Aldbrough Gas Storage Project: Geomorphological assessment of impact of proposed cliff protection works on adjoining areas

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Summary

This report summarises the results of a study undertaken to assess the likely geomorphological impacts of proposed cliff-toe protection near Ringbrough Farm, Aldburgh, which it is intended will reduce the risks to infrastructure from coastal erosion during construction of the Aldbrough Gas Storage Facility.

It is concluded that the proposed works will have a negligible effect on the sediment supply to Spurn Peninsula and the Humber Estuary SAC, and will have no significant impact on cliff erosion rates up-drift or down-drift.

It is estimated from historical erosion records that the potential effect of the protection measures will be to reduce the sediment input from a 90 m length of protected cliff by about 12.335 x 10^3 m^3 over a two year period. This represents only about 0.45% of the total sediment input from erosion of the Holderness cliffs.

Any negative impact of the works on sediment supply to the coastal zone in the short term could be entirely offset by placing a similar volume of material on the beach as sacrificial material. Estimates suggest that a 'surplus' of approximately 30 x 10^3 m^3 of sediment will be generated by re-grading of the cliff top and construction of a beach access ramp. An additional 2.7 x 10^3 m^3 of sediment from these sources could be used to fill the *Secutex Soft Rock*® geotextile bags proposed for use in the toe protection.

Based on a consideration of temporal variations in recent cliff erosion rates and beach morphology, which are closely linked to the alongshore movement of ridge and trough features (ords), it is estimated that it will take between two and four years after removal of the toe protection for the cliff to retreat to the position it would have been in had the toe protection not been installed.

Aldbrough Gas Storage Project: Assessment of Impact of Proposed Cliff Protection Works on Adjoining Areas

1.0 Report scope and purpose

In 2003 Scottish and Southern Energy (SSE), advised by Jacobs, commenced construction of an underground gas storage facility at Bail Bridge, between Aldbrough and East Garton (Figure 1). The scheme involves creation of nine storage caverns in Permo-Triassic salt strata at c.2000 m depth. The caverns are being created by leaching using seawater which is piped onshore from an intake a few hundred metres offshore. Brine produced by the leaching process is piped back to sea. Three pipes (one containing electrical cables) were installed by horizontal directional drilling (HDD) from a point near the cliff top at Ringbrough Farm and are spaced approximately 5 m apart. It takes approximately 2 years to complete each cavern and the work on the final four caverns is not expected to be completed before the end of 2012.

At the time of installation, the alignment and location of the pipelines was based on an estimated worst case erosion scenario of six years with an appropriate contingency allowance. However, the section of cliff to seaward of the pipelines has eroded faster than expected and there is now a danger that the pipelines will become exposed before the leaching process is completed. Failure of the pipelines would bring the leaching process to a halt and would involve costly delays to the overall project.

Jacobs and SSE have concluded that the preferred option is to adopt a maintenance approach and have developed proposals to protect the cliff toe around the pipelines for a projected period of two years. The initial proposals, put forward in May 2010, involved the use of rock armour to protect the cliff toe (Figure 2). The environmental impact of the proposed works was assessed by IECS (Boyes *et al.* 2010). Their report concluded that the scheme might result in a 'sediment transport loss' of 1000 m^3 and a 'sediment supply loss' of 10,000 m^3 over the two-year period. This compared with an estimated sediment volume of 400,000 to 700,000 m^3 moving down the coast over that period (i.e. the proposed development might lead to a reduction in down-drift sediment volume of 1.5 to 2.75%). It was suggested that the sediment supply disruption from the project could be offset by placing sacrificial material on the shore.

Following completion of the IECS assessment, Natural England have requested further information regarding the potential impacts, particularly in terms of sediment flow to Spurn Peninsula and the Humber Estuary SAC, and in relation to the behaviour of the beach and cliffs in the vicinity of the proposed works. Natural England have asked that additional consideration is given to what will happen when the defences are removed, including any longer-term effects on recession rates, and the time required for the cliff

to reach the same position as if no defence was put in place (i.e. the 'recovery time'). These issues are addressed in the present report.

Since the original submission, revised design proposals have been developed which involve the use of *Secutex Soft Rock*® geotextile containers rather than rock armour in the cliff toe protection. Potential sources of material to fill the containers include glacial sediment excavated from the upper part of the cliffs, the beach in the vicinity of the proposed works, and imported material. The potential suitability of using sediment from the cliffs or the beach for use in the Soft Rock containers is also considered in this report.

Assessment of the implications of future longer-term coastal recession rates for the security of the Gas Storage Facility well-heads, taking account of sea level rise projections, has been made in a separate report (Jacobs, 2010).

2.0 Controls on erosion of the Holderness coast

2.1 Composition of the Holderness cliffs

The Holderness coast between Sewerby and Easington (a distance of approximately 60km) is composed of 'soft' Quaternary sediments which form cliffs ranging in height from less than 3 m near Easington to c. 40 m at Dimlington. The average height is about 15 m. The till overlies Chalk bedrock at depths of - 20 to - 35 m OD (Berridge & Pattison, 1994). The cliffs are formed in unconsolidated glacial till and outwash deposits of late Pleistocene age. Three main till units are present in the cliffs (Eyles *et al*., 1994):

Basement Till -	a lodgement till of probable Wolstonian age (c.130,000 - 300,000 years ago); dark grey in colour and containing a relatively low proportion of gravel and boulder-sized material derived largely from Northeast England
Skipsea Till -	a mixed origin till of Late Devensian age (13,000 - 18,000 years ago); generally brown in colour and containing a higher proportion of gravel and boulder-sized material derived from the Chalk and Carboniferous outcrops in North Yorkshire
Withernsea Till -	a mixed origin till of very Late Devensian age (11,000 - 13,000 years ago); often dark brown in colour and

containing a significant proportion of gravel and boulder-sized erratics derived from northern England.

Withernsea Till is present only in the southern part of the area and is very thin in places (Evans *et al*., 2001). The till deposits are locally overlain by fluvio-glacial sand and gravel outwash deposits which sometimes infill palaeo-channels incised into the till. Such deposits are well-developed in the cliff exposures just north of Ringbrough Farm.

All of the tills contain a relatively high silt and clay content, typically 60 - 70% (Catt & Penny, 1966; Madgett & Catt, 1978; Balson & Phillpot, 2004). They are highly cohesive and have been over-consolidated by ice pressure. The uppermost few metres below the surface have been modified by weathering and soil-forming processes. Representative geotechnical properties of the three main till units, reported by Bell & Forster (1991), are shown in Table 1.

2.2 Effects of beach morphology on rates of cliff erosion

The cliffs have been eroding throughout the late Holocene at a long-term average rate of 1.2 to 1.8 m a^{-1} (Pickwell, 1878; Mathews, 1905; Dosser, 1955; Valentin, 1954, 1971, Mason & Hansom, 1988; Pethick & Leggett, 1993). Erosion is accomplished by a combination of processes, including cliff failure by slumping, sliding and toppling, wave erosion of material from the cliff toe, and abrasion of the till shore platform by movement of coarse sediment. Cliff retreat is often episodic, with short-term periods of rapid retreat, amounting to several metres, associated with major cliff failures, alternating with periods of relative stability which can last several years.

The geographical variation in input of sediment from the Holderness cliffs between 1852 and 2009, and between 2003 and 2009, is shown in Figure 3. The volumes of material released from different sections of the coast in different time periods are summarised in Table 2.

South of Hornsea, the cliffs are fronted by mobile, and often thin, sand and gravel beach deposits which overlie an eroded till shore platform. The morphology of the beaches is highly variable in time and space, but often there is a relatively steep, rectilinear or convex upper beach and a flatter, lower beach. South of Barmston, the beaches are characterised by one or more bars on the mid to lower foreshore, separated from the high water mark by troughs or runnels, known locally as 'ords' (Pringle, 1981, 1985). The bars and troughs are oriented at a slight angle to the high water mark but are transverse to the approach of dominant north-easterly waves (Figure 4). The features are most pronounced during winter when they may have a bar crest to trough base elevation difference of >1 m. The bar and trough systems originate in the Barmston - Skipsea area

and migrate southwards along the shore towards Spurn Point at a rate of about 500 m per year (Pringle, 1985). Owing to the oblique angle of the features with respect to the cliff toe, they play a key role in determining the exposure to wave energy and hence rates of cliff recession. Where the deepest and widest parts of the ords lie close to the cliff toe, the level of the back-beach can be reduced by up to 3.9 m, allowing waves to impact on the cliff toe during neap as well as spring high tides (Pringle, 1985). Where the bar crests joins the shore there is a wide backshore and waves may not reach the cliff toe even during spring tides.

In the trough areas the beach sediment is often only a few centimetres thick and the till shore platform may be exposed. Erosional lowering of the till platform plays an important role in controlling the rate of cliff recession. Short-term measured rates of platform lowering range from 0.22 to 3.0 mm a^{-1} (IECS, 1994a). Pethick (1996) noted that erosion rates appear to vary with peaks on a 5-8 year cycle. During this time erosion rates may vary from 0 to 10 m a^{-1}, apparently due to movement of 'slugs' of sediment along the shore which provide spatially and temporally variable protection against wave action at the toe. Pethick suggested that these 'slugs' of sediment arise from periodic cliff-falls. However, the movement of the rhythmic long-shore beach forms (ords) described by Pringle (1981) is probably more important and is related more to longshore variations in wave energy than to inputs of sediment from cliff falls.

2.3. Effects of coastal protection works

Hard coastal defences are present on sections of the coast, notably at Hornsea, Mappleton, Withernsea and Easington. These defences slow or stop the rate of cliff recession and in some instances (where groynes or other shore-normal structures are present), impede the longshore movement of sediment. In extreme cases, lengths of shore down-drift of protected frontages can be starved of sediment, leading to falling beach levels and accelerated rates of cliff recession. Posford Duviver (1993) reported differences in erosion rates of 1.9 to 2.4 m a^{-1} between the cliffs on the northern and southern sides of the Hornsea defences. IECS (1991, 1994a) concluded that construction of the defences at Hornsea and Withernsea led to the development of a zone of accelerated erosion which extended at least 10 km down-drift. However, re-analysis of the East Riding of Yorkshire Council (ERYC) erosion data up to 2008 by Scott Wilson (2009) suggested that the effect is restricted to a relatively short distance down-drift.

Gravel and coarse sand are moved mainly on the upper beach by waves and wave-induced currents, but much of the fine sand, medium sand and mud is rapidly moved offshore and transported in suspension in a southerly direction by the combined action of tidal currents, wind- and wave-driven currents (Blewett & Huntley, 1999; Prandle *et al*., 2001). Aerial photographs reveal a zone of very high turbidity water extending

several hundreds of metres from the shoreline under stormy conditions, well-beyond the seaward limits of the groyne systems. Coastal defences are therefore unlikely to have a significant effect on the transport of fine to medium sand or mud as it moves southwards towards Spurn and the Humber estuary.

