Rock Mechanics and Rock Engineering
https://doi.org/10.1007/s00603-024-04194-w

ORIGINAL PAPER

Rock Mass Classification of Chalk, a UK Perspective

Chrysothemis Paraskevopoulou[1] · Charalampos Saroglou[1,2] · Aditya Kaushik[1]

Received: 18 April 2024 / Accepted: 24 September 2024

Abstract

Investigating the geomechanical engineering behaviour of Chalk is challenging since it is a generally soft rock formation and presents in cases a different behaviour from other competent rocks. Additionally, Chalk is widespread throughout the United Kingdom and other parts of the world. Thus, an in-depth understanding of Chalk is paramount when considered in engineering projects. In this research work, the geomechanical behaviour of Northern Province Chalk is examined. This study mainly involves characterising two significant units of Northern Province Chalk, namely Flamborough and Burnham Chalk, through intensive fieldwork and laboratory testing. Multiple scanline surveys are conducted along the cliffs of Flamborough to characterise the jointed nature of the Chalk. The samples collected are assessed in the lab to determine the physical properties of the intact Chalk. Moreover, the Chalk mass properties are compared to those estimated from empirical classification systems. Finally, the limitations of applying rock mass classification systems to Chalk have also been highlighted.

Highlights

- Chalk from the UK is investigated geomechanically.
- Characterization of Northern Province Chalk from extensive field observations.
- Laboratory assessment of physical properties of Northern Province Chalk.
- Highlighting limitations when applying existing classification systems to Chalk.

Keywords Chalk · Classification system · Northern province · Flamborough · Burnham · Behaviour of Chalk

1 Introduction

Chalk is a typical geological formation in the United Kingdom. It is usually a soft formation, while its behaviour can vary significantly due to both the range of physical properties and its lithological identity. Therefore, developing a better understanding of the behaviour of Chalk is very important (Pettit and Paraskevopoulou 2019). This research work presents the results from the study of two significant formations of Northern Province Chalk, namely the Flamborough and Burnham formations. This work aims to evaluate Chalk's mechanical behaviour while including fieldwork observations and laboratory testing and further analyses to determine in more detail geomechanically the Chalk behaviour.

The results from laboratory testing are presented, which included a series of rock mechanics tests, namely physical property tests and mechanical property tests, such as point load tests, Brazilian tests, and uniaxial compressive test. The application of rock mass classification systems for the classification of Chalk is also discussed, and their limitations are discussed.

Generally, their application is questionable as most of the systems are developed for jointed rock masses, in which

✉ Chrysothemis Paraskevopoulou
c.paraskevopoulou@leeds.ac.uk

Charalampos Saroglou
saroglou@central.ntua.gr

[1] School of Earth and Environment, University of Leeds, Leeds, UK

[2] Department of Civil Engineering, National Technical University of Athens, Athens, Greece

intact rock and discontinuities behavior are equally important in determining the overall rock mass behavior. In the case of Chalk, the rockmass behavior is mainly governed by the characteristics of intact rock and in to a lesser extent by the characteristics of discontinuities. Additionally, the intact rock strength of Chalk is relatively low in relation to the hard rock masses, for which the main rock mass classification systems (i.e. RMR, Q) have been developed. Chalk, being a geologically recent formation has lower intact rock strength and depending on the ground conditions may even have a soil like behaviour, in which case the rock mass classification systems are not applicable. Another, limitation is the presence of bedding planes in Chalk due its depositional history, which result in an anisotropic behavior, when seen in the larger scale. The findings from the field and laboratory testing can be used further to modify the existing classification systems to address these issues.

2 Background

Chalk is an ultra-fine-grained limestone composed of low magnesium, extending widely across Europe and Middle Asia. It is exposed in the UK in eastern and south-eastern England, parts of Ireland and a few places in Scotland. Overall, it covers roughly 15% of England's total surface area (Higginbottom 1965), making it one of the most important engineering materials in the UK. The present Chalk results from the deposition of soft white microscopic plankton algae and shell fragments on the seabed floor in the shallow sea some 66–145 million years ago under warm temperature conditions.

2.1 Chalk in the UK

English Chalk is formed from a carbonate fraction (majorly 95–98% of low magnesium calcite). Chalk is usually composed of meagre quantities of non-carbonate material, mainly clay, quartz and in rare cases, some authigenic glauconite, pyrite, marcasite and phosphates. The carbonate fraction mainly consists of finer sub-microscopic (< 10 µm) skeletal debris secreted by marine plankton algae and coarser fractions (40–100 mm) being represented by mechanically disintegrated hard parts of large-shelled organisms (bivalves, echinoderms, bryozoan, etc.). The English Chalk is divided into three broad provinces based on lithology and biogeography (Fig. 1a): North Province-Yorkshire and Lincolnshire Wolds; 2. Transitional province; 3. Southern or Anglo-Paris Basin.

The current study was limited to Northern Province Chalk extending from Lincolnshire's Wolds to the Cleveland basin's southern margin (shaded purple in Fig. 1a). Several authors have stated a clear distinction between Chalk from these zones (Clayton 1983; Mortimore 1989; Bell et al. 1990; Mitchell 2017). The Chalk from the transitional zone shows properties overlapping with the other two. The Chalk of North province is distinctly stratified, challenging, and consists of stylolites and not all the formations show the presence of flints. In contrast, the Southern province Chalk is soft and shows well-preserved fossils, and the occurrence of flints is throughout.

2.2 Northern Province Chalk

Northern Province is divided into five significant formations: Hunstanton or Red Chalk, Ferriby Chalk, Welton Chalk, Burnham Chalk and Flamborough Chalk (Fig. 1b, c). These formations are further divided into members and beds. A brief lithological description of these formations is presented:

- Hunstanton or Red Chalk consists of generally red Chalk, limestone marlstone and clays that show a brick red colour due to the small amount of Hematite. However, the colouration is lost due to reducing pore fluids' percolation. Age: middle lower Albian to Upper Albian.
- Ferriby Formation, marked by a top erosional surface, consists of a succession of white, grey and pink Chalk/limestone with marlstone bands or flasher marlstone (tidal environment). Gritty sand-grade Chalk is present at multiple horizons, while flints are not present throughout the formation.
- Welton Formation consists of three members: a thick sequence of white Chalk with nodular flints, a thin section of gritty inoceramid-rich Chalk; and, a Black bed (variegated beds).
- Burnham formation consists of a succession of hard white, thinly bedded Chalk containing large flints with thick tabular flints predominating in the lower and middle part (thickness ~ 130–150 mm) nodular flints present in the upper part of the formation.
- Flamborough formation is devoid of flint and consists of a series of thinly bedded white Chalk with numerous marlstone seams.

2.3 Properties of Chalk

The behaviour of any rock depends upon several physical parameters; Chalk consists of sub-microscopic fine fractions (< 10 µm) and variable coarser fractions (500 µm); the variations in their percentage, to an extent, control its overall engineering behaviour. The presence of high low Mg% as observed in the southern province Chalk, explains the survival of low-density, high porous Chalk. Moreover, the high percentage of finer particles results in higher moisture content.

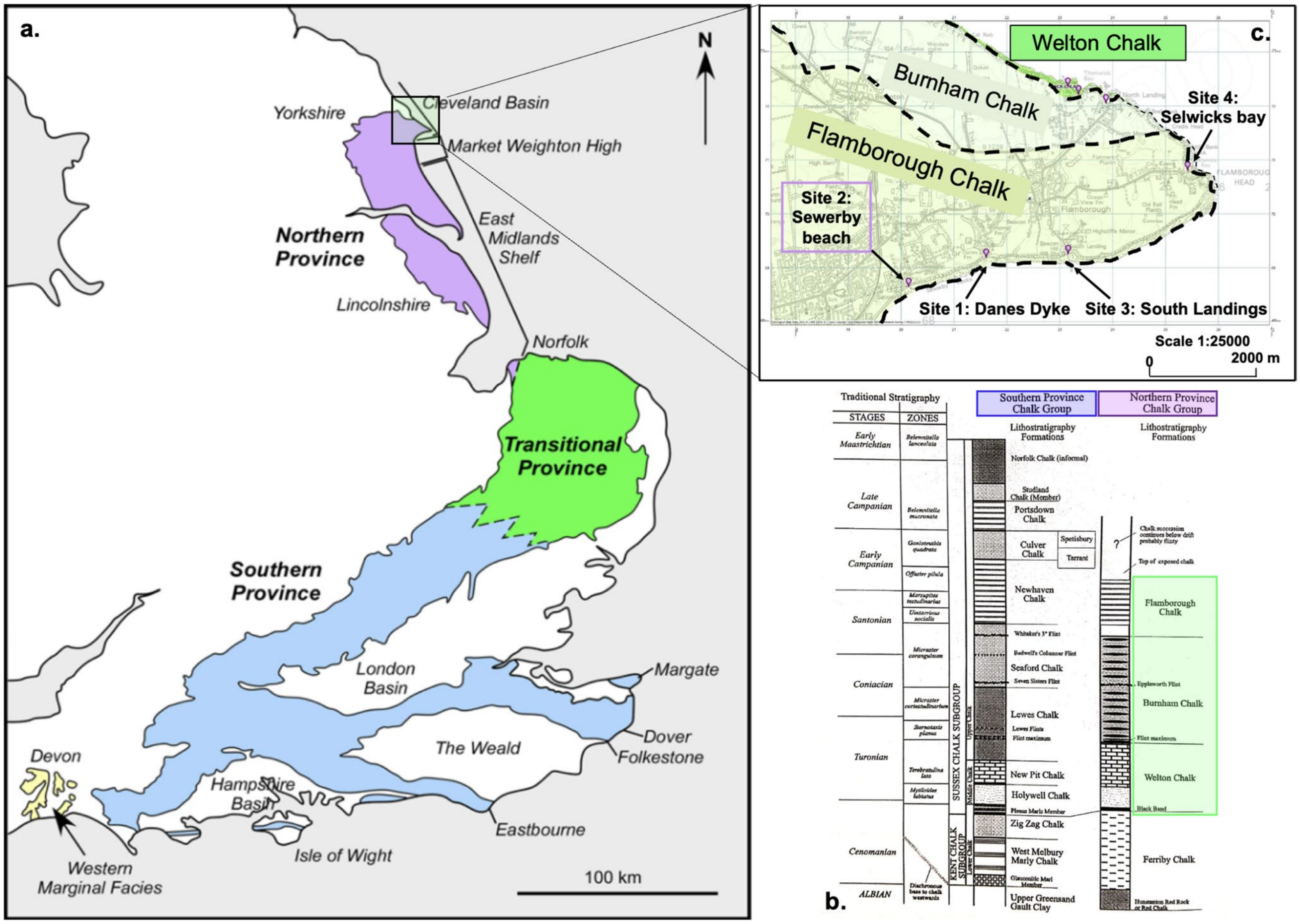

Fig. 1 **a** Distribution of the English Chalk (modified after: Mitchell 2017); **b** Northern and Southern province Chalk stratigraphy, Engineering in Chalk (CIRIA C574 2002); **c** Bedrock Geological Map of Flamborough Head area (modified after www.DigiMap.com)

A significant variation across the Chalk throughout the different units is observed in porosity and density values. Chalk's difference in porosity values is attributed to the localised diagenetic process (Clayton 1983). The Upper Chalk from Kent and Norfolk shows porosity as high as 40% (Bell et al. 1990), whereas Melbourne rock (hard Chalk) shows values as low as 20%. An average porosity value of < 25% has been observed from Yorkshire. Clayton (1983) reported dry density for English Chalk 1.29–2.46 Mg/m^3. Yorkshire's Chalk is considerably denser ranging between 1.76 and 2.30 Mg/m^3, than the south-east region Chalk.

