability

Based on the hydraulic conditions of the estuary and marina, macro instability resulting from changing water pressures, unstable sediments and deformations could occur. The geotextile fabric strengthens the stored sediment and would allow the exertion of an almost equal load on the subsoil of the foreshore, reducing the development of instabilities.

Settlement and consolidation of the sediment must be limited to the specification of the design and could be monitored during the filling process, thereby allowing the control of any subsidence. During the consolidation process, the final height of the retaining structure could be controlled and levelled with the high water level, thereby simulating natural inundation of the saltmarsh on the inner slope. The final height of the structure can be rectified with an additional fill of the bags.

Micro stability

Erosion of the outer slopes and sediment from the bottom of the structure by waves, currents and ice loads, could cause micro instabilities. Rock armour placed on the outer slope could help prevent slope and toe erosion as well as mechanical damage to the geotextile bags. The inner slope is protected by open blocks and marsh vegetation. Micro instability as a result of piping, caused by existing pressure and permeability of the sediment is prevented by the non-woven fabric that acts to reduce the permeability of the structure.

Collisions

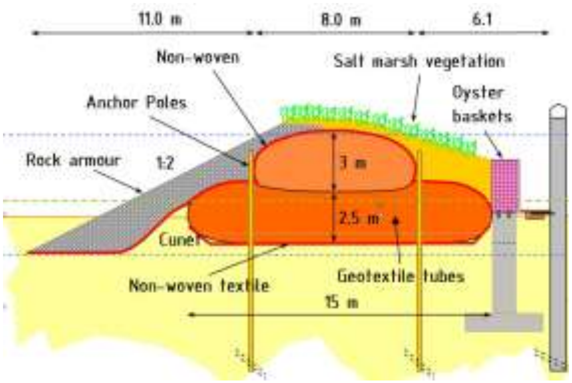
Boats and floating ice were anticipated to be the only potential hazards regarding collisions with the breakwater. The likelihood of collisions with boats can be reduced with appropriate exclusion zones. During winter, drift ice could potentially exert high loads on the structure. However, the curved shape of the geotextile bags would act to lift up and break the ice, thereby avoiding damage. The use of open block would ensure that the vegetation is protected and the top layer retains its strength. The rock armour also protects the structure from potential boat collisions.

Dredging

Dredging would be carried out by a grab or backhoe excavator deployed on a pontoon, whilst a concrete (displacement) pump would be used to fill the geotextile bags mechanically. This would remove the need for expensive flocculants and keep the moisture content of the reused sediment to a minimum. As a result, the geomechanical strength of the sediment would be maintained and expensive dewatering avoided. A secondary benefit is that the stability of the breakwater increases with a decrease in the rate of dewatering. With the mechanical dredging and filling method the bags are quickly filled with sediment so they can be accessed almost instantaneously. Because the primary function of the bags is containment and not dewatering, reduced construction times are advantageous, especially when working in a tidal environment.

ENGINEERING

For the engineering of the structure the newest design and stability formula were developed and used and the combination of different building materials, dredged soft sediment as base material, mechanical filling method and the stacked layout with geotextile bags is unique. This all makes the



bespoke structure a perfectly suited to this situation.

Fig. 4 Breakwater design and engineering features.

Geotechnical Calculations

Deformation and settlement of the bags due to consolidation are important for dimensioning the cross-section of the structure during the execution phase and the final state. Determining the soil type and the properties of sediment as both infill material and subsoil allows the calculation of the breakwater strength and settlement. The total settlement of the retaining structure during filling equals the sum of the subsidence of the subsoil and consolidation settlement of the geotextile bags. Several geotechnical models were trialled on the basis of the model scheme for the geotechnical calculations.

The geotechnical parameters were based on soil investigations and expert judgement. Calculations with and without gravel, the latter representing a scenario with the greatest settlement and least stability, resulted in a settlement of between 0.37 and 0.67 m, with stability calculations determining a stability factor of between 1.42 and 1.43. Consequently, the design was found to be suitable for the environment. Data from monitoring the breakwater's settlement during construction would update the calculation model and allow a more accurate prediction of the final height.