2.4 Fluxes of sediment from the Holderness coast

It has been estimated that an average of 3 to 4 x 10^6 m^3 a^{-1} of sediment is supplied to the coastal zone as a result of cliff recession, shore platform lowering and seabed erosion along the Holderness coast (Balson *et al*., 1996, 1998; Newsham *et al.*, 2002; Balson & Philpott, 2004). Wingfield & Evans (1998) suggested that 23% of the sediment is eroded from the cliffs, 33% from the shore platforms and 44% from the sea bed. The entire coastal profile moves landward over time. Approximately two-thirds of the till material consists of silt and clay which is rapidly dispersed over a wide area in suspension. Of the remainder, approximately 21.5% consists of fine sand which can also be dispersed rapidly in suspension. Only 9% consists of medium to coarse sand and 3.5% consists of gravel, which are the sediment size fractions most likely to be transported along the beach and nearshore bars by longshore drift (Balson & Philpott, 2004).

Table 2 presents a more recent estimate of the sediment yield from the Holderness cliffs, based on historical map and field monitoring data compiled by East Riding of Yorkshire Council. The importance of the Hornsea to Withernsea section of coast is evident during all time periods. The long-term average rate of sediment supply from the whole Holderness coastline over the period 1852 to 2009 was 86 x 10^3 m^{-1} a^{-1}, while the average rate between 2003 and 2009 was 101.6 x 10^3 m^{-1} a^{-1}.

North of Barmston the net sediment drift direction is northerly, and some sediment eventually accumulates on the Smethic Bank south of Flamborough Head (HR Wallingford *et al*., 2002; Halcrow, 2002). South of Barmston the net drift direction is southerly. The potential longshore sediment transport rate for sand increases in a southerly direction due to reduced shelter from northeasterly waves afforded by Flamborough Head, but overall it has been estimated to be between 200 and 350 x 10^3 m^3 a^{-1} (Posford Duvivier, 1992; IECS, 1994b; HR Wallingford *et al*., 2002). Transport rates are highest during major storm events, and within about 2 km of the shore (HR Wallingford, 2003). Owing to the change in coastal orientation near Easington and Kilnsea, up to 60% of the sand transported in suspension may be deflected offshore (Halcrow & GeoSea Consulting, 1990). Ciavola (1997) concluded from volumetric changes in beach transects that only about 6% of the total sediment entering the coastal waters reaches the Spurn Peninsula, the remainder being transported offshore near Kilnsea. A significant proportion of the fine sand, together with suspended mud, is

transported across the Humber estuary mouth towards Lincolnshire, North Norfolk and the Wash. Some of the suspended material finds its way into the Humber Estuary (Townend & Whitehead, 2003). A fine sand transport pathway may also exist between the Binks and the beach along the southern end of the Spurn Peninsula.

Coarse to medium sand and gravel moving down the Holderness coast are less likely to be lost offshore at Easington and Kilnsea. Unless intercepted by groynes or other structures, such material is able to move along the Kilnsea Warren frontage towards the Bents and Spurn Head.

2.5 The Spurn Peninsula

The Spurn Peninsula is a narrow sand and gravel barrier which has a curved, spatulate form in plan and is capped by dunes up to 15 m high along its central and southern parts. The lower, northern end of the barrier is aligned NNW - SSE, but south of its most easterly point the barrier orientation changes to NE - SW. At its narrowest point the neck of the barrier is less than 30 m wide, but near the Humber Pilot station the spatulate 'Head' attains a maximum width of >300 m (Figures 5 & 6). At the south-eastern corner of Spurn Head there is a W-E trending bank of sand and gravel (Stony Binks), separated by a narrow channel. A series of other, mixed sand and gravel banks (the Binks), extends further offshore in a north-easterly direction.

The barrier is underlain by glacial till which slopes in a southerly direction from c. -1.0 m OD near Kilnsea to -20 m OD near the southern end. The till basement acts to hold the barrier in position. The volume of supratidal sediment in the barrier has been estimated at 5 x 10^6 m^3, while the total volume of sediment above the till basement could be as much as 50 - 100 x 10^6 m^3 (Balson & Philpott, 2004). The sea floor to the east and west of the barrier is dominated by exposed till and lag gravels over which there are thin, discontinuous layers of mobile sediments (mainly medium to fine sands). Towards the wider, spatulate end of the barrier there is a thicker sequence of sand and gravels (up to 18 m) which extends eastwards towards the Binks (ABPmer, 2008). These banks apparently owe their existence to two underlying ridges of glacial deposits at c. -15 m OD (IECS, 1992, 1994b).

The Spurn Peninsula is an old feature which has displayed some westward movement and southerly extension in recent times. De Boer (1964) proposed that the barrier has evolved in a cyclic manner on a timescale of c.250 years, with four main periods of spit growth followed by breaching of the neck and subsequent re-growth along new alignments further to the west. While there have undoubtedly been periods of breaching and shortening of the feature, the evidence for self-limiting cyclical behaviour is limited. Borehole evidence suggests the neck of the barrier has moved only a short

distance landward during the past few centuries. Back-barrier estuarine deposits are present beneath the landward side of the neck but do not outcrop on the seaward side (IECS, 1992), providing no stratigraphic evidence for major barrier retreat.

De Boer (1964) postulated that the entire Spurn Peninsula and southern Holderness coast had moved westwards by c. 5 km since 1066, but confirmatory evidence is lacking. Comparison of the First Edition Ordnance Survey Six Inch map of 1852 with present day maps and aerial photographs suggests that there has been only very limited westward movement over that time period (Figures 7 & 8). Some of the sediment eroded from the shoreline along the neck has moved southwards, contributing to southerly extension of Spurn Head, while some has been blown landward to accumulate in the dunes which have become higher over the period.

Sand which is moved southwards along the Binks towards Spurn Head, and which is brought into the Humber estuary by tidal currents, is transported northwards up the western shore of Spurn Head, mainly by refracted waves from the southeast (Phillips, 1963, 1964; Ciavola, 1997). Sand from the upper beach on the south-western side of the Head is transported by south-westerly winds to form dunes, and this process has contributed significantly to westward growth of the spatulate end of the barrier since 1852 (Figure 8).

In 1849 a significant breach was formed in the barrier just to the south of the Inner Ridge of glacial till (Figure 5). This followed a number of smaller breaches and washovers during the 1840's. The 1849 breach developed into a 60m wide channel with a maximum depth of 5 m at low water (De Boer, 1981; May, 2003). This breach was eventually sealed by placing of timber piles and Chalk rubble in 1855 and 1870. A smaller and shallower breach was formed about 1 km to the north in 1850 and a further breach formed on the neck in 1855. A factor contributing to the formation of the breaches was the removal of thousands of tonnes of cobbles, gravel and sand from the barrier, for construction and industrial purposes, during the 18th and early 19th centuries. This practice gradually declined after 1870 but continued on the Binks until the 1920's (Mathison, 2008). Another factor was the natural southward extension of the barrier during the 18th and 19th centuries, as recorded by the construction of new lighthouses (Halcrow, 2002; ABPMer, 2008). This would have contributed to a reduction in sediment volume on the beaches further north as the barrier became 'stretched'. Southward extension of the barrier is driven by strong longshore transport under the influence of north-easterly waves, possibly combined with addition of sand to the end of the barrier from the Binks. This trend has continued to the present, although at a reducing rate as the end of the barrier advances closer to the deep water channel of the Humber.

Between the 1850's and the Second World War, when Spurn assumed great strategic importance, a variety of man-made defences was constructed along the eastern side of the Peninsula (De Boer, 1981; Crowther, 2008). These were finally abandoned when the military left the area in the 1960's and have since fallen into disrepair. This has contributed to an increase in shoreline recession rates along the neck since the 1970's (IECS, 1992; ABPMer, 2008). The presence of hard defences has acted to hold the shoreline position, while the shore at Easington and Kilnsea has continued to erode. Consequently, it has been suggested that the eastern part of the barrier north of Middle Bents now lies too far seaward of the equilibrium position, and a period of rapid landward readjustment may be expected as the defences progressively fail (IECS, 1992, 1994b).

Since the late 1970's over-washing events have been of limited extent and no significant new sediment has accumulated on the landward side of the barrier (other than fringing saltmarsh). Consequently, the most exposed north-east and east-facing parts of the barrier have become narrower (but also locally higher, due to accumulation of windblown sand around piles of dumped rubble; Saye *et al*., 2005; Pye *et al*., 2007). In the absence of groynes, longshore sediment transport rates in this area are high, and sediment is moved around the 'corner' onto the south-east facing shore where transport rates are lower. Continued supply of sediment from areas between Easington and Kilnsea Warren, and the rate of coastal recession along this part of the Holderness coast, are of critical importance to the stability of the northern part of the neck. It is likely that, as erosion at Kilnsea proceeds, the neck of Spurn Point will move landwards through a combination of shoreface erosion, washover deposition and windblown sand transport.

The modern beaches of the Spurn Peninsula consist of a mixture of sand and gravel and show a high degree of textural variability, depending on wave and tide conditions. Concentrations of gravel and sandy gravel often occur on the lower beach, but most of the beach area consists of sands with 5 to 20% admixed gravel. Along the neck of the barrier significant gravel accumulations are also often found on the backshore and across the full width of the foreshore. The dominant modal size of the sand fraction on the beach and in the dunes lies in the range 325 - 390 um (Figure 9). The modal sand size of sand on the western side of Spurn Head is slightly finer (250 - 300um).

3.0 Beach and cliff changes near the Aldbrough Gas Storage Facility

3.1 Recent beach and cliff changes

The Aldbrough Gas Storage Facility pipelines cross the present cliff-line at national grid reference TA 274372, just south of Ringbrough Farm, approximately 3 km south of

Seaside Road, Aldbrough (Figure 10). The site lies on a small hill in the till, and the cliffs in this area achieve a maximum height of about 22 m. Comparison with the First Edition Six Inch Ordnance Survey map and aerial photographs suggests that the cliff top in this area has receded by approximately 230 m since 1852 (Figure 11), 40 m since about 2000 (Figure 12), and 20 m since May 2007 (Figure 13). Erosion monitoring data compiled by ERYC indicate recession at monitoring profile 68, closest to the site, of c.90m since 1951. As on other parts of the Holderness coast, erosion at Ringbrough has been episodic, with periods of relative stability between 1951 and 1966 and between 1984 and 1999, and periods of more rapid erosion between 1967 and 1983, and after 1999. There was a shorter period of stability between 2001 and 2004, followed by significant recession in 2005, and a return to slightly slower recession until September 2008, after which time there was further period of rapid retreat (Figure 14). Owing to this short-term temporal variability, forecasts of future potential sediment yield due to cliff erosion should be based on a period of several years; the period 2003-09 has been used in this report.

