Alde and Ore estuary, U.K. – levee overtopping performance – defence upgrade with 50 km of simultaneous overtopping.

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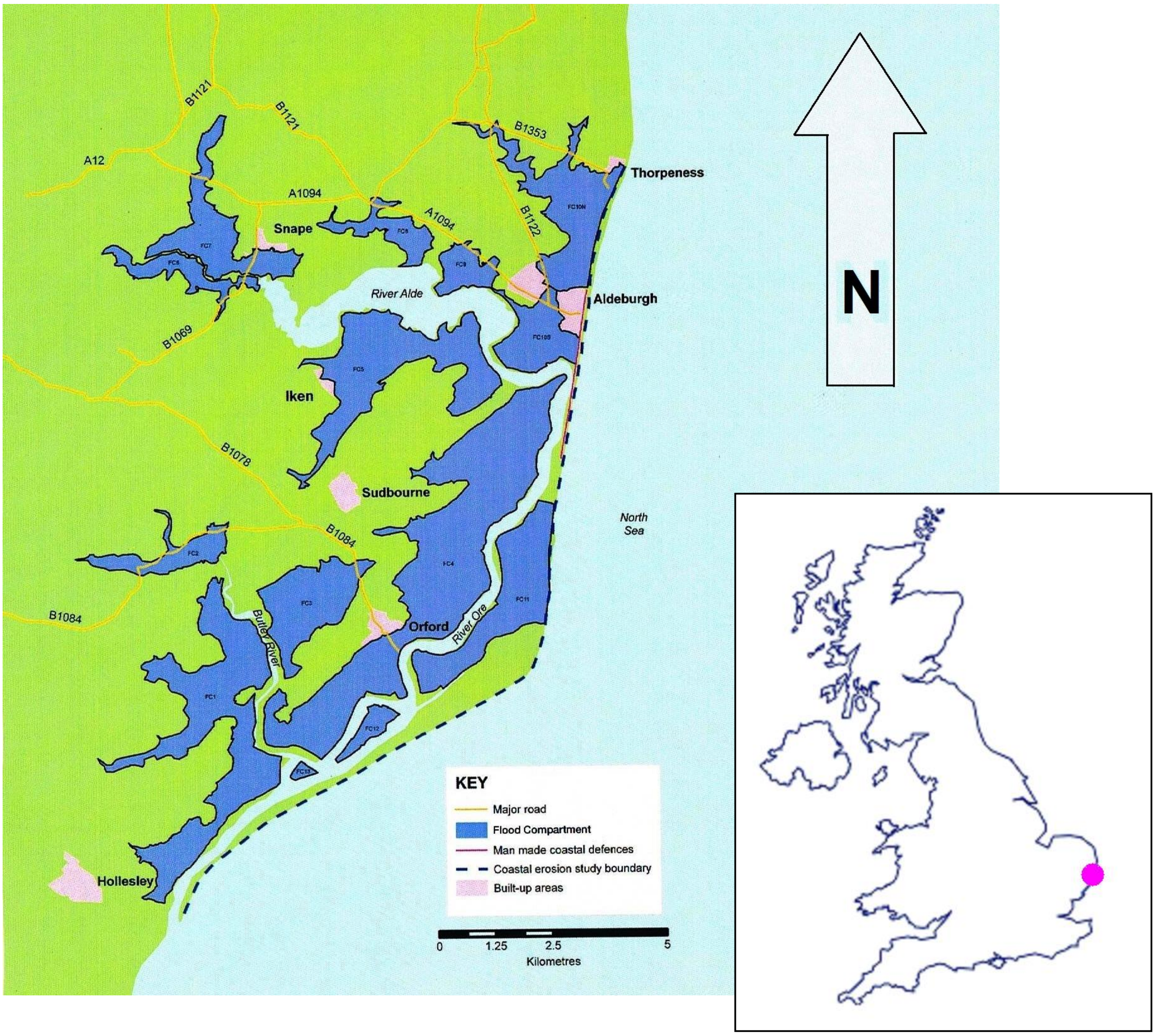


Introduction.
The Alde and Ore estuary is protected from open coast attack by the longest shingle spit in northern Europe, extending 17km from Aldeburgh in the north to Shingle Street in the south. The low lying land adjacent to the tidal estuary is divided into a number of flood cells protected by more than 50 km of levees, locally referred to as “river walls”.