Moreover, a reasonable correlation between uniaxial compressive strength (UCS), point load strength and dry density have been reported by Matthews and Clayton (1993). Mathews (1993) and Mortimore and Feilding (1990) first observed a dependency of tensile strength on porosity and saturation. A range of 0.1–0.2 MPa and 2.5–5 MPa strength was noted for high porosity and low porosity samples. Bell et al. 1990 reported a range of UCS between 0.2–23.1 MPa for low porosity Chalk, Brazilian tensile strength in the range of 0.8–3.1 MPa and 0.2–2.1 MPa for point load strength for the Yorkshire Chalk. The uniaxial compressive strength ranges from 18.1 to 36.4 MPa for the Yorkshire Chalk (Bell et al. 1990). From the triaxial and shear box test carried out on Norwich Chalk, an average value of 39°–36° was reported for friction angle at peak strength and residual strength state with cohesion varying from 0 to 0.02 MPa at the residual state (Twine and Wright 1991). CIRIA C574 suggest $c' = 0$ MPa and $\phi' = 34°$ for a worst-case scenario. The geotechnical properties of English Chalk based on multiple literature research works have been summarised in Table 1, where CIRIA C574 provides a typical range of index properties for Chalk.

2.4 Classification of Chalk

Multiple classification systems have been developed to classify Chalk based on several properties. Table 2 summarises the previous known classification systems based on density. Chalk has been classified based on the latest CIRIA PR11

Table 1 Typical range of index properties for Chalk

Reference	Chalk province/unit	Porosity	Dry density	Permeability	Dry UCS	Brazilian tensile strength	Point load	Young's modulus	Poisson's ratio	Angle of friction	Cohesion	Saturated moisture content
		% (min, max)	Mg/m^3 (min, max)	$\times 10^{-9}$ ms^{-1} (min, max)	MPa (min, max)	MPa (min, max)	MPa (min, max)	(GPa)		° (peak and residual)	MPa	%
Bell (1977)	Lower Chalk, Yorkshire	20.6 (17.2, 30.2)	2.08 (1.85, 2.13)	0.9 (0.3, 1.2)	26.4 (19.1, 32.7)	2.2 (1, 2.4)	1.4 (0.3, 1.8)	12.7 (18.4, 7.5)	0.28 (0.2, 0.39)			
	Middle, Yorkshire	21.8 (35, 16.2)	2.14 (1.76, 2.3)		30.7 (25.2, 36.4)	2.1 (1.2, 3.1)	1.7 (0.6, 2.1)	15.2 (9.1, 21.7)	0.29 (0.21, 0.36)			
	Upper, Yorkshire	23.9 (36.4, 17.7)	2.06 (1.77, 2.23)		25.6 (18.1, 34)	1.7 (0.8, 2.4)	1.2 (0.2, 2)	11.7 (7.4, 17.1)	0.27 (0.2, 0.35)			
	Lower, Norfolk	26.5	1.99		21	1	0.8	11.7	0.27			
	Melbourne rock	19.8	2.17		29.1	2.1	1.7	8.7	0.27			
	Middle, Norfolk	34.4	1.76		13	0.8		13.5	0.33			
	Upper Kent	41.7	1.44		5.5	0.5		6.7	0.36			
Bell (1990)	Upper Chalk, Kent									17	2.6	
Clayton (1983)	Northern Chalk		1.97–2.25									
CIRIA C570		9.0–52	1.29–2.46	5–250	0.7–40		0.01–1.15					4.0–40
Flexer and Honigsrten (1989)	Eocene Chalk, Israel	27–45	1.4–1.8	4.95×10^{-4}–$1.48\times10-3$	11.78	1.17			0.3	44	1.56	
	Maastr. Chalk, Israel	28–46	1.3–2.1		9.8–24.5	0.5–8.3						
	Campian Chalk, Israel	23–59	1.1–2.1	2.17×10^{-3}	0.7–22	0.4–2.5			0.25	27–29	0.3	
	Cenomanian Chalk, Israel	14–38	1.5–2.7	9.9×10^{-5}–$2.96\times10-4$	6.0–43	6–16.1				20–40	0.28–0.5	
Higginbottom (1965)	Upper and Middle (white), Southern P	41–50	1.36–1.6									25–36
	Lower (grey), Southern P	21–30	1.89–2.13									8.0–25
Hutchinson (1972)	Cliff, Isle of Thanet									42 (30-residual)	0.131	

Table 1 (continued)

Reference	Chalk province/unit	Porosity	Dry density	Permeability	Dry UCS	Brazilian tensile strength	Point load	Young's modulus	Poisson's ratio	Angle of friction	Cohesion	Saturated moisture content
		% (min, max)	Mg/m^3 (min, max)	$\times 10^{-9}$ ms^{-1} (min, max)	MPa (min, max)	MPa (min, max)	MPa (min, max)	(GPa)		° (peak and residual)	MPa	%
Lawrence (2013)	Newhaven Chalk unit-Southern P		1.6 (1.53, 1.64)		1.5–3.8							25.45 (24.8, 26.01)
Lake (1990)	Upper, middle and lower Chalk-S.P.	5.0–15			0.5–10			50–400 (1000)		30–40 (< 24-post failure)		
	Melbourne rock				20							
	Highly indurated Chalk				30–50							
	Welton Chalk			10–1000 (0.01)	15–63					33	35	
	Chalk Marl			10.0–50	2.0–4.0							
Lauridou et al. (1986)	Flints				391	68						
Mortimore and Duperret (2004)	Cliff of Sussex		1.45–2.2				0.1–0.7					
O'Reilly et al. (1979)	Chalk of Chinnoe, Oxfordshire		2.13 (1.78, 2.42)		7.42 (2.1, 43.9)							
Plinninger et al. (2002)	Flint, CTRL		2.55 (2.52, 2.58)		636 (467, 748)		10.7 (1, 25)					
Twine and Wright (1991)	Upper Chalk, Norwich									39 (36-residual)	> 0.02	
Lab results (this study)	Flamborough Chalk	17.4 (14.9, 21.7)	1.9 (1.82, 2.13)		20.31 (18.11, 24.57)	1.85 (0.848, 2.21)	1.355 (0.81, 1.83)	13.6 (10.3, 18.4)	0.22			
	Burnham Formation	12.9	2 (1.93, 2.1)		37.1	2.9 (2.43, 3.59)	1.78	28	0.245			

Table 2 Classification of Chalk based on density

Classification of Chalk based on dry density	
Mortimore and Fielding (1990)	(1) Extremely soft < 1.55 Mg/m^3
	(2) Very soft: 1.55–1.6 Mg/m^3
	(3) Soft: 1.60–1.7 Mg/m^3
	(4) Medium hard: 1.7–1.8 Mg/m^3
	(5) Hard: 1.8–1.95 Mg/m^3
	(6) Extremely hard > 1.95 Mg/m^3
Lord et al. (1994)	(1) Low density < 1.55 Mg/m^3
	(2) Medium density: 1.55–1.70 Mg/m^3
	(3) High density: 1.7–1.95 Mg/m^3
	(4) Very high density > 1.95 Mg/m^3

classification system (Lord et al. 1994). This classification uses the following parameters to categorise different Chalk units.

- hardness of intact Chalk (density and strength)
- Discontinuity spacing,
- Discontinuity aperture

Most of these classification systems are only limited to the description of Chalk. Though for estimating rock mass strength and other parameters, empirical classification systems like RMR, Q, and even GSI are still used. Mortimore (2012) has presented the application of RMR and Q system in some cases studies in the UK (A26 Cuilfail Tunnel) and noted that the analyses of the parameters collected for the classification systems closely corresponded to the rock conditions encountered in these cases. Harris et al. (1996) suggested that the RMR and Q rock mass classification systems were too insensitive to identify the conditions found when TBM tunnelling in the marl-rich Chalks and the fracture zones were underestimated during construction of the Channel Tunnel. Polishook and Flexer (1998) studied various Chalk rock masses in Israel and concluded that Q and RMR classification methods are too conservative and therefore unsuitable for a Chalk rock mass, as Chalk is characterised by non-continuous joints and bedding planes.

3 Area of Interest and Geology

Northern Chalk successions are well exposed as cliffs and platforms along with the Flamborough head, spanning from Upper Cretaceous Red Hunstanton Chalk to Lower Campanian Flamborough Chalk unit (Fig. 1c). A field plan is developed covering multiple sites along the Flamborough head area. However, due to limited accessibility and protected site (SSSI-Natural England), the fieldwork is restricted to only four sites: Sewerby, Danes Dyke, South Landing, and Selwicks bay (Fig. 1c).

3.1 Field Work and Site Description

The fieldwork is completed in several site visits. Table 3 summarises the main fieldwork activities. Figure 1c shows both Flamborough and Burnham formation exposures at the cliffs of Selwicks Bay (Site 4), while only the Flamborough formation is exposed at the other three sites (Site 1, 2, 3).