Beach profile data obtained by ERYC show that the entire beach profile has moved landwards as the cliffs have receded (Figure 15). In September 2009 the beach consisted of a relatively narrow upper beach slope, a shallow runnel (ord), a mid beach ridge, and a lower beach slope down to the low water mark. Owing to the relatively narrow upper beach, waves are able to reach the cliff toe on almost all tides.

The beach between Aldbrough and Ringbrough Farm was examined during a site visit on 22 September 2010. Photographs taken at selected points along the beach are presented in Appendix 1. The locations where the photographs were taken are shown on Figure 9. It was evident during this site visit that the beach in front of the pipeline is at present characterised by an ord which creates an area of standing water in front of the cliff. The detailed form and thickness of the beach in this area appears to have been modified, involving localised redistribution of sediment, possibly during installation of the pipelines. However, the effect of this disturbance is being progressively diminished by natural sediment re-distribution processes.

The ord approaches the cliff toe and becomes narrower and shallower in a northerly direction, pinching out altogether just south of Cliff Farm (Grange Farm Cottage shown on Figure 10). To the south of Ringbrough Farm the ord moves further offshore and there is a relatively wide till platform in front of the cliffs. The general association of upper beach slope, till platform, water-filled trough and mid beach sand ridge is similar to that described by Pringle (1985) and shown schematically in Figure 4.

The upper beach fronting the eroding cliffs contains a significant amount of brick and concrete material derived from the buildings which have collapsed onto the beach, together with gravel and sand derived from the till. This material forms a relatively thin

layer (< 0.5 m) overlying the eroded till shore platform. The floor of the trough (ord) to seaward consists of medium sand with some gravel, while the mid-beach ridge is composed mainly of medium sand (Figure 17).

3.2 Potential effects of the proposed cliff protection works on erosion rates and sediment yields

Analysis of the ERYC beach survey data for profiles P66, P67, P68 and P69 since October 2007 shows that the ord has moved southwards along this frontage at a rate of approximately 500 m per year (Figure 15), which is very similar to the rate of movement reported by Pringle (1985). On this basis, it is likely that within two years the main part of the ord will have moved southwards, beyond Ringbrough Farm, and the northern end of the mid-beach ridge is likely to lie against the cliffs in this area. Without a major increase in storminess, a period of lower cliff recession may be expected after 2012. However, slower recession rates will only be temporary since a further ord, presently centred near Seaside Road, Aldbrough, will also move southwards and affect the Ringbrough Farm frontage after about 2016.

Based on the average cliff recession rate between mid-2003 and September 2009, determined by ERYC to be 3.12 m a^{-1}, the average volume of sediment which might be supplied from a 90 m length of cliff near the pipelines is estimated to be 6.138 x 10^3 m^3 a^{-1} (Table 3). Over the projected two year period that the toe protection would be in place, the potential reduction in sediment yield could be 12.355 x 10^3 m^3. This is equivalent to approximately 0.45% of the potential sediment yield from the Holderness cliffs as a whole (Table 3).

Of the total material supplied to nearshore waters from Holderness coastal erosion, only about one third is sand and gravel, the rest being mud. Based on Ciavola's (1997) conclusion that only about 6% of the eroded sediment reaches the Spurn Peninsula, the maximum volume of sand which might not reach Spurn, as a result of the proposed works, over a two year period, is unlikely to exceed 0.74 x 10^3 m^3. It is unlikely that all of the released sand would eventually reach Spurn, but in any event this represents less than 0.1% of the total volume of sand present on the Peninsula. This assumes that all of the released sand could eventually reach Spurn, which is very unlikely, and in any event represents less than 0.1% of the total volume of sand present on the Spurn Peninsula. Any potential effect of changes in sand input at Ringbrough would be indistinguishable from the natural variation experienced on the Spurn Peninsula.

3.3 Effects of the protection works on the beach and rates of cliff recession

Current proposals are to install toe protection over the winter of 2010-11 and to remove it when the leaching process is complete, about two years later.

The *Soft Rock* geotextile bags will need to be filled with sediment. Given the relatively thin veneer of sediment overlying the shore platform in the vicinity, the beach itself does not present a viable source. Any lowering of the beach would increase wave energy at the shoreline and lead to an increase in potential erosion rates. Observations during the site visit suggested that suitable sources of material exist in the upper parts of the cliffs immediately to the north of site. Use of this material would be preferable to importing material from an external source, both on environmental and cost grounds.

It is envisaged that the upper part of the cliffs will need to be re-graded for health and safety reasons and a new access ramp from the cliff top may need to be constructed. Calculations suggest that the total volume of material which could be made available from these sources would be approximately 33.5 x 10^3 m^3. Approximately 2.7 x 10^3 m^3 would be required to fill the geotextile bags used in the toe protection, leaving up to 30.8 x 10^3 m^3 available for placement on the beach as sacrificial material.

If erosion rates in the period January 2011 to January 2013 remain as high as during the period September 2008 to September 2009, the proposed defence works could prevent further cliff recession of approximately 12 m over the design life period. If, however, the rate of erosion is similar to the average for the period 2003-09, cliff recession would be approximately 6.25 m during the two year period. The cliffs on either side of the works could retreat by between 6 and 12 m, leading to the formation of a salient, 90m long and up to 12 m 'deep'. This feature could be effective in trapping some sediment moving along the upper beach, and might act to reduce the cliff erosion rates slightly on the up-drift side while leading to a slight increase in erosion rates on the partially sediment-starved down-drift side. However, the effect on the longshore sediment transport rates across the beach as a whole is likely to be minor in the short term and non-existent in the medium to longer term (>5 years).

3.4 Likely response of the beach and cliffs following removal of the toe protection

Under conditions similar to those which prevailed between September 2008 and September 2009, when the cliff recession rate was almost double the longer-term average, it would take two to two and a half years for the cliff to retreat to its expected position had no toe protection been put in place. However, given the fact that longshore movement of the ord is taking place, erosion rates by the end of 2012 may well be significantly lower than those recorded during 2008-09. It is therefore considered more

appropriate to use the average erosion rate for the period 2003-09 (3.12 m a^{-1}) as the basis on which to forecast future erosion rates for the period from early 2013 onwards. On this basis it would take up to four years for the cliff to retreat to the position it would have occupied in the absence of toe protection.

4.0 Conclusions

It is concluded that, given the small scale and short duration of the proposed cliff toe protection works, the direct effect on the sediment supply to Spurn Peninsula and the Humber estuary SAC will be negligible, even without provision of sacrificial material on the beach. The impact of the proposed works on cliff erosion rates down-drift and up-drift of the proposed works is also likely to be insignificant, both on the short term and longer term.

It is estimated from historical cliff erosion records that the effect of the protection measures could reduce the sediment input from a 90 m length of protected cliff by approximately 12.355 x 10^3 m^3 over a two-year period. This represents only about 0.45% of the total sediment input generated by erosion of the Holderness cliffs.

The potentially negative impact of the works on sediment supply to the coastal zone could be entirely offset by placing an equivalent volume of material excavated from the upper part of the cliffs on the beach as 'sacrificial material'. A 'surplus' of approximately 30.8 x 10^3 m^3 of material could be created by re-profiling of the cliff top and creation of a new beach access ramp.

The most suitable source of material for infilling of the Soft Rock geotextile bags now proposed for use in the construction of the toe protection would be the upper parts of the cliffs. The quantity required for this purpose is estimated to be 2.7 x 10^3 m^3.

Based on a consideration of temporal variations in recent cliff erosion rates and beach morphology, which are closely linked to the alongshore movement of ridge and trough features (ords), it is estimated that it will take between two and four years for the cliff to retreat' to a more 'natural' position following removal of the toe protection.

The beach and underlying shore platform in the affected area are also expected to regain a more natural profile within two to four years.

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Tables

Table 1 Summary of the geotechnical properties of the glacial tills at Dimlington (mean values). After Bell and Forster (1991).

Till	Natural moisture content (%)	Plastic limit (%)	Liquid limit (%)	Pasticity index (%)	Unconfined compressed strength (kNm^{-2})	Triaxial shear strength (c')	Effective angle of friction (ϕ')
Basement	17.0	18	34	17	160	23	25
Skipsea	15.5	16	30	14	186	28	30
Withernsea	16.9	20	36	19	186	34	29

Table 2 Volumes of sediment eroded from the cliffs along the Holderness coastline between 1852 and September 2009, from measurements made by East Riding of Yorkshire Council: (a) volumes eroded in different time periods; (b) rates of erosion in different time periods; (c) volumes eroded per metre length of coastline in different time periods; (d) rates of erosion per metre length of coastline in different time periods.

(a)	Length of cliff frontage (km)	Total volume of sediment eroded (m^3)			
Section of coastline		1852 to Sep 2009	2003 to Sep 2009	Sep 2008 to Sep 2009	Apr 2009 to Sep 2009
Flamborough to Bridlington (profiles 1-3)	0.6	0	13030	2125	0
Bridlington to Hornsea (profiles 8 to 42)	17.4	31024726	1128652	85185	11877
Hornsea to Withernsea (profiles 45 to 90)	22.4	80617597	5599117	729068	131630
Withernsea to Easington (profiles 94 to 110)	8.0	34222510	1300187	157787	21468
Easington to Kilnsea (profiles 113 to 115)	1.0	1900407	67014	0	0
Kilnsea to Spurn (profiles 118 to 123)	2.7	5314812	118427	22608	698
Entire Holderness coastline	52.1	153080052	8226427	996774	165673

(b)	Length of cliff frontage (km)	Aveage annual volume of sediment eroded (m^3 a^{-1})			
Section of coastline		1852 to Sep 2009	2003 to Sep 2009	Sep 2008 to Sep 2009	Apr 2009 to Sep 2009
Flamborough to Bridlington (profiles 1-3)	0.6	0	2172	2125	0
Bridlington to Hornsea (profiles 8 to 42)	17.4	197610	188109	85185	23755
Hornsea to Withernsea (profiles 45 to 90)	22.4	513488	933186	729068	263260
Withernsea to Easington (profiles 94 to 110)	8.0	217978	216698	157787	42935
Easington to Kilnsea (profiles 113 to 115)	1.0	12105	11169	0	0
Kilnsea to Spurn (profiles 118 to 123)	2.7	33852	19738	22608	1395
Entire Holderness coastline	52.1	975032	1371071	996774	331345

(c)	Length of cliff frontage (km)	Total volume of sediment eroded per metre length of coast (m^3 m^{-1})			
Section of coastline		1852 to Sep 2009	2003 to Sep 2009	Sep 2008 to Sep 2009	Apr 2009 to Sep 2009
Flamborough to Bridlington (profiles 1-3)	0.6	0	22	4	0
Bridlington to Hornsea (profiles 8 to 42)	17.4	1782	65	5	1
Hornsea to Withernsea (profiles 45 to 90)	22.4	3597	250	33	6
Withernsea to Easington (profiles 94 to 110)	8.0	4278	163	20	3
Easington to Kilnsea (profiles 113 to 115)	1.0	1900	67	0	0
Kilnsea to Spurn (profiles 118 to 123)	2.7	1950	43	8	0
Entire Holderness coastline	52.1	2936	158	19	3