Last heightened following a catastrophic North Sea storm surge in 1953 the additional weight of the defences has resulted in significant consolidation settlement, by up to 1m.

With little or no government funding for improvements to the existing degraded defences an innovative approach has been required to ensure an affordable solution. This strategy being given more impetus following a North Sea tidal surge in December 2013, recorded as a 1 : 17 year event, which left the defences wanting.

Agriculture.

This low lying coastal strip in Suffolk is bordered by heavily irrigated sandy uplands which can provide up to 20% of the UKs vegetable production at any one time. The irrigation water is abstracted from the springs issuing onto the levee protected lowlands. This fresh water is pumped to reservoirs during the winter months.

A loss of the irrigation water to saline contamination would have very serious repercussions to the agricultural economy of this area.

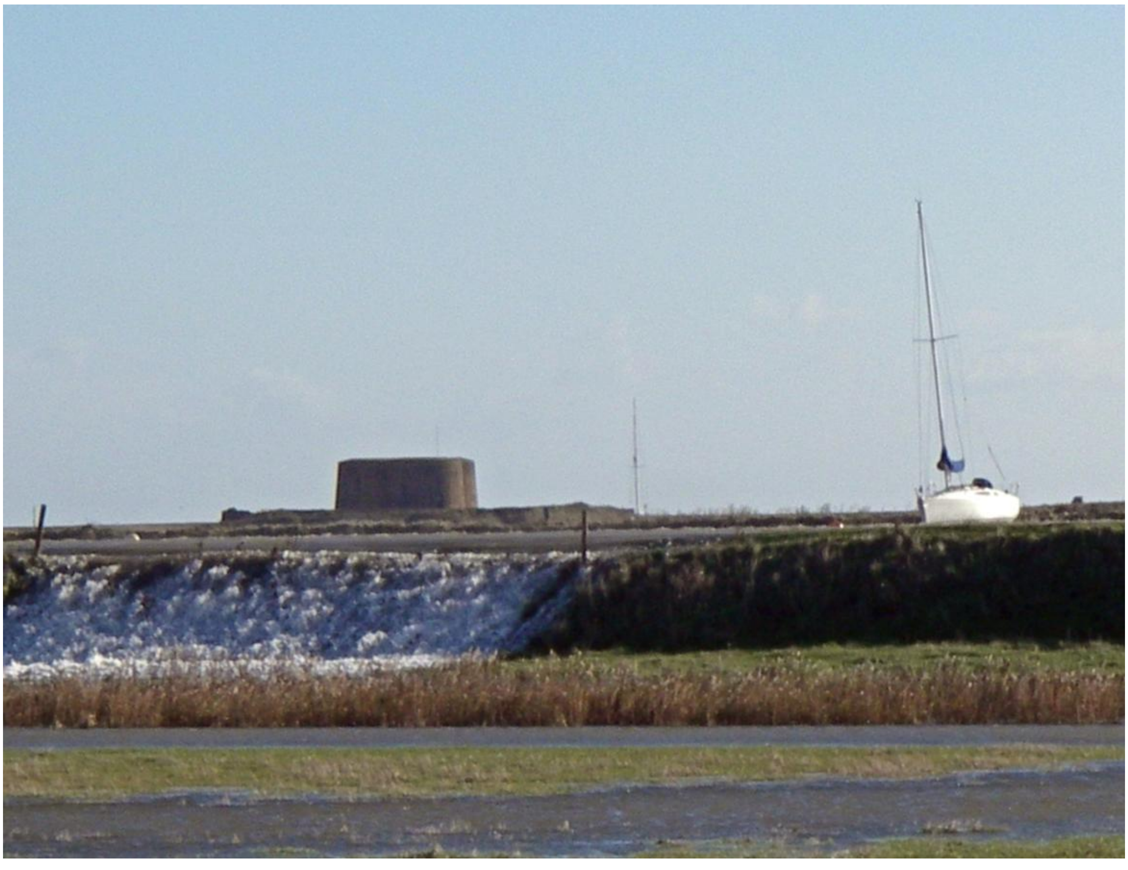
Ecology.