3.1.1 Site 1: Dane's Dyke

Flintless Flamborough Chalk formation is exposed at Danes Dyke. The Chalk is a very fine-grained and highly

Table 3 The fieldwork methodology

Task	Field equipment	Methodology
Engineering rock description	Standard geological equipment	Carried out in accordance with BS 5930:2015 and use of Soils engineering identification and description guide sheet
	Schmidt hammer (L-type)	
	Compass	
	Pocket penetrometer	
	Geological map	
	Geological hammer	
Discontinuity survey (scanline survey)	Tape measure (30 m), scanline datasheets and standard geological equipment	A total of 16, 3 m scanline survey was carried-out
		Measurement is taken along 3 orthogonal directions to better quantify the discontinuity in a 3D space
Sample collection	Plastic bags, wheelbarrow and geological hammer	Loose and easy to remove block samples of varying sizes were picked out from the cliff face maintaining necessary safety

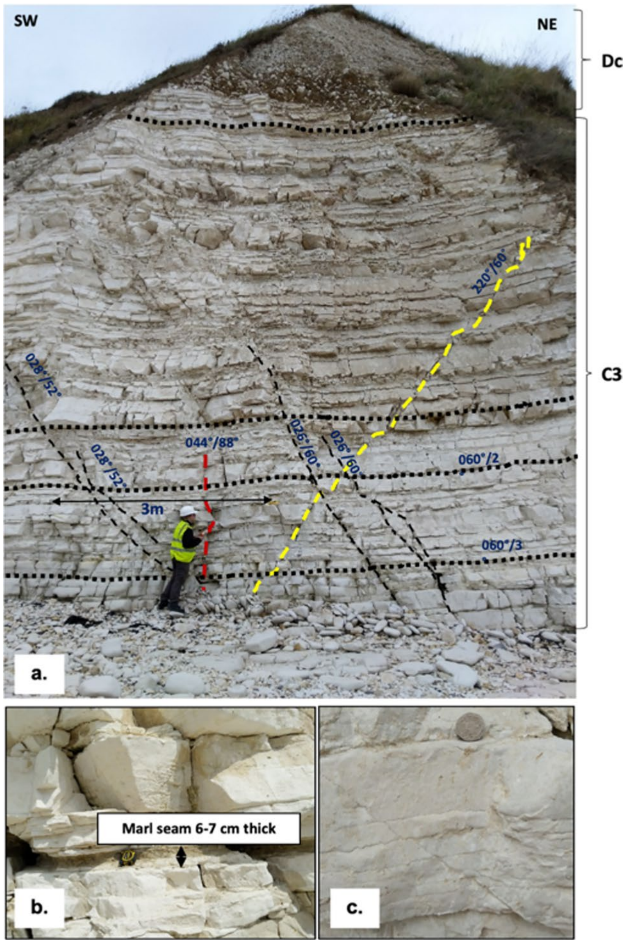

Fig. 2 **a** Chalk cliff at Danes Dyke with discontinuities sets highlighted, **b** Thick marl section; **c** Stylolites cuttings

jointed/fractured blocky rock mass. Apart from low persistent random oriented joints, two major high persistent faults can be identified in the field (Fig. 2a), cutting across the sub-horizontal beds of varying thickness. The spacing between these faults was observed to be non-consistent. The fault surface is smooth to slickensides with either clean or clay and small crushed fragments of Chalk occurring as infillings. The fragmental infilling is observed to be intact, maybe due to recrystallization between the fragments (Fig. 2b). On the other hand, the joints are tight and mostly clean or covered with a coating of powdery Chalk. The stylolites (Fig. 2c) were observed in Chalk blocks; these features can be easily recognized in the field as they show a rough surface with clay smear along the contact surface.

Schmidt hammer showed a value of 40 MPa along the wall surface. New hammer pic and 150 mm nail observed to have less than 6 mm penetration thus defining the very high-density of the Chalk. The sub-horizontal beds (60°/3°–4°) are separated by thin marl seams (1–6 cm wide), which are observed to be mostly loose and solidified at few horizons.

The cliff section can be subdivided into two significant grades of Chalk at this site. The following description of Chalk is per CIRIA PR11 (Lord et al. 1994).

1. Structureless CHALK, composed of silty sub-rounded to angular GRAVEL and some cobbles. Gravels are strong, white. Matrix is uncompacted and loose, dark brown. Vegetation present. [Grade Dc]
2. Moderately strong, very high density, white, unstained, blocky CHALK. Bedding discontinuity (060°/03°), medium spaced (10, 96, 280), open and infilled with marl (1–2 cm thick). Conjugate inclined discontinuities (028°/52° and 220°/60°), irregularly spaced, moderately narrow to narrow, clay and small fragmental infilling at places to clean. Random oriented predominantly sub-vertical-inclined joints, closely spaced, predominantly clean. Presence of stylolites. Thick marl seam (6–7 cm) present near the base. [Flamborough Chalk, very high density, Grade C5 (horizontal discontinuity), Grade C3 (vertical discontinuity)]

Two block samples of size $30 \times 30 \times 30$ cm^3 are picked for lab testing to determine the tensile and uniaxial compressive strength. Four in-situ moisture content samples are picked from the cliff face and sealed in plastic bags later transferred in the fridge till the testing. Irregular block samples of the size between 2 and 7 cm are also collected for point load testing.

3.1.2 Site 2: Sewerby Beach

Flintless Sewerby member of the Flamborough Chalk formation is exposed at Sewerby Beach, a very fine-grained and highly jointed/fractured blocky rock mass. Three major faults are observed cutting across the formation apart from low persistence random joints and horizontal bedding planes. The rock blocks' size was observed to decrease from the base towards the top of the cliff face (Fig. 3a). The Chalk is overlain by glacial-fluvial till deposit of variable thickness (Fig. 3b–d). The overall spacing of the bedding planes decreases towards the top of the cliff.

Schmidt hammer recorded a strength of 33 MPa. New hammer pic and 150 mm nail observed to have less than 6 mm penetration; thus, defining very high-high density Chalk.

Chalk shown in Fig. 3 can be subdivided into two units based on the rock mass observed. According to CIRIA Chalk classification, these two units can be further described as follows:

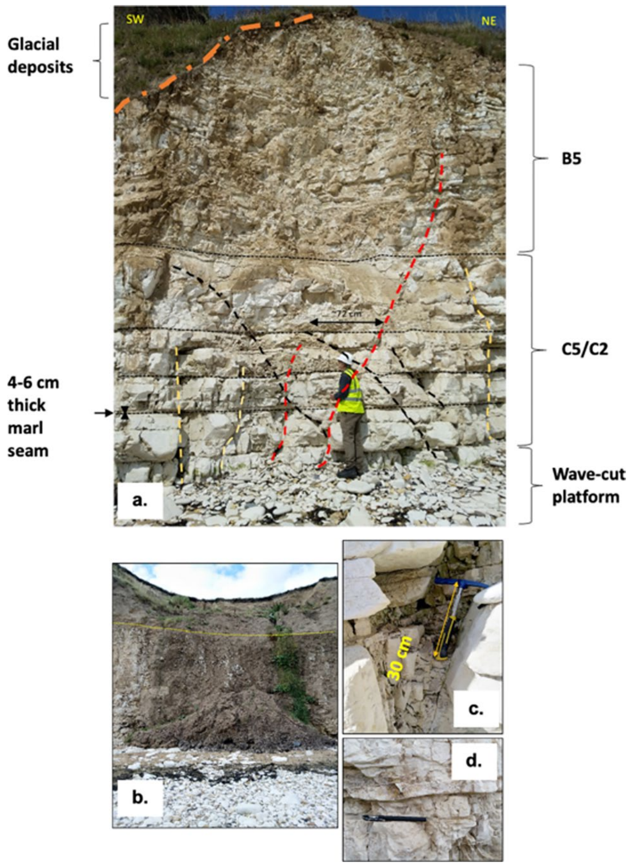

Fig. 3 **a** Chalk cliff at Sewerby Beach with discontinuities sets highlighted, **b** Boundary between Chalk and Till, **c** Fault infilling with fragmental material, well cemented; **d** Thin Marl seam at Sewerby Beach

1. Medium-strong, high-density white, yellow–brown stained at places, flintless CHALK. Bedding fractures (213°/2°–4°), medium-spaced (150/300/650), marl-infilled, moderately wide, grey light and dark coloured. Random oriented sub-vertical-inclined joints predominantly, closely spaced (20/280/640), generally infilled (0/2/60) with clay or clean. Prominent three sets of faults at 238°/70°, 40°/80° and 89°, moderately wide, clean. Slight yellow–brown staining and black specks at random places. [Flamborough formation, high density, Grade C5 (horizontal fractures), Grade C2 (vertical fractures)]
2. Medium-strong, high-density white, yellow–brown stained at places, flintless CHALK. Bedding fractures (almost horizontal), thinly spaced clean or infilled, tight. Random oriented sub-vertical-inclined joints predominantly, very closely spaced, tight, majorly clean. Slight yellow–brown staining and black specks at random places. [Flamborough formation, high density, Grade B5]

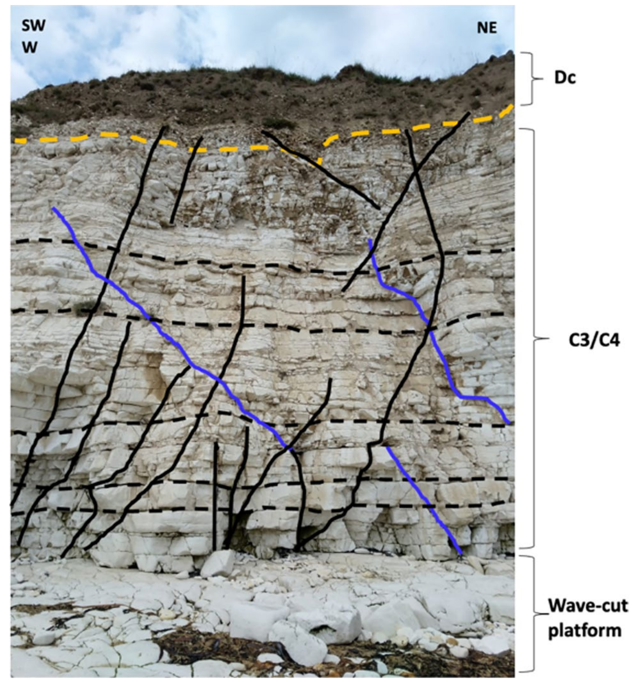

Fig. 4 Chalk cliff at South Landings with discontinuity sets highlighted

For in situ moisture content, samples are picked from the cliff face. Irregular block samples of the size range 2–7 cm are also collected for point load testing.