(d)	Length of cliff frontage (km)	Aveage annual volume of sediment eroded per metre length of coast (m^3 m^{-1} a^{-1})			
Section of coastline		1852 to Sep 2009	2003 to Sep 2009	Sep 2008 to Sep 2009	Apr 2009 to Sep 2009
Flamborough to Bridlington (profiles 1-3)	0.6	0.0	3.6	3.5	0.0
Bridlington to Hornsea (profiles 8 to 42)	17.4	11.4	10.8	4.9	1.4
Hornsea to Withernsea (profiles 45 to 90)	22.4	22.9	41.6	32.5	11.7
Withernsea to Easington (profiles 94 to 110)	8.0	27.2	27.1	19.7	5.4
Easington to Kilnsea (profiles 113 to 115)	1.0	12.1	11.2	0.0	0.0
Kilnsea to Spurn (profiles 118 to 123)	2.7	12.4	7.2	8.3	0.5
Entire Holderness coastline	52.1	18.7	26.3	19.1	6.4

Table 3 Predictions of volumes of sediment which might be eroded from the cliffs at the Aldbrough Gas Storage Facility (in the viscinity of Profile P68), assuming different historical erosion rates: (a) calculations for a 90 metre frontage centred on Profile P68, and for the entire length of the Holderness cliffs; (b) calculations for a period of two years, and comparison with the entire length of Holderness cliffs over the same time period. Top line erosion rates are taken from East Riding of Yorkshire Council monitoring reports.

(a)	Monitoring period	
	1852 to Sep 2009	2003 to Sep 2009
Assumed erosion rate at P68 (m a^{-1})	1.11	3.12
Number of years	157	6
Assumed height of cliff (m)	22	22
Volume of sediment eroded per metre length of cliff per year (m^3 m^{-1} a^{-1})	24	69
Volume of sediment eroded from a 90 metre length of cliff per year (m^3 a^{-1})	2198	6178
Volume of sediment eroded from the entire length of Holderness cliffs per year (m^3 a^{-1}) (values from Table 2)	975032	1371071

(b)	Monitoring period	
	1852 to Sep 2009	2003 to Sep 2009
Volume which could be eroded from a 90 metre length of cliff at the Aldbrough Gas Storage Facility in 2 years (m^3)	4396	12355
Volume which could be eroded from the entire length of Holderness cliffs in 2 years (m^3)	1950064	2742142
Volume for a 90 m length of cliff at the Aldbrough Gas Storage Facility as a percentage of the entire length of Holderness cliffs	0.23%	0.45%

Figures

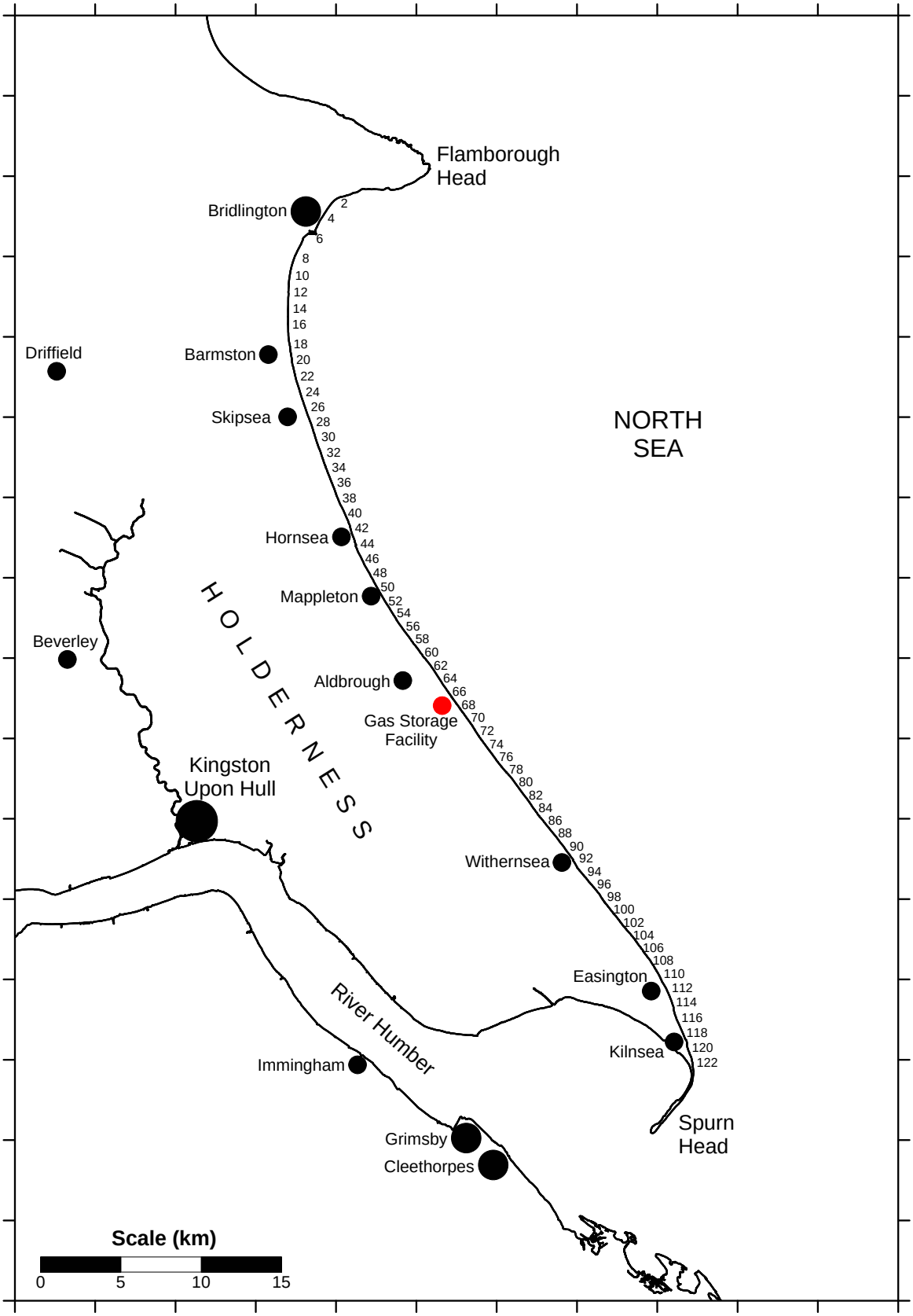

Figure 1 Location map showing the study site in the context the Holderness coastline, from Spurn Head to Flamborough Head. Beach monitoring profile numbers are indicated along the coastline.

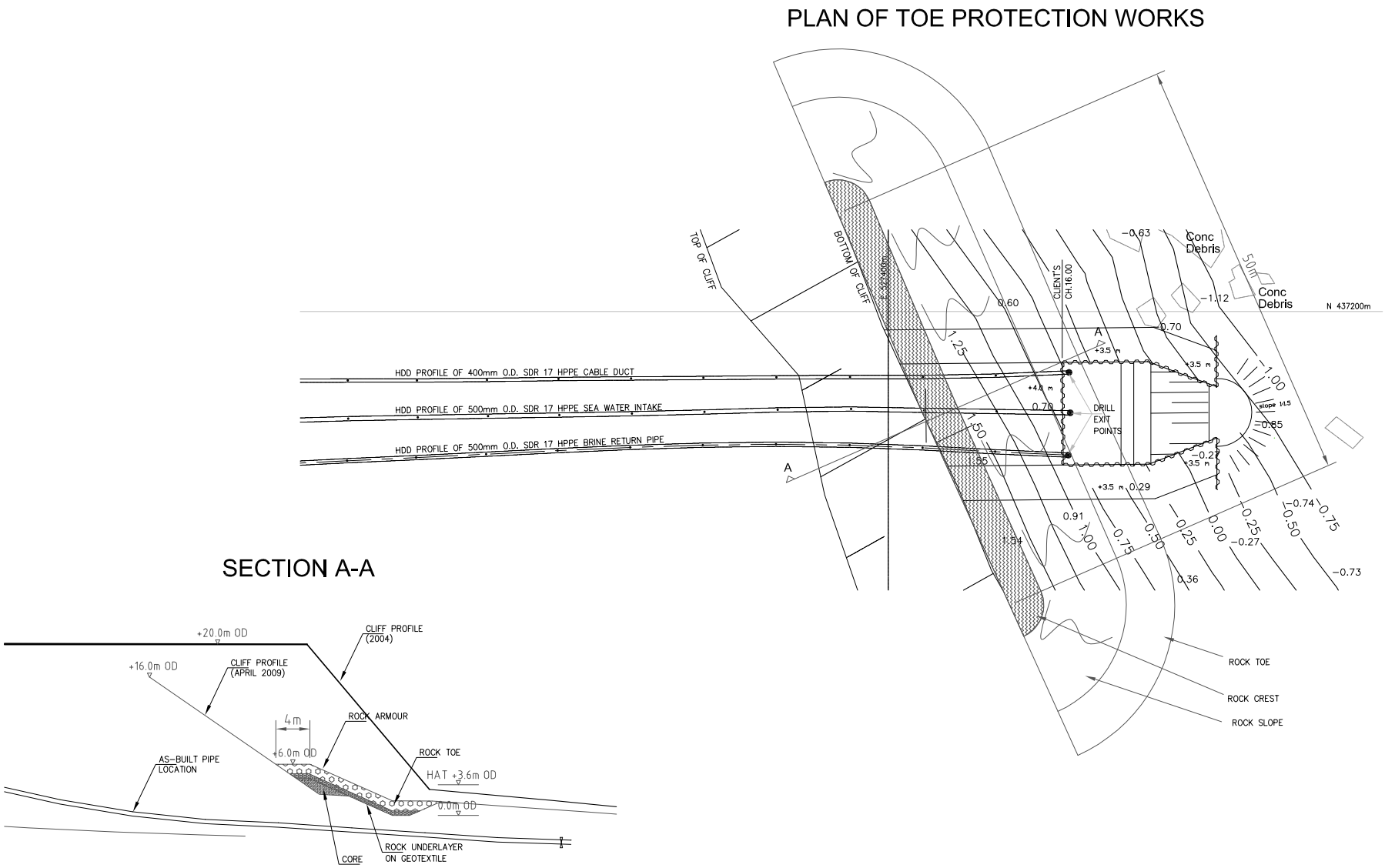

Figure 2 Diagram of the proposed works to protect the cliff toe and underground pipe from the Gas Storage Facility from coastal erosion. Source: Boyes *et al*. (2010).