The saltings on the seaward side of the levee defences are **Special Protection Areas** (**SPAs**), strictly protected sites classified in accordance with Article 4 of the EC Birds Directive. This designation restricts the working areas available when upgrading the existing defences.

On the landward side of the river walls water voles, small snails, reptiles and ground nesting birds enjoy protection from the Habitat Regulations. This can necessitate the construction of new habitats and the relocation of reptiles and water voles placing seasonal restrictions on the works. The mitigation cost can amount to around 10% of the total in particular flood cells.

Leisure.

Of the 50 km of river wall 45 km of these levee defences are topped by Public Footpaths. Upgrade designs must accommodate these Rights of Way. Historically it can be seen that the footpath surfaces can be detrimental to overtopping resistance.



1. 9th November, 2007, overtopping event, Aldeburgh marshes.

Levee overtopping performance, theory and observation.
The expected overtopping performance of the estuary defences was initially based upon the CIRIA 116 Figure 9: *Recommended limiting values for erosion resistance of plain and reinforced grass.*

Additional design confidence was gained from an overtopping event in 2007 (photo 1) which identified that a well grassed landward slope, mean angle of 20^{o}, is able to withstand a tidal surge peaking with an approach height of 400mm (300mm of still water with a 100mm wave allowance) above the levee crest. The event duration lasted approximately two hours, one hour either side of the peak tide.

It was decided that a deliverable improvement would be possible with overtopping velocities peaking at 4 m/s with mean velocities of approximately 3.8 m/s. This would allow both unreinforced and reinforced turf to play a significant role in the solutions.

At all stages in design a conservative approach is needed as it is clear that both existing grass cover and the extent of desiccation cracking cannot be practically quantified on such a large scale.

Desiccation cracking.
It was recognised that desiccation cracking plays an important part in the overtopping performance of clay banks. These levees have been constructed with alluvial clay dug from a “borrow ditch” within reach of a dragline or hydraulic excavator usually within 10m to 20m of the defence. The silty clays used have been placed with a moisture content well in excess of that required for optimum compaction. This method of construction is often unavoidable but will result in shrinkage cracking developing.

In extreme situations the cracking can result in hydraulic fracture, when the full hydraulic head of the flood surge is transferred through the cracking to the landward side of the levee, lifting blocks of material off the face. This situation soon develops into a breach of the river wall.

The levees most susceptible to hydraulic fracture are those which are thinner and older, here desiccation cracking is often more advanced and the hydraulic losses across the width of the levee less.

North Sea storm surge - night of 5th/6th December 2013.

In 2013 a storm surge, comparable in estuary water levels to that of the 1953 catastrophic event, tracked down the north sea coast and into the Alde and Ore estuary.

The peak surge level of +3.1m O.D. in parts of the estuary caused significant over topping damage (photo 2 + 3) and a number of breaches (photo 4) together with flooding to around 30 houses.

I was able to inspect the levee protecting the town of Aldeburgh at the peak of the surge early in the morning of the 6th of December, the water level reached the top of the levee with minor overtopping at low points, however what was of real interest was the amount of free water flowing through the desiccation cracking and issuing from the landward bank.

2. Typical overtopping damage, a shallow slip triggers rapid erosion. Here a full breach has been prevented by the Armourlok revetment.

The fact that the surge levels and duration were well documented allowed a back analysis of all the damaged defences. With the help of the level profiles and cross sections of all 50 km of estuary defence the overtopping depths, duration and damage were used to confirm the validity of the estuary upgrade design model.

What became immediately apparent was that the damaged or beached levees had performed as the design model predicted. This provided a significant confidence boost to the design team.

3. The "crumbly" nature of the exposed alluvial clay illustrates the extent of desiccation cracking.

4. Hydraulic fracture can explain this particularly large breach. This wall had not been maintained and was heavily desiccated with cracking across its full width.

Both before and after the storm surge of 2013 innovative solutions have been adopted to enable the delivery of low cost overtopping resilience as part of the early stages of the estuary wide defence upgrade.

Estuary wide conceptual design.
Currently the existing defences, based on 5th/6th December 2013 performance and following subsequent emergency repairs, can withstand, undamaged, a North Sea tidal surge to +3.0 m O.D. a 1 : 17 year event.