3.1.3 Site 3: South Landings

Flintless Flamborough Chalk formation is exposed at South Landings, a very fine-grained and highly jointed/fractured blocky rock mass, as shown in Fig. 4. Two major inclined conjugate sets of faults (200°/80° and 65°–70° dipping in NE direction) are observed cutting across the horizontal bedding sets (270–280°/1°–2°) apart from low persistence random joints (Fig. 4). A few cm thick marl seams separate the bedding units. The thickness of these units is highly variable, but broadly, a decrease in the thickness of bedding units is observed towards the top of the cliff. A glacial-fluvial overlies the Chalk till deposit of variable thickness (5–6 m).

The discontinuity surface along the joints is observed to be very narrow to tight and clean with powder Chalk coating. On the other hand, the faults have a narrow aperture in general (6–20 mm wide), either clean or showing clay infillings. Fault (210°/80°) showed small-sized fragmental infilling (gouge). As observed at Danes Dyke these fragmental materials are remarkably intact, maybe due to recrystallisation after the upliftment.

Schmidt hammer showed a value of 42 MPa along the wall surface. Field Intact Dry Density (IDD) tests define a very high-density Chalk. The cliff section can be majorly grouped into two major grades of Chalk based on the CIRIA Chalk classification, CIRIA PR11 (Lord et al. 1994).

1. Structureless CHALK, composed of silty sub-rounded to angular GRAVEL and some cobbles. Gravels are strong, white. Matrix is uncompacted, dark–light brown. Presence of vegetation. Banding can be seen at the base and top is mostly sand (very high percentage) with remains of Chalk (pebbles and gravel-sized) [Grade Dc].
2. Moderately strong, high density, white, unstained, blocky flintless CHALK. Bedding discontinuity (280°/01°–02°), closely to medium spaced (80, 216, 600), open and infilled with marl (few mm to cm thick). Conjugate inclined discontinuities (200°/80° and 55°–70° dipping in NE direction), irregularly spaced, narrow to extremely narrow, clean at most places to clay infilled, Fault (210°/82°) showed small-sized fragmental infilling (fault gouge). Random oriented sub-vertical-inclined joints predominately, closely spaced, predominately clean, presence of stylolites. [Flamborough Chalk, high density, Grade C3 (horizontal discontinuity), Grade C4 (vertical discontinuity)].

3.1.4 Site 4: Selwicks Bay

Burnham formation is exposed at the south-east end of Selwicks bay, whereas the flintless Flamborough formation is exposed on the bay's northwest section. A fracture zone separates the two; the Chalk beds of Flamborough formation are overturned and tilted, nearly dipping vertically. These are seen to be resting over Burnham formation. The Burnham formation's Chalk is observed to be hard and intact, where the cliff slope is dipping nearly vertical. Due to wave action formation, sea stacks and arch are observed around the bay

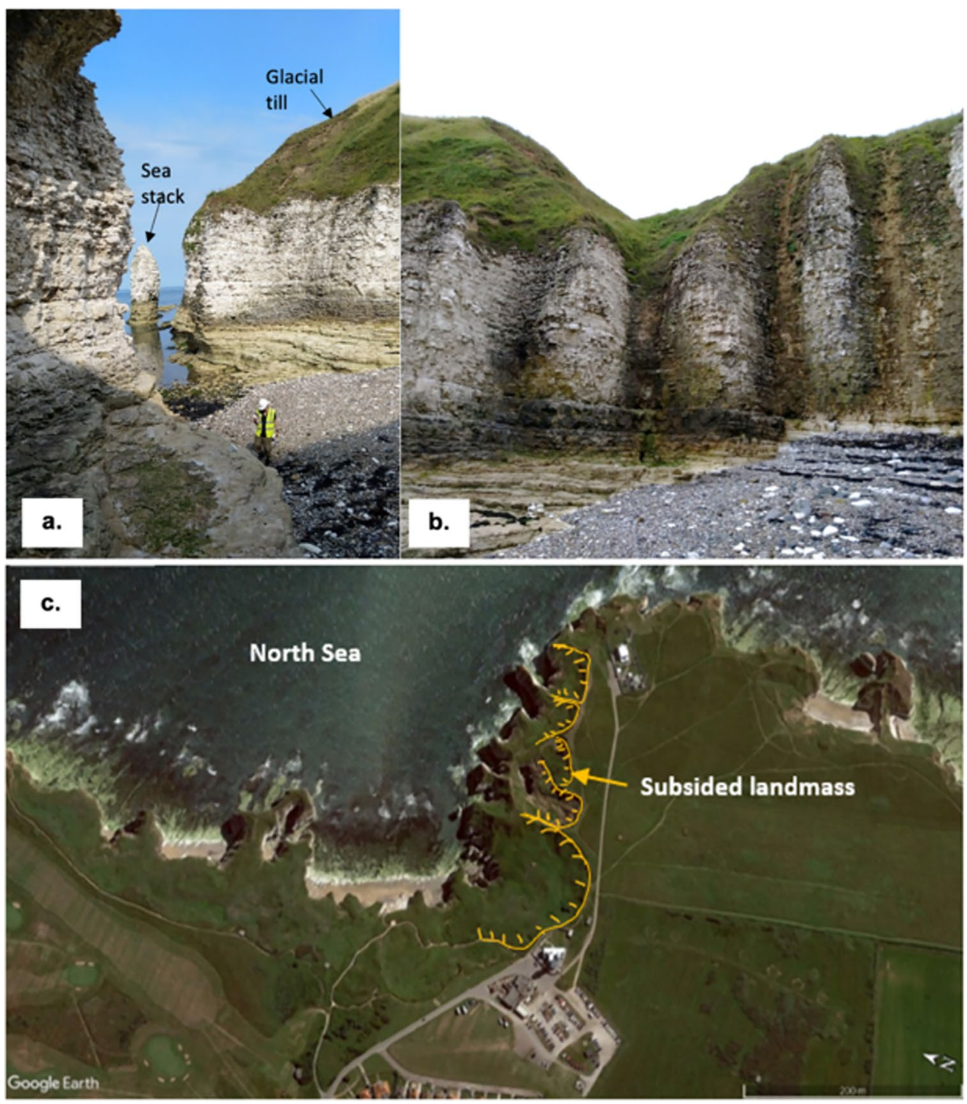

Fig. 5 **a** Geomorphological features at Selwicks Bay formed due to wave action and dissolution; and, **b** Satellite Image showing the effect of the subsidence (source: Google Earth)

(Fig. 5a). A high dissolution rate of Chalk has caused subsidence of the ground (Fig. 5b). The erosion is found to be more prominent along the weak planes of discontinuities, forming narrow vertical arches.

Majorly two sets of faults (000°/80° and 150°/70°) are observed cutting across the Burnham formation (Fig. 6a). The density of these inclined conjugate faults is very low compared to the fault frequency observed in the previous sites' Flamborough formation. The cliff shows a dip of nearly 90°. Though the high density of very low persistence, tight to very tight aperture and predominantly clean random oriented joints are observed throughout the cliff face. The discontinuity surface of these joints is rough to very rough, while faults show a smoother surface. The thickness of beds appears to be highly variable with marl infillings. The tabular flint layers demonstrate similar dip and dip direction as bedding planes (178°/2°–3°) (Fig. 6b, c).

Schmidt hammer records the strength of the Chalk in the range of 35–50 MPa. The Burnham Chalk exposed at

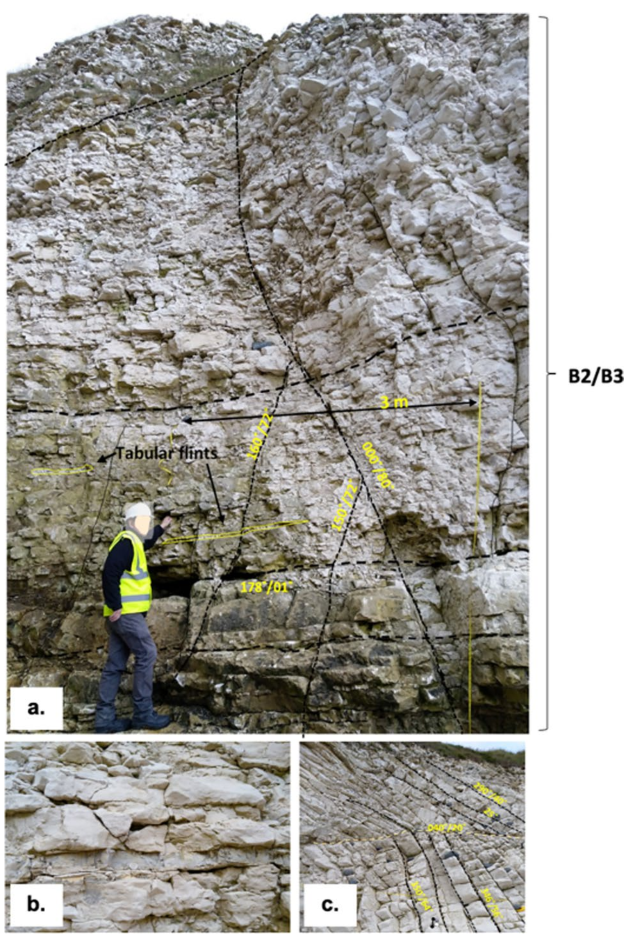

Fig. 6 **a** Chalk cliff (Burnham Foundation) at Selwicks Bay with discontinuities sets highlighted, **b** Tabular flint layer; and, **c** Fracture zone, overturned Flamborough beds

Selwicks Bay can be grouped into a single rock mass based on the CIRIA Chalk classification scheme.

1. Strong, very high density, white, green-black stained, blocky CHALK. Bedding discontinuity (178°/01°), medium spaced (50, 160, 400), open and infilled with marl and Chalk fragments (1–2 cm thick). Conjugate inclined discontinuities (000°/80° and 150°/70°), very widely spaced, moderately narrow, predominantly clean. Random oriented sub-vertical inclined joints, closely spaced, tight, clean. Discontinuous flint layers observed dipping like bedding direction. [Burnham Chalk, very high density, Grade B2 (horizontal discontinuity), Grade B3 (vertical discontinuity)]

3.1.5 Field Work Observations

The orientation and distribution of discontinuities (joints/faults) are observed to be wide-ranging. Figure 7 shows the stereographic projection (pole-plot) of discontinuities from different sites. A high concentration of discontinuities in the N–E and S–W quadrants is inferred based on the comparison. Based on the above observation and weighted average, three main discontinuity sets are identified in the Flamborough formation (Fig. 7b, c). The orientation of discontinuities at Selwicks bay (Burnham formation) is observed dissimilar compared to other sites. The latter might be due to a different (a) time of deposition as Burnham is older than Flamborough formation, (b) tectonic history and/or (c) local tectonic activity at Selwicks Bay. Also, the presence of a major fault at Selwicks Bay plays an important role (Fay-Gomord et al. 2018).