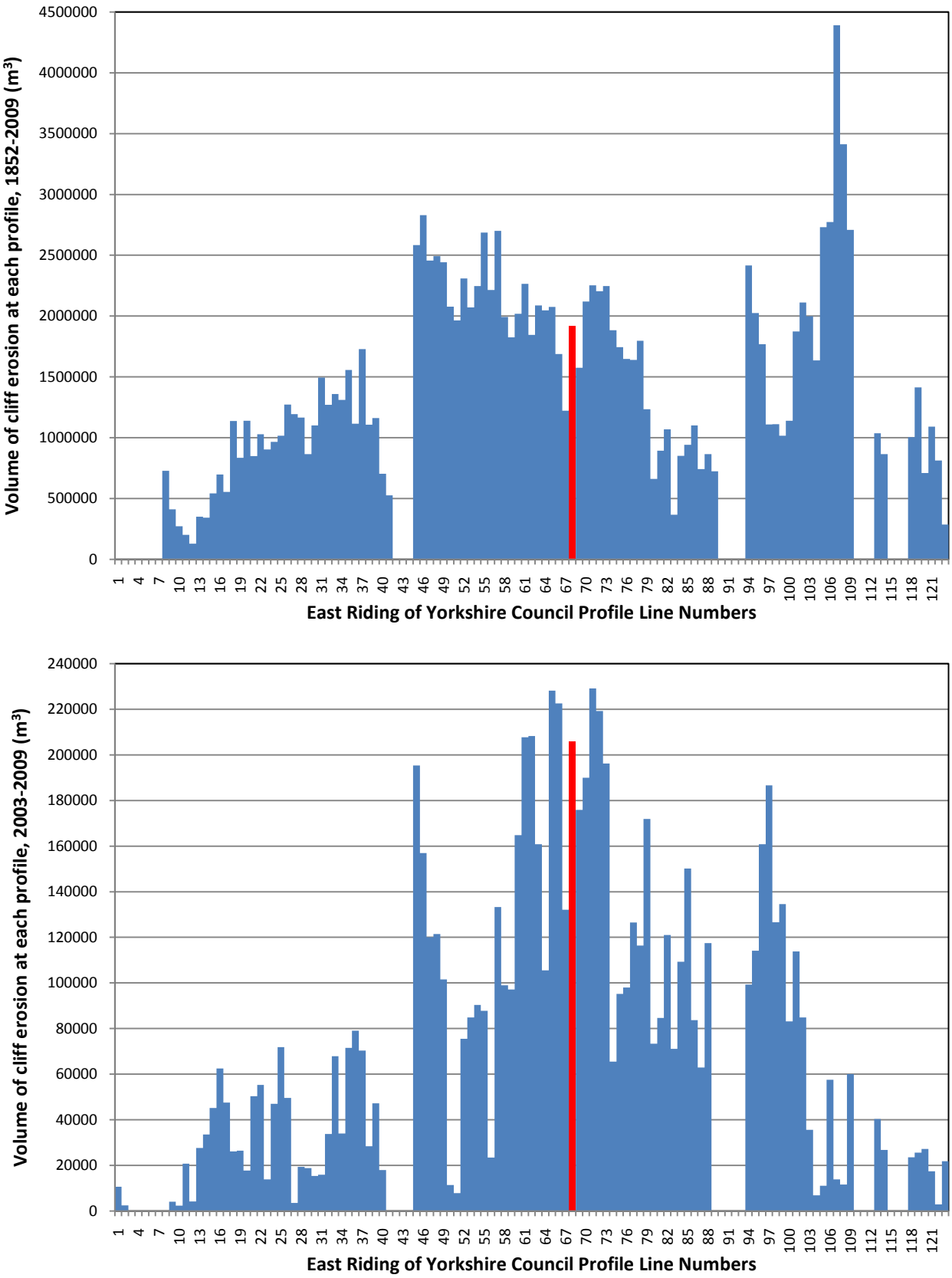

Figure 3 Volumes of sediment eroded from the cliffs along the Holderness coastline between: (a) 1852 and 2009; and (b) 2003 and 2009. Volumes are calculated for 500 metre lengths of coastline, centred on each East Riding of Yorkshire Council profile line. Volumes for Profile 68 (the 500 metre section closest to the Aldbrough Gas Storage Facility) is highlighted in red. Note the different vertical scales.

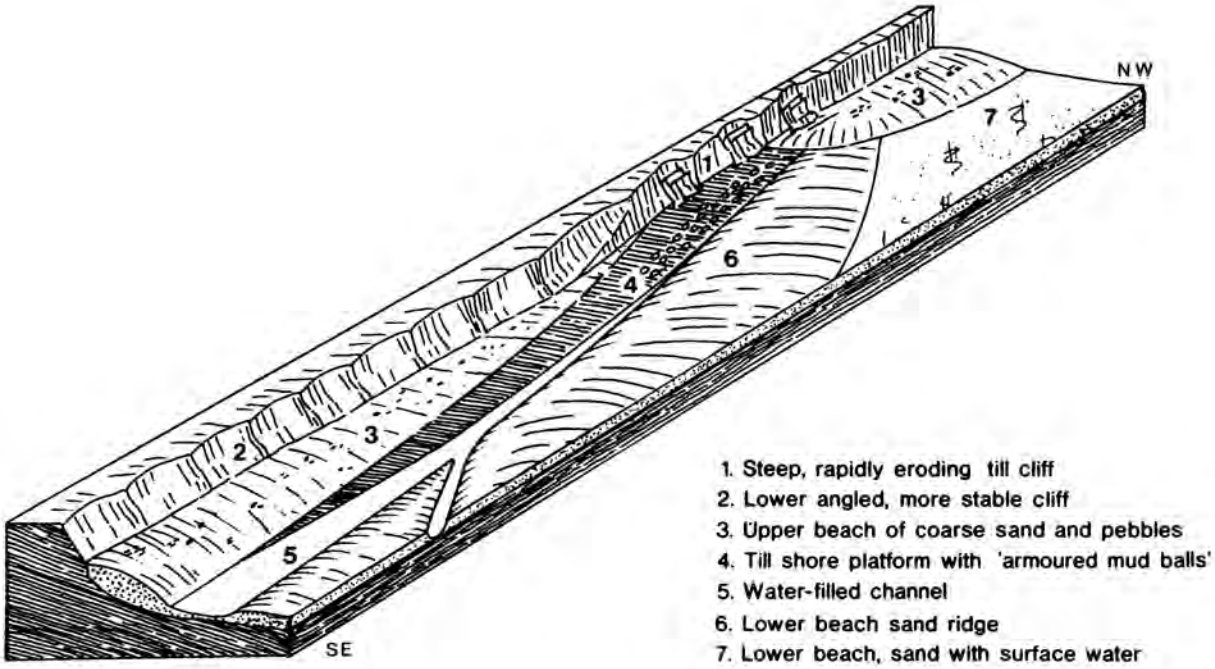

Figure 4 Schematic diagram of a Holderness ord. After Pringle (1985).

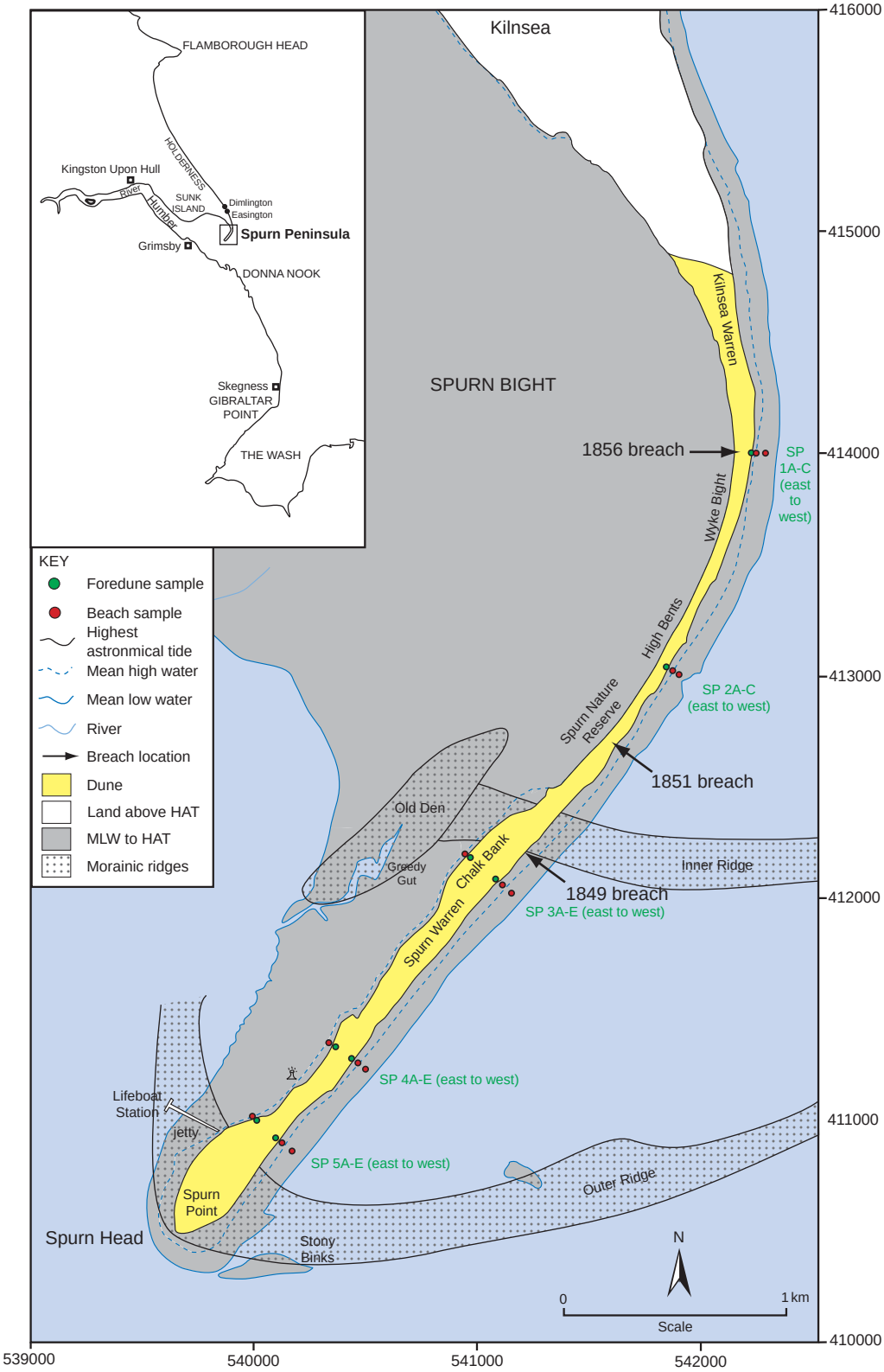

Figure 5 Location map of Spurn Peninsula, showing dune and beach sampling locations.

Figure 6 Aerial photograph of Spurn Head, taken in 1996. Source: tlfe.org.uk.