It is proposed to improve defences so they can withstand, undamaged, a 1 : 200 year event in the year 2050, this is referred to as the design event and has allowed for a 300mm sea level rise due to global warming.

The design event must withstand a peak still water overtop of 300mm, this equates to an overtopping duration of around 2 hours depending on the offset of the storm surge from the high tide.

According to the statistical flood surge modelling by raising levee heights to +3.4m O.D. nearer the mouth and to +3.3m O.D. further upstream it is possible to achieve design event survivability.

Estuary wide overtopping, along 50 km of levee defence, is an essential element in the concept. The design event, a North Sea tidal surge to +3.7m O.D. nearer the mouth and to +3.6m O.D. further upstream will simultaneously overtop the full length of the defence. At the peak of the surge a very large volume of flood storage is brought into play as the sea spills into lowlands, effectively attenuating the peak of the surge.

Four techniques are being employed to achieve the design event survivability:

i) Re profiling and raising existing levees.
Much of the existing defences are too low for Turf Reinforcement Mesh (TRM) to achieve the overtopping performance required. For this reason significant lengths will be raised by conventional clay borrow by widening the existing borrow ditches and compacting the alluvial clay to form a minimum stable crest level of 3.3m O.D.

To avoid the creation of planes of weakness it is important that the existing material on the landward side is “benched out” to provide a shear key. The landward slope must not exceed 24^{o} (1 : 2.3) if design overtopping velocities are not to be exceeded. Where available space and material allows it is hoped to achieve a slope of 18^{o} (1 : 3).

Integral to the design is the establishment of a healthy grass sward, this can be helped by the re use of the stripped turf and enhanced by hydro seeding with a suitable seed mix. The importance of this stage cannot be over emphasised. Without the immediate establishment of grass weeds soon invade, these provide little or no resistance to overtopping.

Advantages: Achieves design performance. No import of material required.

Disadvantages: The fill material will add weight and as such increase the total stress beneath the embankment which will trigger consolidation settlements. Significant ecological mitigation is required adding cost and delaying completion.

ii) Adding TRM with soil anchoring to existing profile.
Around 30% of the total defence length can be brought up to the required design performance by simply close cutting the existing grass banks tightly profiling a mesh onto the bank.

Soil anchors installed along the landward slope provide resistance to shallow seated slip failures which tend to be the breach triggers for total failure during overtopping. The anchoring also greatly assists the tight profiling of the mesh, it is important that the grass grows through the mesh without lifting it.

Advantages: Reduction in required ecological mitigation. No increase in total stress beneath the defence so no settlement issues. With BBA Certification on the meshes used of 120 years long term performance and lack of settlement can be expected. Low cost.

Disadvantages: Only applicable to levees already at or above +3.1m O.D. If a footpath exists a new surface will be required which should be resistant to overtopping.

iii) Raising the levee with Reinforced Earth integrated with turf reinforcement.
In particular locations across the estuary there is limited availability of suitable clay due to the proximity of an overworked borrow ditch. To extend the borrow ditch on the landward side results in significant habitat relocation measures which can delay construction by a year whilst the replacement habitat and relocation is implemented.

By the use of Reinforced Earth it is possible to minimise the clay required, the same materials, mesh or a cellular system, used to reinforce the additional defence height can also be used as the turf reinforcement on the landward face.

Advantages: Applicable to all levees. Significant reduction in required ecological mitigation. Minimal increase in total stress beneath the defence so no settlement issues. With BBA Certification on the materials of 120 years and no ultra violet exposure long term performance can be expected. Low cost.

Disadvantages: If a footpath exists a new surface will be required which should be resistant to overtopping.

Case history: 480m section of defence, south of Orford, raised by 0.4m to 0.7m using alluvial clay dug from behind the levee and compacted with a sheep's foot roller into a mesh (Double twist rock fall mesh, Galmac steel with UPVC cover, 40kN/m, joined with 316 stainless Spenax rings) encapsulated structure forming the new crest. The same mesh extends down the landward bank to provide reinforced turf which includes Platipus Anchors (6kN S06 anchor at 1 m c/c installed to 1.5m depth) to increase stability during overtopping.