The nature and condition of discontinuities were further analysed in detail, outlined below. High variability in the discontinuity spacing throughout the study area is observed along with the scanline profiles (Fig. 8). However, most of the spacing lies in the range of 10–30 cm. Figure 8 shows the spacing between two discontinuities along the scanlines irrespective of their sets.

The type of discontinuities at the site was grouped into either fault, bedding planes or joints. Histogram plots of aperture, infillings' nature, and persistence for each site are presented below in Figs. 9, 10 and 11. In general, joints show tight to narrow aperture with clean or clay infillings. Marl beds infill the bedding planes with a thickness from a few millimetres to centimetres. The faults show variable aperture infilled by either clay or small-sized fragmental material (fault-gouge). Clean faults are also recorded during the scanline survey. Less than a metre persistence is observed for joints throughout the site, while faults showed a very high persistence. The discontinuous surface shows

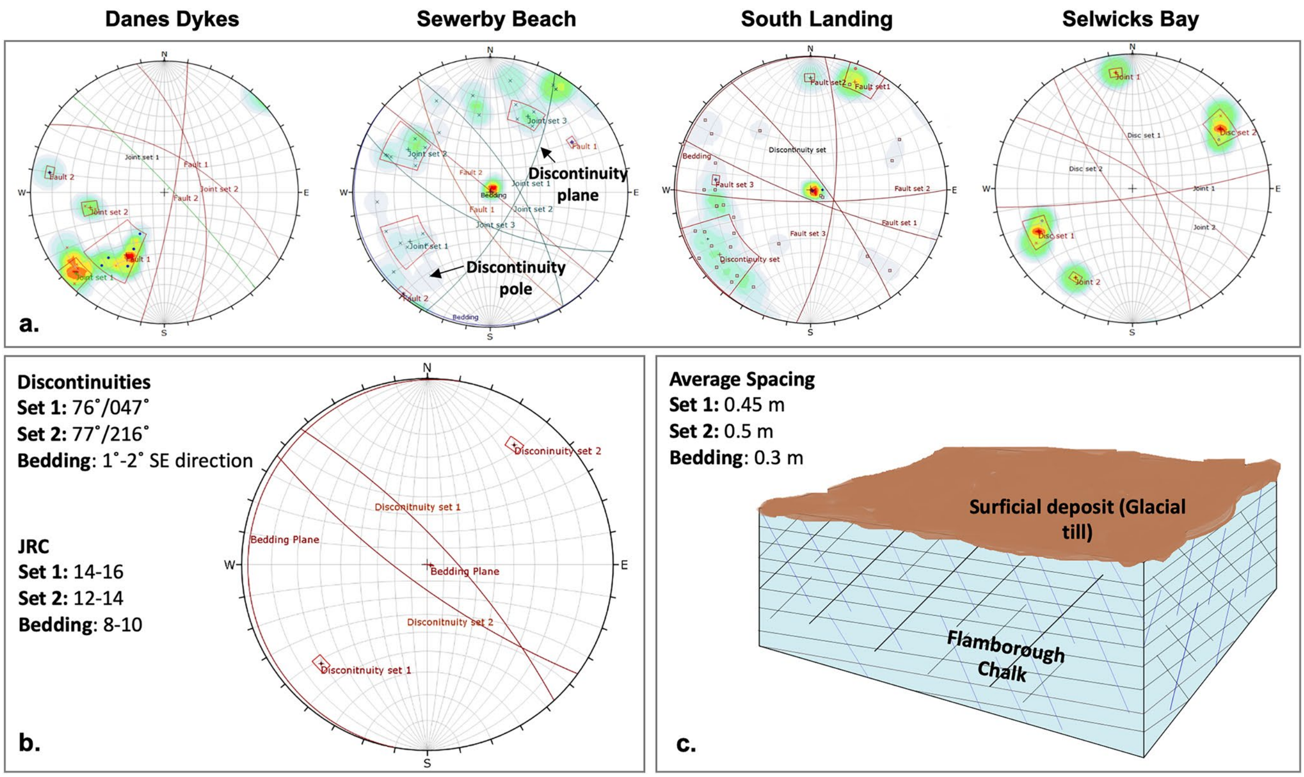

Fig. 7 **a** Stereographic projection of discontinuities from each site using Dips (Rocsience), **b** representation of discontinuities sets stereographic plot; **c** 3D block model (not to scale)

roughness being smooth in case of faults for bedding planes and joints. No major surface staining is observed.

It should be stated that these observations served as input in the following sections. A conservative approach considering lower range values was adopted to characterise the Chalk mass.

4 Laboratory Testing

A series of laboratory testing is undertaken to determine the geotechnical properties of Northern Province Chalk. The different Chalk units are tested for intact dry density (IDD), in-situ moisture content, compressive (UCS and point load) and tensile strength (Fig. 12). Moreover, a comparative analysis of the values obtained is done to highlight further the overall significant difference in these Chalk formations' mechanical strength. All the tests are carried out following the International Society for Rock Mechanics (ISRM: 1974–2006) standards guidelines. Table 4 summarises the test results carried on samples from each site.

4.1 In Situ Moisture Content

The Chalk shows high variability in water content (4–40%; CIRIA C574 2002) and porosity. In addition, a very rapid evaporation rate is noted in Chalk samples once it is sampled and sealed. Thus special care is taken while sampling. Smaller dimension Chalk samples are collected directly from the cliff face from all the site locations. The samples are immediately sealed in plastic bags and later transferred to cold storage to retain moisture content as close to the natural state. Chalk lumps for each site are weighed before and after drying. The water content from each site is shown in Table 4.

4.2 Intact Dry Density (IDD) and Porosity

There is a direct correlation between intact dry density and other index tests, which can be further used to derive other parameters. Thus, in most geological engineering scenarios, only the density and saturated moisture contents are reported and based on these, different index values have been estimated. The saturation and calliper method is adopted to calculate the Chalk samples' density, where the bulk volume is computed using calliper measurements and pore volume

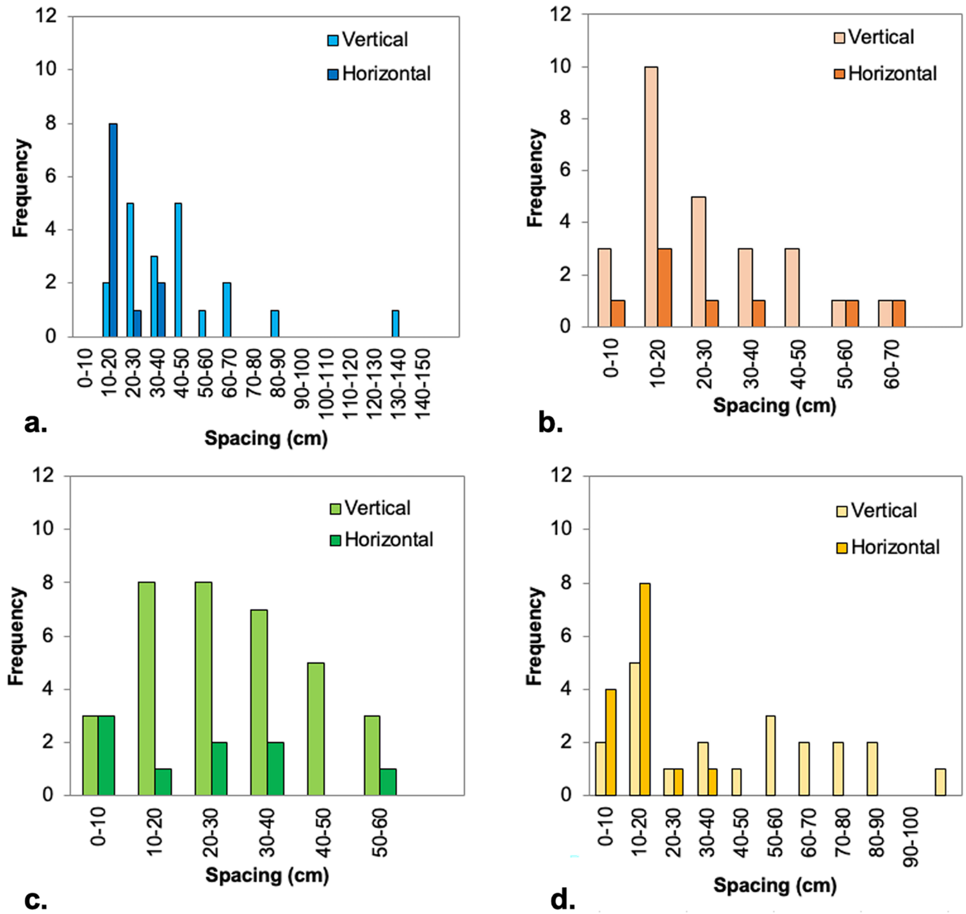

Fig. 8 Distribution of discontinuities spacing at: **a** Danes Dykes, **b** Sewerby Beach, **c** South Landings, **d** Selwicks Burnham

by water saturation (Fig. 13). Three saw-cut Chalk samples from each site conforming closely to a cube for density determination. The average density and porosity values for each area are shown in Table 4.

4.3 Point Load Test

Point Load Testing is used to characterise the strength of the material. An irregular lump or block test is carried out on at least ten Chalk samples collected from each site, with the exception only three samples are tested from Flamborough formation at Selwicks Bay. The samples are further trimmed using saw-cutting such that D/W is close to 1.0. Since the samples get wet during the cutting, they are air-dried for a couple of days (1–2 days) before the testing, as saturation is seen to cause a significant reduction in strength. The observed load (P) is corrected for instrumental errors. As samples of different dimensions are tested, a size correction is applied to the calculated values to determine a Point load strength index $I(50)$ of a sample when De = 50 mm using Eqs. 1 and 2. Samples from Flamborough formation (Danes dyke, Sewerby and South Landing) show the presence of stylolites, which acted as a weak plane (Fig. 12a). In most cases, a very low value is recorded when the loading direction is in-plane to the stylolites and a high value when perpendicular (Fig. 14).

$$F = \left(\frac{De}{50}\right)^{0.45} \tag{1}$$

$$Is(50) = F * Is \tag{2}$$

where F—size factor F, De—equivalent core diameter (50 mm), $Is_{(50)}$—Corrected Point Load Strength Index, Is—Point Load Index.