Settlement of the dredged sediment to a certain initial density, estimated to be 1260 kgm^{-3}, is dependent on the plasticity of the sediment and was used to estimate the relationship between the undrained shear strength, water content and plasticity limits [5]. The geotextile bags would spread the load over the surface, therefore resulting in an evenly distributed settlement. Tracking this settlement during filling would allow the identification of any need for additional refills to attain the designed storage capacity.

Geometry and Strength Calculation

Following filling of the bags to a height of approximately 3.5 m, a final settlement height of 3.0 m is predicted. To achieve the designed height, the geotextile bags should achieve a maximum degree of filling of 80 %, resulting in the crest of the bags being positioned 10 cm above mean high water level in its final state, thereby allowing saltmarsh vegetation to develop.

DISCUSSION

Whilst adhereing to engineering requirements, the breakwater design was underpinned by the 'Working with Nature' philosophy of PIANC, which encourages going beyond merely avoiding impacts and aims to make a positive contribution to the built and natural environment. To achieve this, it was crucial to have an understanding of the enviornment. The breakwater was designed to create saltmarsh habitat on the inner slope and to support further micro-algal species [6]. This local study found that pioneering species, favoured non-woven fabrics over woven fabrics. As a result, the non-woven geofelt was incorporated into the design with the expectation to enhance natural colonisation.

Environmental modelling is increasingly used in an effort to better predict the impact of anthropogenic activity on complex ecosystems. The modelling study of Brightlingsea Creek indicated that the hydrological and morphological changes that would be induced by the construction of the breakwater were variable. All models resulted in a change to the hydrographical regime that would directly impact on erosion and deposition processes within the Creek. However, variation between the results of the models highlighted the complexity, range and magnitude of potential impacts that can be expected as a result of infrastructure development. Monitoring environmental parameters to verify the model prediction, both during construction and following the completion of works, is as important as gaining baseline data to understand the environment and generate input data for the models in the first instance. Only then can the accuracy and effectiveness of predictive models be assessed.

Although the morphological response predicted by the models was deemed to be negligible, the morphological response in and around the marina would be an important parameter to monitor. As well as monitoring compliance and verifying the predictive models accuracy, this would allow the creation of a long term management programme for the safe running of the marina [7].

The engineering of the structure was dependent on many parameters, such as hydrodynamic conditions, soil structure, functional requirements and existing infrastructure. For this design, the properties of the dredged sediment governed the settlement and consolidation of the geotextile breakwater and were therefore of upmost importance in order to attain the functionality of the design. The use of a excavator to dredge sediment and a concrete pump to fill the geotextile bags, removes the need for expensive flocculants and dewatering process. It also allows the geomechanical strength of the sediment to be maintained. This innovative building method has proven itself in pioneering projects such as Salhouse Broad Spit (UK) [8] and Islands at De Putten (Netherlands) [9]. The benefit of the design was that settlement could be monitored throughout the construction phase and as a result, deviations from the predictions could be responded to through repeated filling cycles, until the desired height of the breakwater was attained.

CONCLUSIONS

The Waterside Marina in Brightlingsea, Essex, required the removal of approximately 11,000 m^3 sediment in order to maintain the designed, functional water depth of the marina. Exo Environmental was approached by the client to engineer a geotextile breakwater that would be able to contain the entire volume of dredged sediment, whilst also providing shelter to the marina. Together with long standing associates from NETICS, a bespoke design was developed, consisting of a series of overlain geotextile bags that permanently store the sediment. Further to requirements, the structure featured habitat conditions for saltmarsh, mudflat and the local oyster populations. The design was underpinned by the 'Working with Nature' philosophy that encourages going beyond merely avoiding impacts and aims to make a positive contribution to the built and natural environment. This project is a unique example of how theoretical infrastructure can be successfully designed whilst incorporating wider environmental benefits in its engineering, maximising the opportunities and working with natural processes.

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