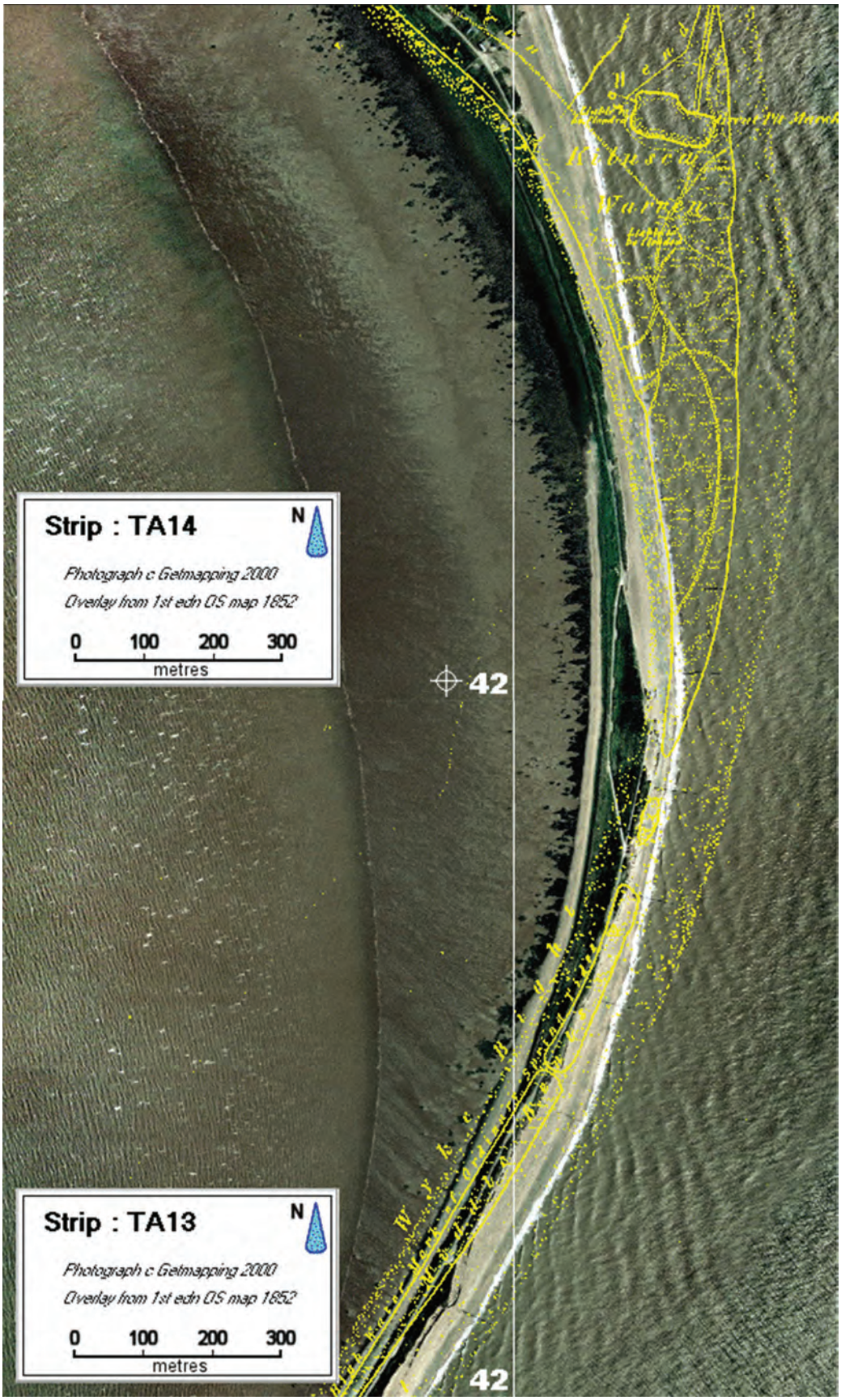

Figure 7 Aerial photograph of the neck of Spurn Peninsula, taken c. 2000, overlain with the first edition County Series Ordnance Survey map surveyed in 1852 (shown in yellow). Source: University of Hull Geography Department of Geography website (www.hull.ac.uk/erosion/index.htm).

Figure 8 Aerial photograph of Spurn Head, taken c. 2000, overlain with the first edition County Series Ordnance Survey map surveyed in 1852 (shown in yellow). Source: University of Hull Geography Department of Geography website (www.hull.ac.uk/erosion/index.htm).

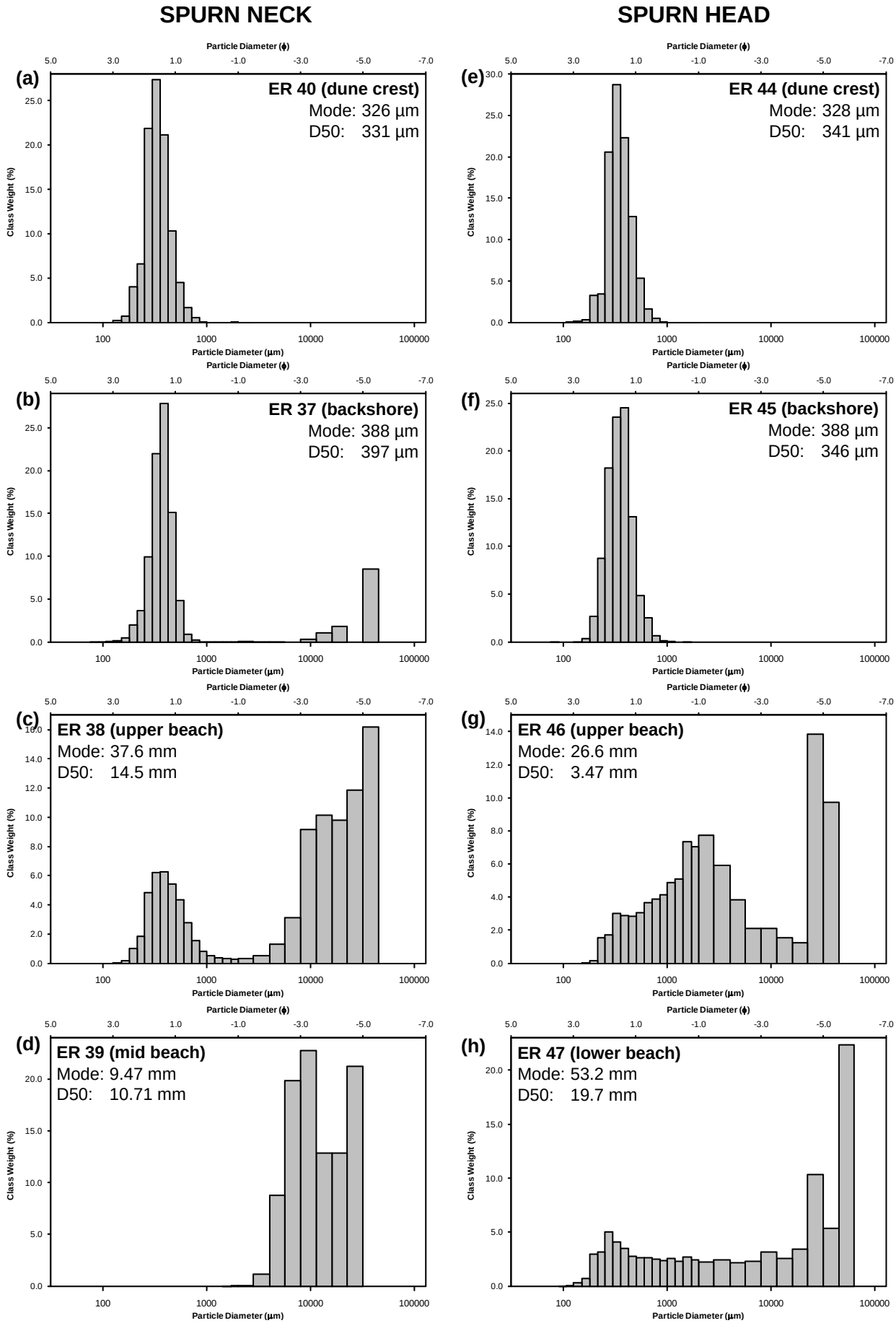

Figure 9 Particle size histograms for sediment samples collected at four cross-shore positions at two locations on the seaward side of Spurn peninsula: (a to d) Spurn Neck; (e to g) Spurn Head.

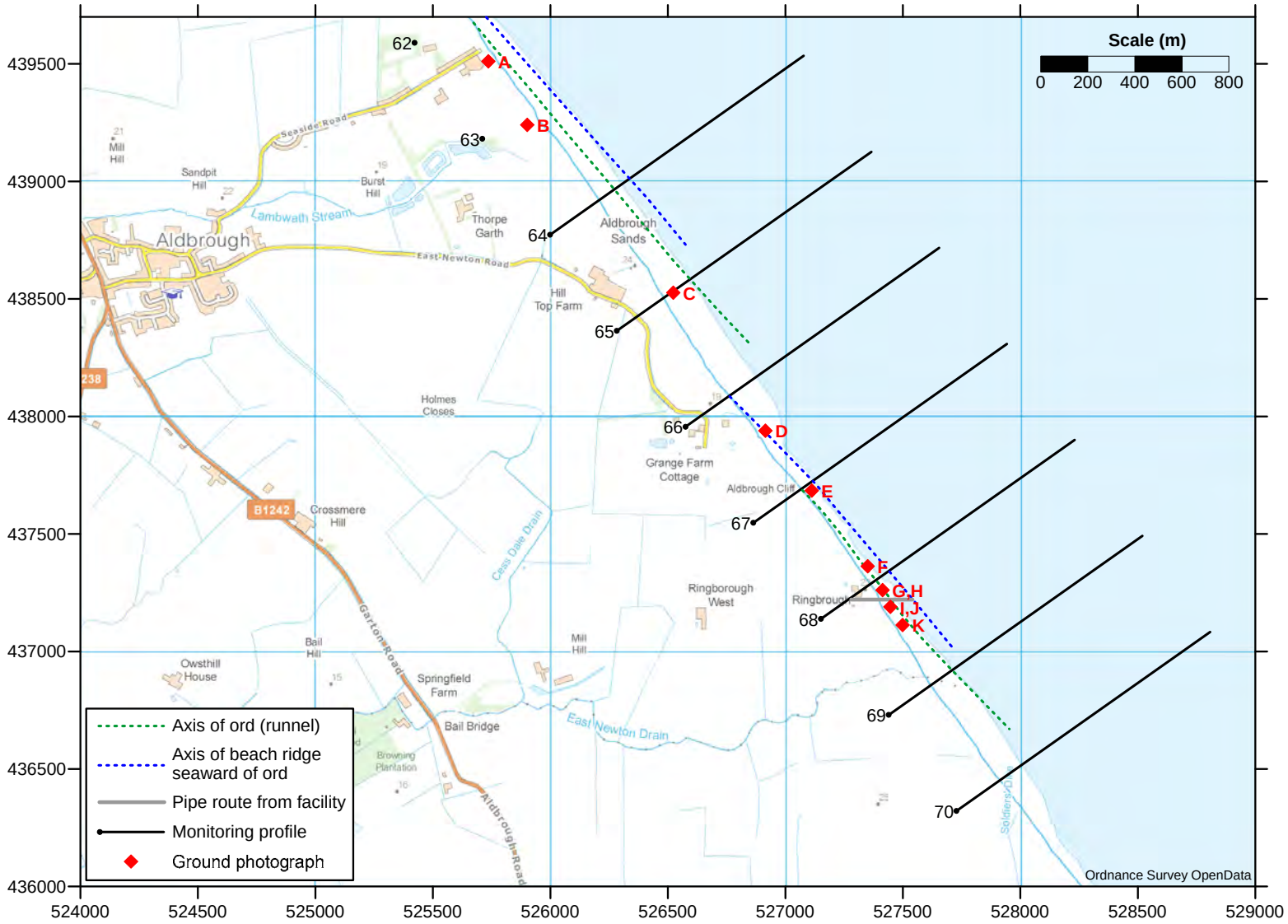

Figure 10 Location map of the study area, with a schematic representation of the position of the ords (runnels) and beach ridges to seaward, mapped in the field during September 2010. Also indicated are the positions of the pipe from the Aldbrough Gas Storage Facility, the position of beach monitoring profiles, and the position of ground photographs.