A lower Point load index value for Burnham formation can be associated with high moisture content. Similarly, a low value is observed for samples from Sewerby Beach. The average Point load index is summarised in Table 4.

4.4 Unconfined Compressive Strength (UCS)

UCS is a widely used index test to measure and characterise the rock's strength. The deformation is measured using strain gauges placed along the axial and circumferential direction and two external transducers measuring the axial displacements. Circular cylinders of NX core (54 mm) size with a diameter to length ratio of 2.5–3 are used for the testing. A

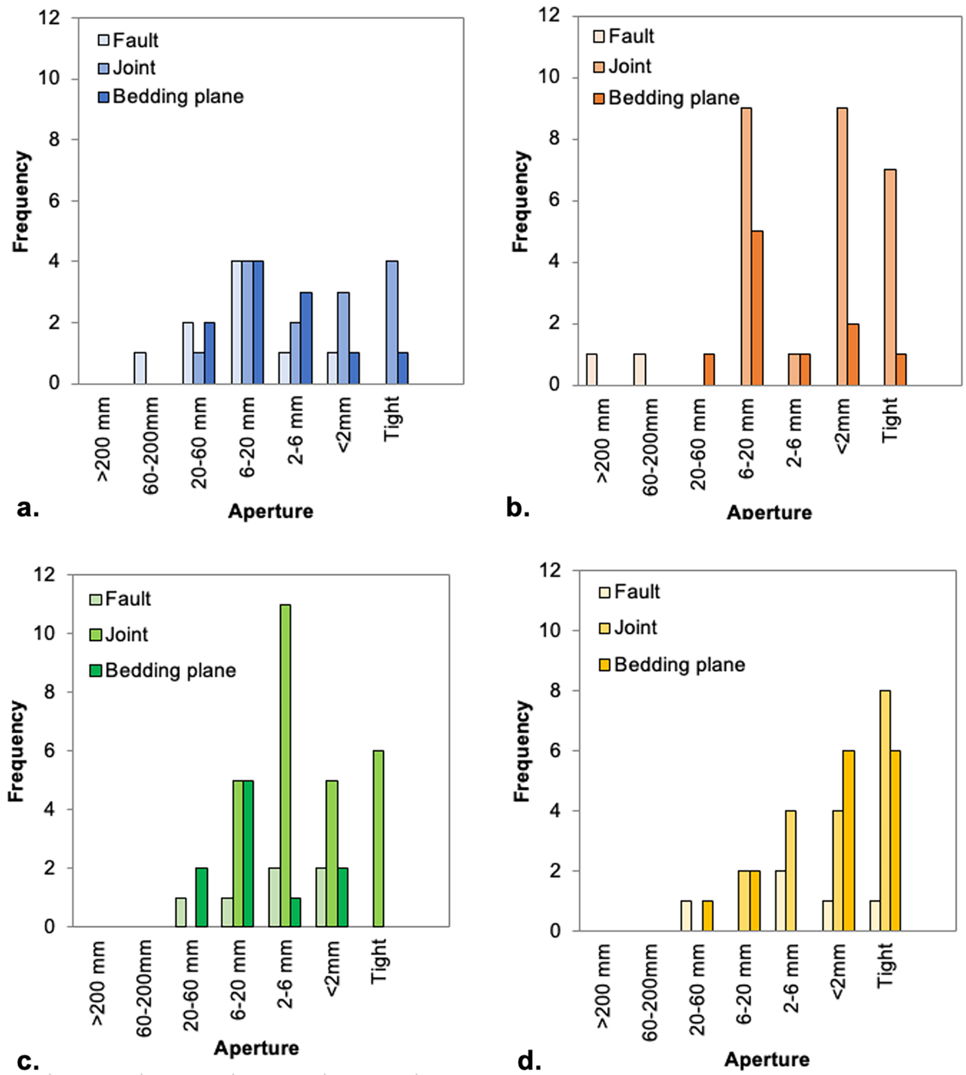

Fig. 9 Distribution of discontinuities aperture at: **a** Danes Dykes, **b** Sewerby Beach, **c** South Landings, **d** Selwicks Burnham

total of 10 samples are tested, out of which seven samples are from the Flamborough formation of Danes Dyke, two are from the Selwicks Bay, and one sample is from the Burnham formation of Selwicks Bay. A displacement rate of 0.2 mm/min is set according to ISRM (1981) and the moisture content of each sample is recorded at the time of testing.

The complete stress–strain plot recorded from the two strain gauges determines Young's modulus and Poisson's ratio at 50% of UCS strength. The presence of stylolites is seen in the sample collected from Danes Dyke close to the edges, forming a wedge (Fig. 12b). These weak planes further act as failure surfaces when loaded uniaxially. The failure mode is majorly tensional, but shear failure is observed along the stylolites. In samples where stylolites are perpendicular to the loading, tensional failure dominates while tearing along stylolites observed (Fig. 12b). Average UCS, Young's Modulus and Poisson's ratio are summarised in Table 4; outlier values are disregarded. From the above, it can be inferred that Burnham formation is comparatively stronger than Flamborough, with higher Young's Modulus and Poisson's ratio value. Strain values are rejected due to faulty gauges. Figure 15 shows the stress–strain plot for all Flamborough samples.

4.5 Brazilian Test

Chalk's tensile strength is determined indirectly through the Brazilian test, based on the principle that under the biaxial stress field sample fails at its uniaxial tensile strength. NX core (54 mm) sized samples are prepared with thickness almost equal to their radius. Twenty-four samples were tested, out of which eighteen samples were from the Flamborough formation of Danes Dyke, five samples from Burnham formation and one from the Flamborough formation exposed at Selwicks Bay. A constant stress rate is set at 15 N/s for all the tests. Both time to failure and maximum failure load is recorded, and the test results are shown in Table 4.

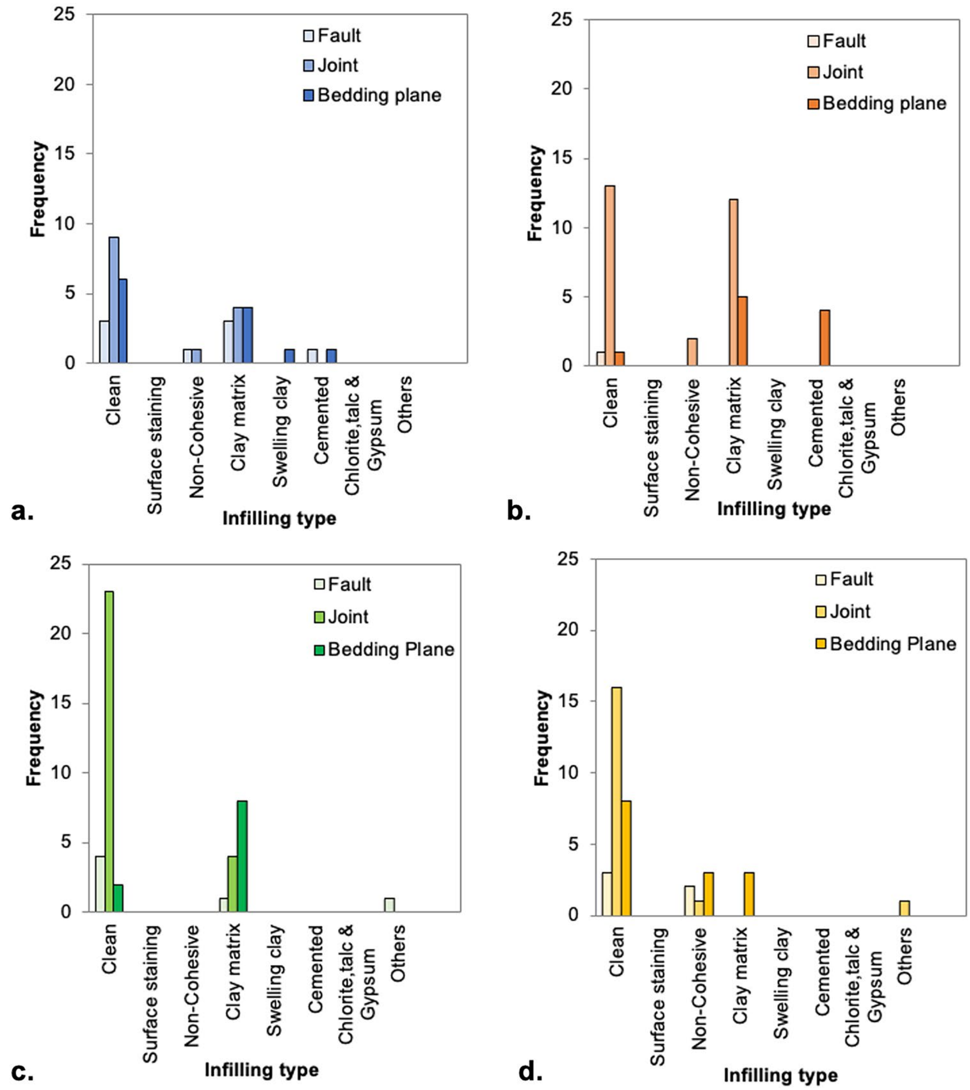

Fig. 10 Distribution of discontinuities Infilling type at: **a** Danes Dykes, **b** Sewerby Beach, **c** South Landings, **d** Selwicks Burnham

The stylolites cutting across the thickness are observed in the Flamborough formation of Danes Dyke and Selwicks Bay samples. An attempt is made to characterise the effect of these stylolites when aligned at different angles to loading. In Fig. 12c, the red dashed line on the left shows the surface of failure, while the black dashed line highlights stylolites in the sample collected from Danes Dyke. A failed Burnham sample on the right is also shown in Fig. 12c.

4.6 Test Result Discussion

Overall, Northern Province Chalk is observed to be relatively stronger as compared to Southern province Chalk. Low moisture content (< 10%) is reported when compared to data from the literature [~ 25% (8–36%)], which may be attributed to loss of moisture before testing. Thus, better methods need to be adopted to preserve natural moisture content (i.e. paraffin wax coating), which was not the scope of this research presented, but further work is suggested to be done to propose a new method for preparing and handling Chalk samples as the existing ones cannot cover this multi-facet behaviour of the Chalk.

Density results are very consistent and reliable when compared to previous studies. An average of 1.86 Mg/m^3 and 2.02 Mg/m^3 for Flamborough and Burnham formation are reported. Bell (1999) reported densities higher than 1.8 Mg/m^3 for Northern Province and ~ 1.5–1.7 Mg/m^3 for the Southern Province Chalk. Porosity is observed to be quite variable.