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Pre cut 12.5m lengths of mesh are rolled across the levee (photo 5.) clay is then compacted and shaped along the crest and the mesh is pulled back tightly and fixed to itself and topsoil added (photo 6.).

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Compacted and shaped clay top (photo 7.) prior to mesh encapsulation, see 5m surplus on water side. Platipus stainless steel soil anchors are driven through the mesh for additional stability and mesh profiling (photo 8.).

Case history: 80m section of defence, west of Snape Bridge, raised by 1.0m using clay washings from soil recycling plant compacted into a 20kN/m 200mm deep cellular confinement membrane, the five horizons of cells provide overtopping protection on the landward face. Ankalok revetment has been used to reinforce the pathway.

Clay compacted with adapted bucket with integral sheep's foot compactor into 5 horizons of cellular mattress (photo. 9) final finish with seeded topsoil and Ankalok pathway.

iv) Lowering and re profiling sections of a defence and, if overtopping time and velocity dictates, armouring them to create a spillway to allow full or partial inundation of the flood cell during the design event.

One of the three spillways constructed to date was at Havergate Island owned by the Royal Society for the Protection of Birds (RSPB). Here the small size of the flood cell is such that full inundation can take place rapidly during a North Sea storm surge.

To prevent damage to the existing levees surrounding the bird reserve, which vary in height and structural integrity, the construction of a spillway has removed the risk of overtopping damage to these old walls.

By the introduction of a mesh or cellular armoured spillway at a level below that of the lowest degraded river walls a flood surge is able to completely fill the flood cell in well under two hours. Limited duration overtopping over the upper sections of some of the degraded walls around the rest of the defence is unable to cause damage.

By introducing this "drowning out" feature into small flood cells it is possible to create defences that can withstand any magnitude of surge.

Advantages: Low cost. Limited ecological mitigation. No settlement problems. Theoretical survival of any magnitude of tidal storm surge.

Disadvantages: Does allow full flooding during storm surges. The particular application at Havergate Island will inundate the flood cell several times a year on all the large spring tides.

Case history: 100m long spillway, Havergate Island - RSPB, lowered by up to 0.8m and re profiled with an 11° spill slope (1:5). Meshed and tightly profiled with pins.


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Condition after 2013 tidal surge (photo 11.). Completed and functioning spillway (photo 12.) grass needs to establish, reseeding planned in early spring. Four overtopping events to date with no erosion due to rapid inundation time.

Case history: Repair of 30m wide breach on Orfordness. Alluvial clay used to build levee founded on a 40 kN geogrid. High performance geotextile (HPS 6 by Geofabrics) laid over 11° spill slope (1:5) spillway as foundation for 150mm deep cellular mattress. Gravel infill as no soil available.


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Breach from the air (photo 13.). Long reach machine to enable alluvial clay to be borrowed (photo 14.)


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Cellular mattress prior to gravel filling (photo 15.). ***No damage from overtopping (photo 16.).***

Case history: Loss of 120 Ha. of grazing marsh to multiple breaches along a 1000m length of levee. Retreated defence in the form of a 400m long levee spillway. Alluvial clay used to build levee founded on a 40 kN geogrid with 11^{o} spill slope (1:5). High performance geotextile (HPS 8 by Geofabrics) to provide front face erosion protection. Hydro seeding to rapidly establish grass (Hydra CX by Salix). Levee performs well in overtopping, which occurs once or twice a year.


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Multiple breaches in foreground with debris field visible beyond (photo 17.) Construction of new defence behind temporary tidal barrier of marsh clay (photo 18.).


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Introduction of high performance geotextile as erosion protection (photo 19.). First overtopping event resulted in full flood cell inundation and no damage to defence, sluice drainage in 48 hours (photo 20.).

References:

a) **Soil Mechanics Studies of Failures in the Sea Defence Banks of Essex and Kent" by Leonard Frank Cooling, D.Sc. and Arthur Marsland, MSc., Grad. I.C.E.** *Reprinted from Conference on the North Sea Floods of 31st January – 1st February , 1953. A collection of papers presented at the Institution of Civil Engineers, December 1953, pps. 58 – 73.*

b) **C.I.R.I.A. Report 116. Design of reinforced grass waterways.**
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