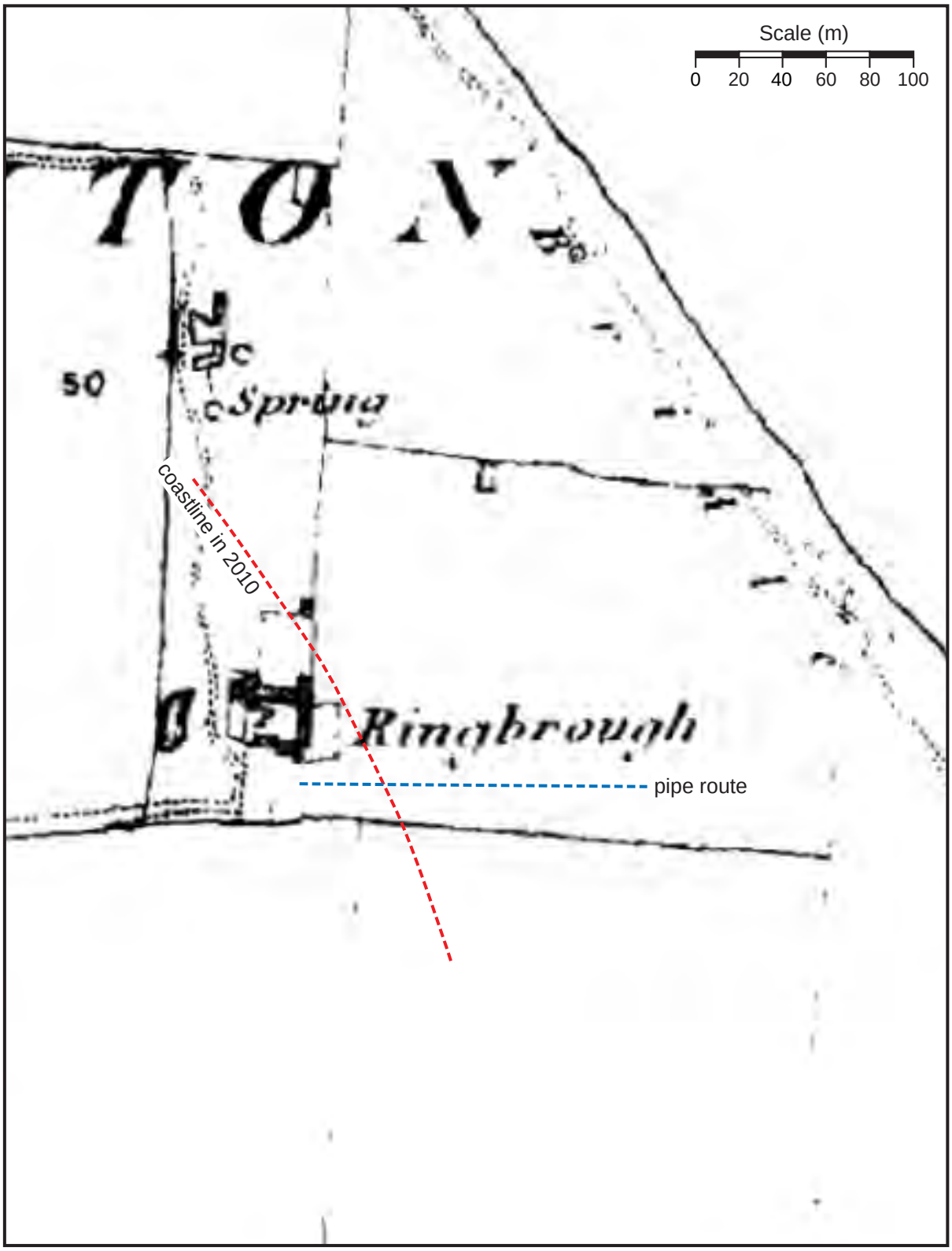

Figure 11 Six inch County Series map of the coastline near Ringbrough Farm, surveyed in 1852 . Dashed lines mark the approximate position of the top of the cliff in 2010, and the position of the underground pipe from the Gas Storage Facility.

Figure 12 Aerial photographs of the coastline near Ringbrough Farm taken c. 2000. Dashed lines mark the approximate position of the top of the cliff in 2010, and the position of the underground pipe from the Gas Storage Facility. Aerial photograph source: Multimap.

Figure 13 Aerial photographs of the coastline near Ringbrough Farm taken on 7th May 2007. Dashed lines mark the approximate position of the top of the cliff in 2010, and the position of the underground pipe from the Gas Storage Facility. Aerial photograph source: Google Earth.

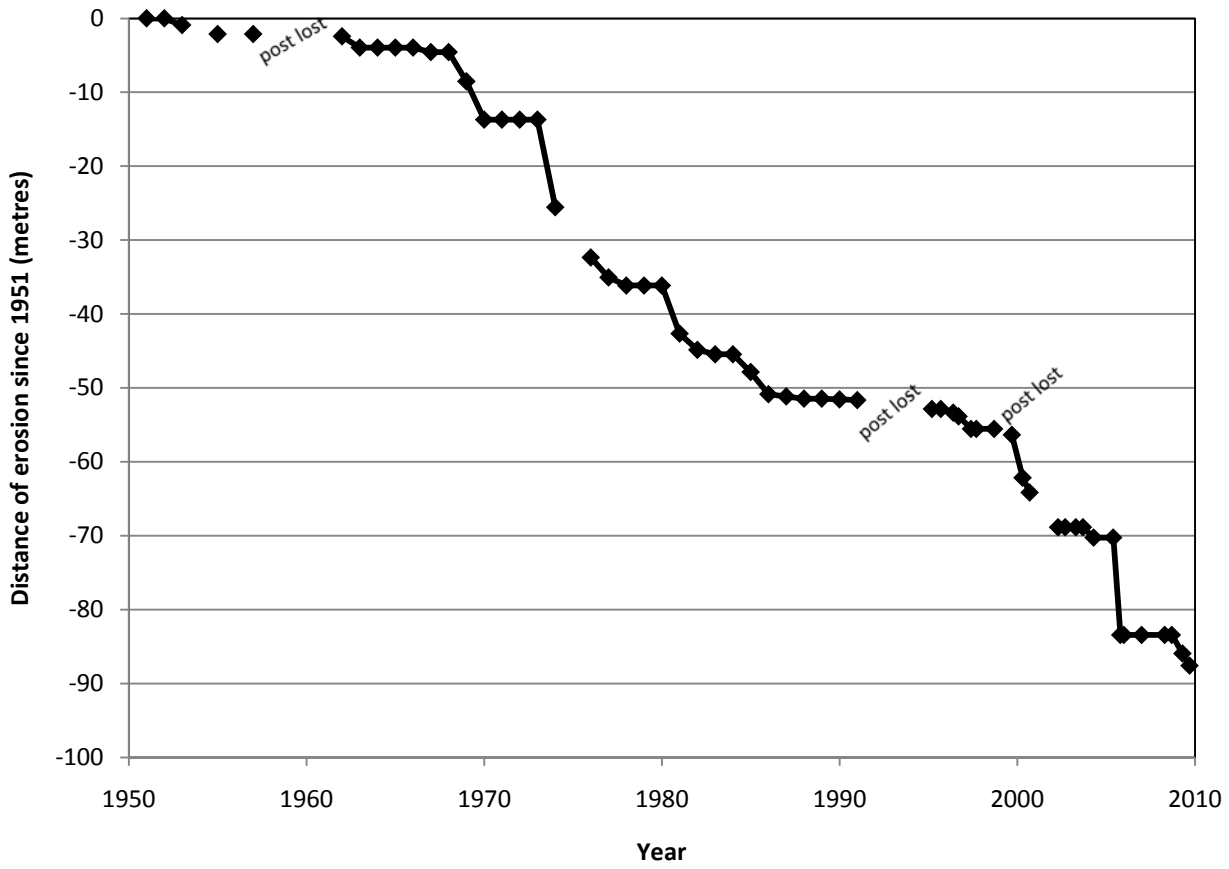

Figure 14 Distances of cliff erosion at Ringbrough Farm (present profile number 68, previous profile number 64), from annual surveys (1951 to 1993) and six-monthly surveys (June 1993 to September 2009). Note that the distances of erosion are unknown between 1957-1961, 1991-1994 and 1997-1998 due to the marker posts being lost. Other breaks in the data indicate periods when no surveying took place.