Strength index tests showed Burnham formation to be stronger than the Flamborough Chalk unit, shown in Table 5 and Fig. 16.

In summary, the English Chalk investigated is comparatively stronger than other Chalk found in outside the UK.

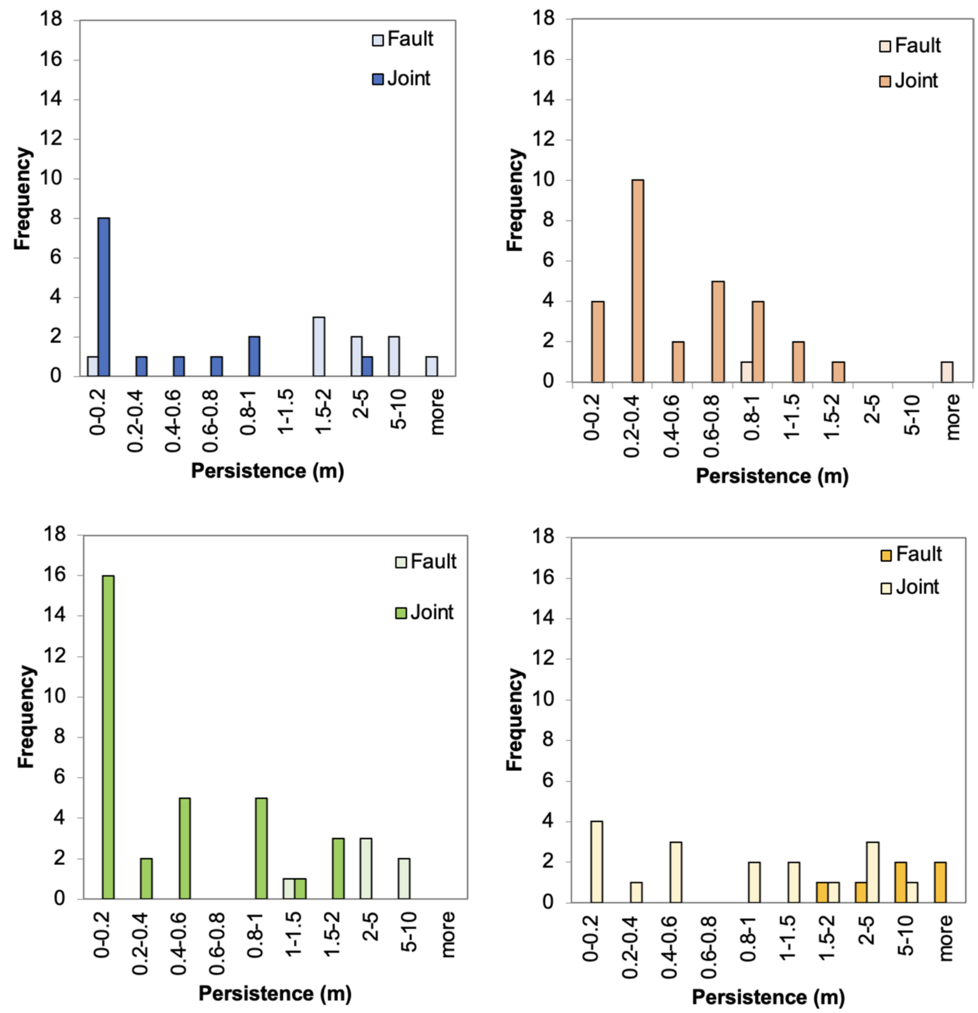

Fig. 11 Distribution of discontinuities persistence at **a** Danes Dykes, **b** Sewerby Beach, **c** South Landings, and **d** Selwicks Burnham

The variability in results can be due to several reasons, such as:

- moisture content: the amount of moisture content is observed to have a significant role in overall strength. More than 50% loss of strength is noted when samples are saturated for a week (Bell 1999). Since samples are partially wet during cutting, thus alteration of strength is expected.
- presence of stylolites: the Flamborough formation shows stylolites' presence, thus affecting the strength of the Chalk. Stylolites are observed to act as a weak plane even though it has high asperities. The sample failed along with them when loaded (primarily dependent on loading direction).
- presence of calcite veins: the higher strength of the Northern Province Chalk than Southern Chalk can be explained by the later stage localised tectonism and a higher rate of recrystallisation and redeposition (solution and precipitation) of calcium carbonate crystals, producing a hard, stronger unit.

5 Rock Mass Classification

The application of empirical rock mass classification systems for the classification of Chalk generally gives unsatisfactory results as most of the systems are developed for jointed rock masses, where discontinuities are well developed and govern the overall behaviour of the rock mass. On the contrary, Chalk is mainly governed by intact rock properties and, to a lesser extent, by the presence of joints.

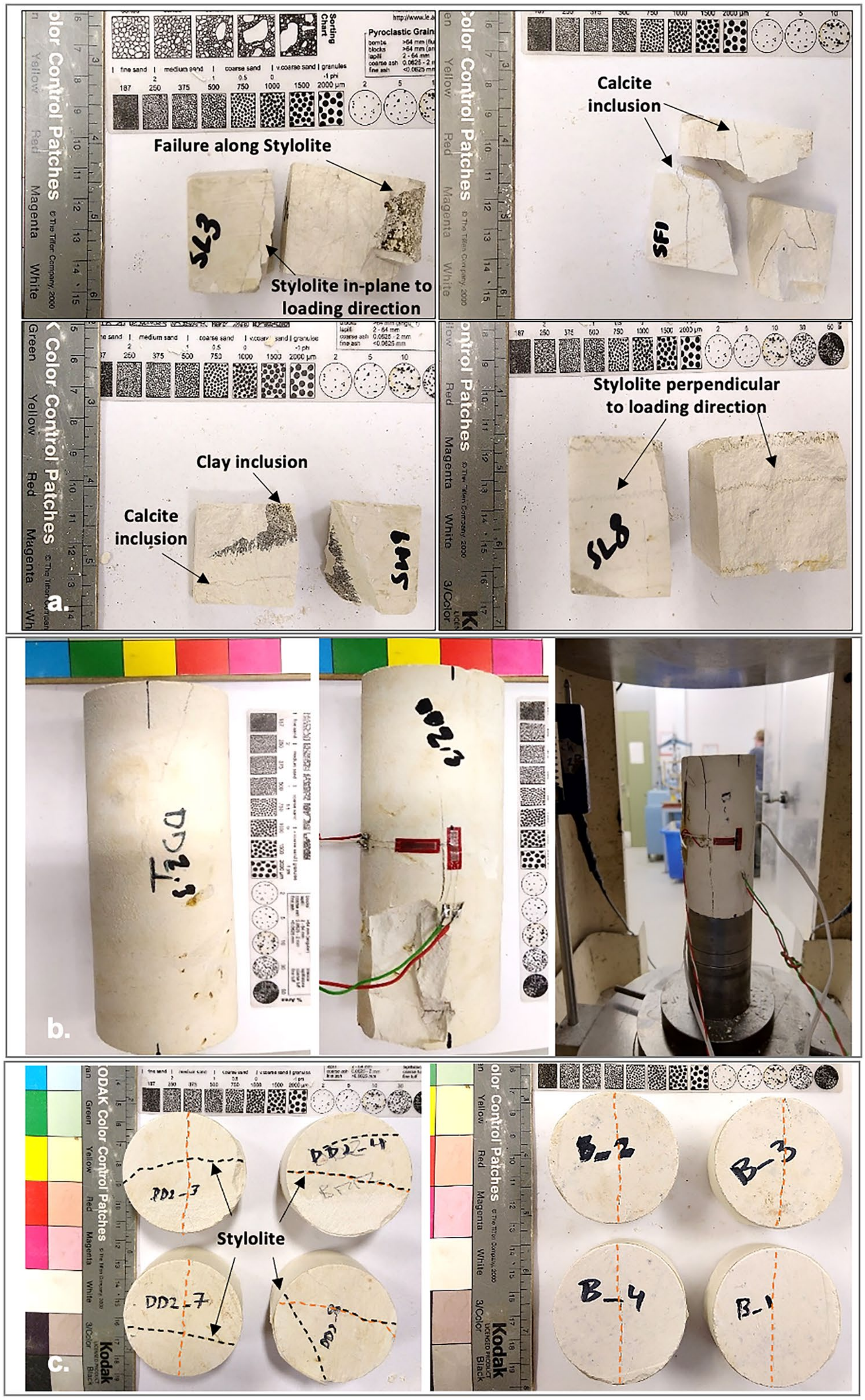

Fig. 12 **a** Point load test samples after testing from sites Danes Dyke (top left), Sewerby Beach (top right), South Landing (bottom left) and Selwicks Burnham (bottom right), **b** UCS testing in Flamborough samples from Danes Dykes; and, **c** Brazilian test samples from Danes Dyke (left) and Selwicks Bay (right). Stylolites and failure surface highlighted with black and red-dashed line

RQD has been used as an index in the various rock mass classifications for tunnelling in rock (e.g. Barton et al. 1974; Bieniawski 1973; Hoek and Brown 1980; Sissins and Paraskevopoulou 2021) and is applied to the Chalk for all the case studies reported by Mortimore (2012). However, in some geological settings, such as the A26 Cuilfail

Table 4 Lab testing results

Location	Moisture content (%) (after 24 h)	Average density (Mg/m^3)	Average porosity (%)	Mean $Is_{(50)}$ (MPa)	Moisture content (%)	UCS (MPa)	Young's Modulus (GPa)	Poisson's ratio	Min. tensile strength (MPa)	Avg. tensile strength (MPa)	Max. tensile strength (MPa)
Danes Dyke-Flamborough Formation	4.45	1.978	14.9	1.23	0.79	19.4	14.21	0.223	0.848	1.523	2.07
Sewerby Beach-Flamborough Formation	1.94	1.849	21.7	1.55	4.92	23.52	11	0.22	–	2.21	–
Sewerby Beach-Bunham Formation	–	–	–	1.78	5.26	–	–	–	–	–	–
South Landings-Flamborough Formation	7.56	1.89	15.6	1.83	1.32	37.1	28	0.245	2.43	2.903	3.59
Selwicks-Burnham Formation	6.9	2.02	12.9	0.81	6.31	–	–	–	–	–	–

Tunnel at Lewes, the high RQD values created by widely spaced joints give false confidence in the tightness of the rock mass. For such settings, the alternative method of measuring RQD (Priest and Hudson 1976) is used in the tunnelling rock quality assessments giving a more realistic estimate of rock conditions for support requirements. Mortimore (2012) states that factors that needed to be included in rock mass classification were fracture style, orientation and general geological setting (i.e. a stress relief situation parallel to a river cliff).