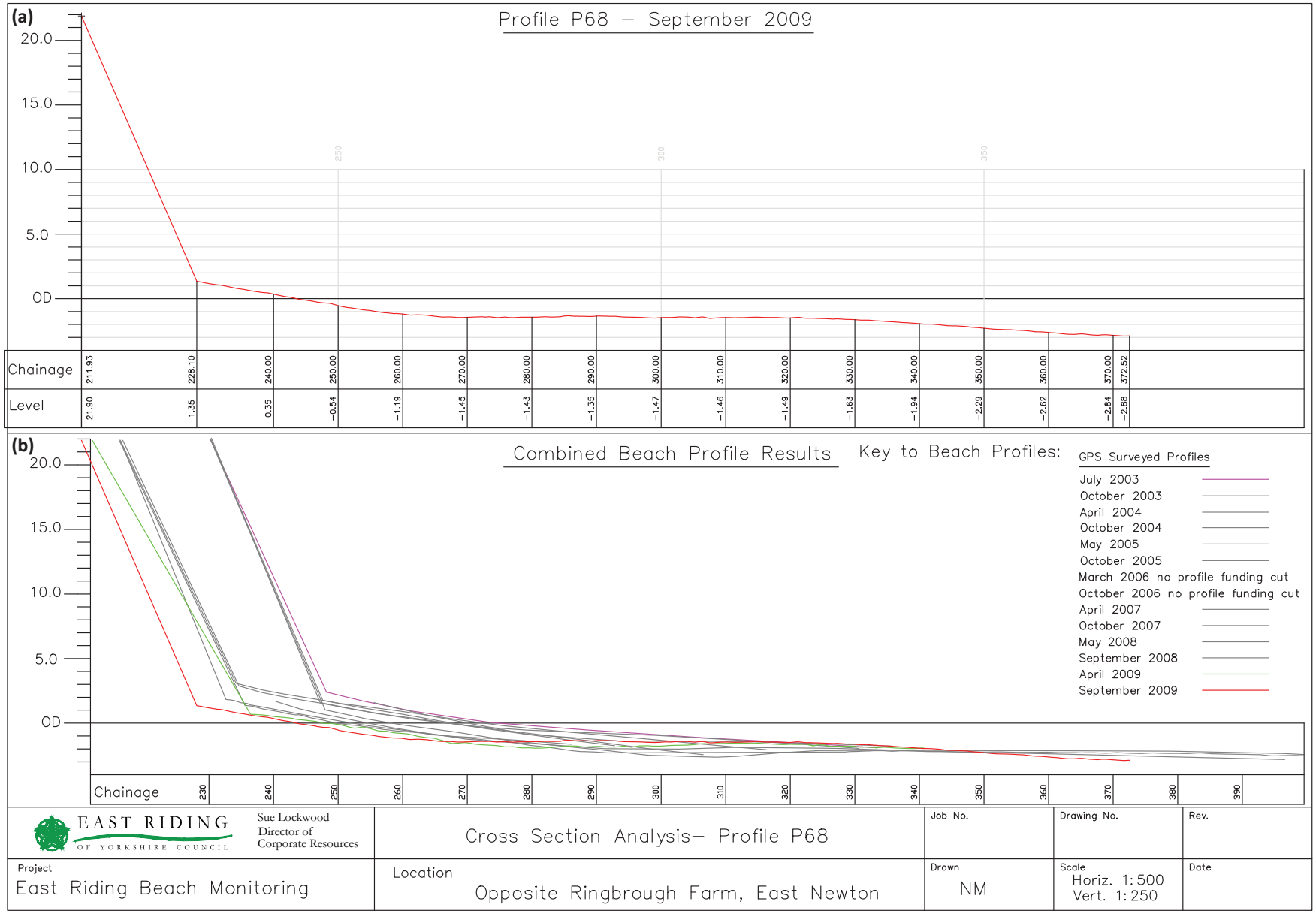

Figure 15 Beach profile 68, at Ringbrough Farm, measured using terrestrial LiDAR by East Riding of Yorkshire Council: (a) the profile measured in September 2009; (b) over of profiles measured July 2003 to September 2009.

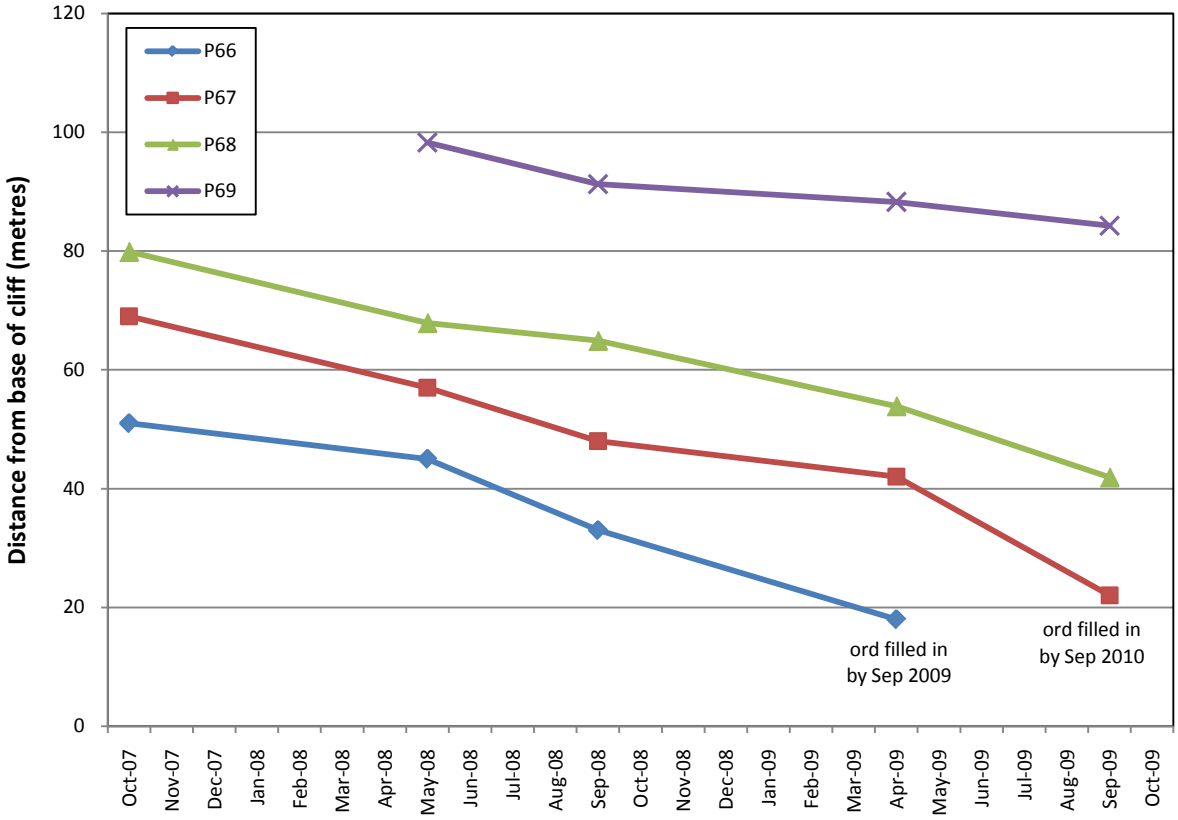

Figure 16 Measurements of the distances of the deepest part of an ord from the toe of the cliff at four profile locations (P66 to P69) near Ringbrough Farm between October 2007 and September 2009.

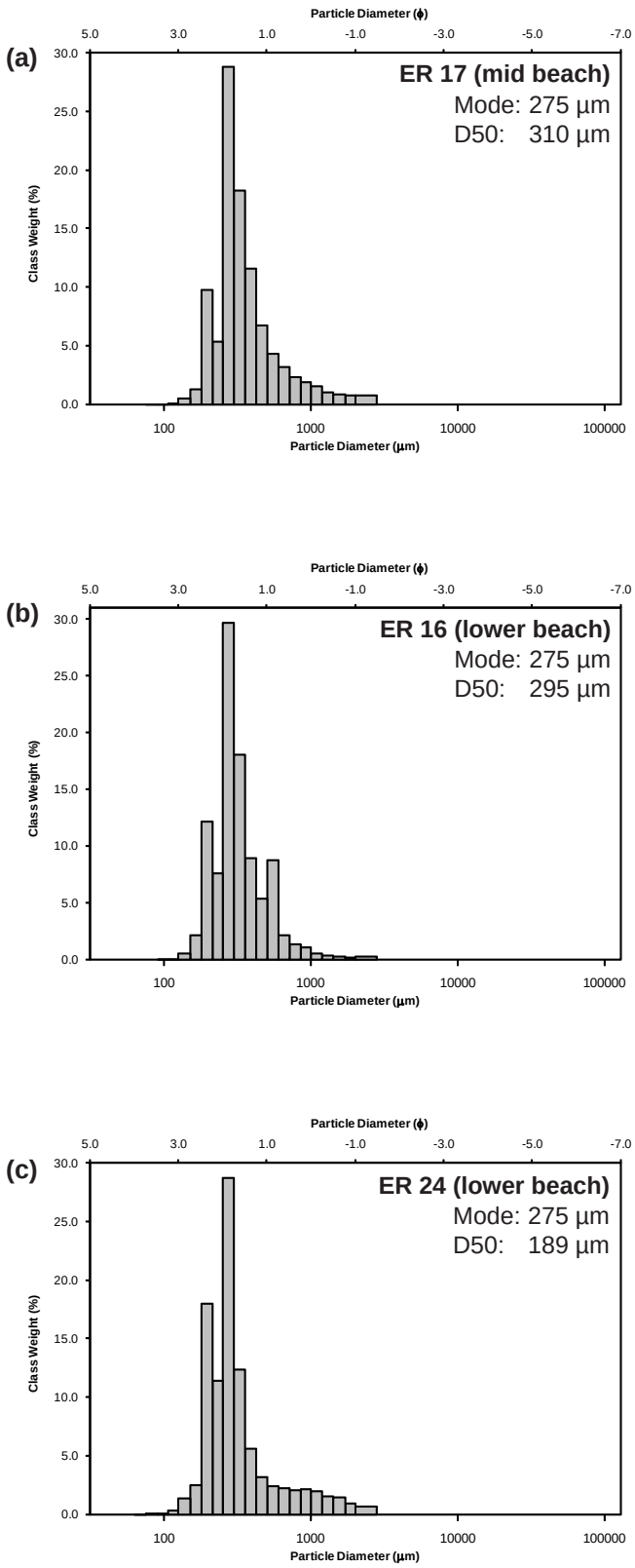

Figure 17 Particle size histograms for sediment samples collected at three cross-shore positions at Aldbrough.

Appendix 1

Ground photographs taken during field visit, 22 September 2010

Photo A View northwards at Seaside Road, Aldbrough, showing ord and mid beach ridge close to the cliff toe.

Photo B View northwards from caravan park south of Seaside Road, Aldbrough, showing active cliff movements.

Photo C View northwards from beach near Hill Top Farm, showing high and wide upper beach ramp in front of the cliffs.

Photo D View northwards from beach near Cliff Farm, showing beach access ramp and wide backshore in front of the till cliffs.

Photo E View northwards, midway between Cliff Farm and Ringbrough Farm, showing northerly limit of the ord which widens and deepens southwards towards Ringbrough.

Photo F View northwards from the beach at the northern end of Ringbrough Farm, showing ord close to the cliff toe and concrete debris from collapsed buildings.

Photo G View landwards from beach opposite Ringbrough Farm, showing water-filled ord close to the cliff toe and collapsed WWII observation tower.

Photo H View seawards from the beach near Ringbrough Farm, showing the water intake tower opposite the pipeline.

Photo I View northwards from the beach just south of Ringbrough Farm, showing water-filled ord close to the cliff toe.

Photo J View southwards from the beach just south of Ringbrough Farm, showing exposed till shore platform.

Photo K View southwards from the beach just south of Ringbrough Farm, showing ord diverging seawards from the cliffline.