The following systems have been applied for the classification of Chalk: (a) RQD (Deere and Miller 1966), (b) RMR (Bieniawski 1973), (c) ARMR (Saroglou et al. 2018), (d) RMQR (Ayden et al. 2013) and (e) GSI (Hoek and Marinos 2000). Table 6 summarises the results from different classification systems applied to the studied Chalk types. Overall, Chalk is classified as fair to medium quality rock mass showing a slightly to moderate anisotropic nature.

RQD classification is considered appropriate to quantify the intensity of the jointing, but in the case of Chalk, it fails to depict the actual rock mass condition. Several authors highlighted the limitations of RQD concerning orientation-dependence. Based on ARMR, the Chalk is classified as slightly to moderate anisotropic. RMQR aims to assess better the physical state of the rock mass (Aydan et al. 2013) and shows better applicability in weak rocks. GSI resulted in an average value of 60 for Flamborough formation and 65 for Burnham formation. The difference can be attributed to the relative age and degree of diagenesis. It should be noted that GSI should not be applied if Chalk does not have discontinuities and the strength is relatively low (uniaxial compressive strength less than 5 MPa), in which case the classification is not reliable. In the cases where Chalk has greater strength and is intersected by discontinuities, the GSI can be cautiously applied and be used as an input in the Hoek–Brown criterion to estimate the strength of the rock mass. Table 6 summarises the results from different classification systems applied to the studied Chalk types.

6 Conclusions

The presented work quantifies the geomechanical behaviour of the Northern province Chalk, and Flamborough and Burnham formations are evaluated in detail. All the Chalk units observed in the field are described strictly according to the CIRIA classification system. Chalk stratification is very distinct, and bedding planes are observed to be horizontal (dip $< 2°$–$3°$). Several types of discontinuities, either consistent or random, are observed for simplification and are approximated to 3 major sets. In general,

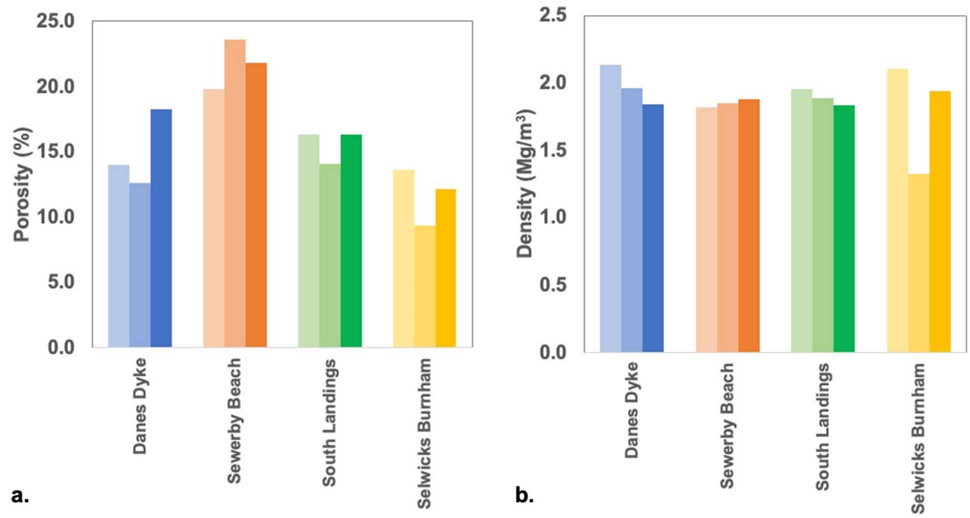

Fig. 13 Density (Mg/m^3) and porosity (%) plot for each site

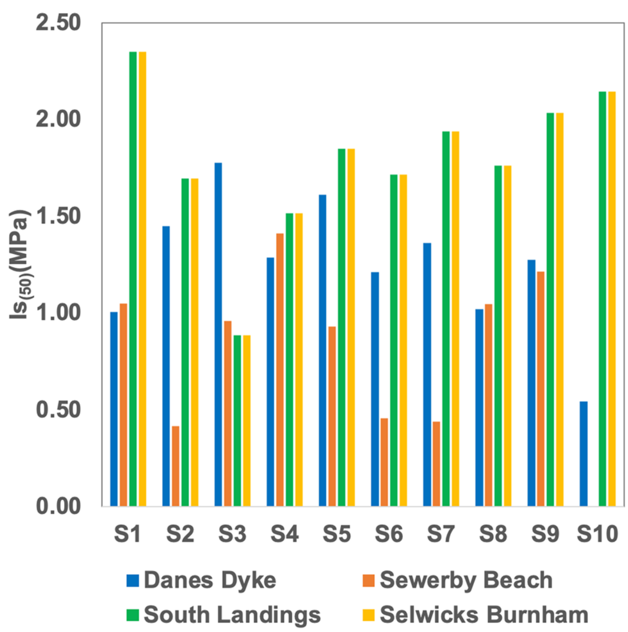

Fig. 14 Point load index values $Is_{(50)}$ for all samples from sites: Danes Dyke, Sewerby Beach, South Landing and Selwicks Burnham

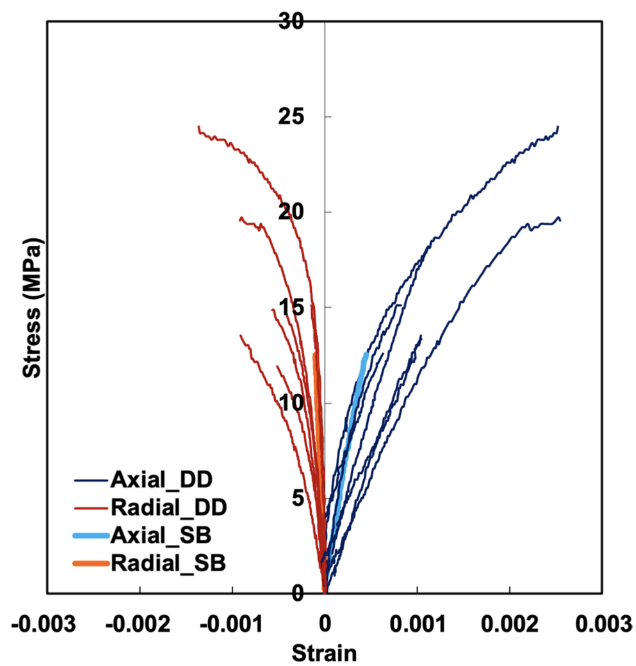

Fig. 15 Stress–strain plot from all the Flamborough formation samples from DD—Danes Dyke and SB—Selwicks Bay

the discontinuity planes are clean, narrow and rough with variable persistence. A 10–20 m thick glacial till deposits overly the Chalk known to restrict the Chalk units' meteoric water infiltration. The movement of glaciers in the past has caused significant weathering and erosion of the Chalk top, disintegrating it into smaller fragments that seemed to be re-worked and sub-rounded in shape. Major faults showed gouge infilling, which has been recemented and observed to be very intact. The marl beds were only limited to the bedding planes. Folding and tilting of beds are seen at Selwicks Bay; this has been associated with late-stage tectonism and reactivation of basement faults. Furthermore, the strong nature of Northern province Chalk

Table 5 Summary and comparison of strength index tests

Strength index test	Laboratory results		Literature review		
	Flamborough Chalk	Burnham Chalk	Southern Province Chalk	Melbourne Chalk	Northern Province Chalk
Point load $Is_{(50)}$ (MPa)	Variable	1.55	0.8–1.2	~1.7	~1.4–1.8
Brazilian tensile strength (MPa)	~2	2.9	<1	2.1	>2
UCS (MPa)	~20	37.1	2–4 (Chalk Marl)	30–50	>25

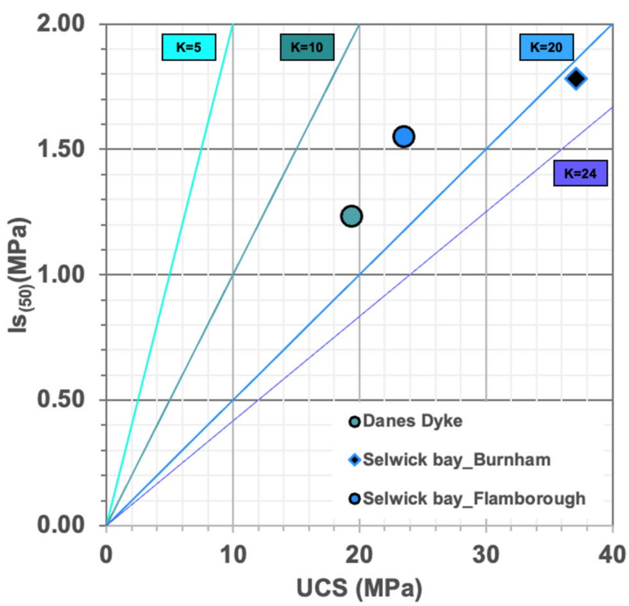

Fig. 16 Strength index tests results

has been explained by pressure solution and Chalk blocks' re-cementation.

As expected, Burnham formation is observed to be comparatively stronger than the Flamborough unit being an older formation thus more intact and compact. Higher density ranges are reported from Burnham formation compared to the Flamborough unit. A similar response is observed during point load, Brazilian-tensile and UCS strength testing. The presence of calcite veins and stylolites, formed due to late-stage tectonism and high overburden stress, is observed to alter samples' strength to a great degree. Chalk showed an average Poisson ratio of 0.2 and Young's modulus of less than 20 GPa.

Based on the review of rock mass classification systems used for Chalk, it can be concluded that the Q and RMR classification methods are rather conservative and should be used with caution for Chalk rock masses. Based on the cases studied in the present paper using the commonly used classification systems, Chalk is classified as fair to medium quality rock mass showing a slightly to moderate anisotropic nature. One limitation of the classification systems is that the effect of bedding orientation (anisotropy) and spacing cannot be effectively considered. An alternative approach is to consider an anisotropic rock mass classification, as that proposed by Saroglou et al. (2018).

It is concluded that Chalk behaviour shows a higher dependence on intact strength followed by the effect of discontinuities. Based on the presented assessment for the Northern province Chalk, the main factors that control its behavior are mainly intact rock strength, nature of discontinuities, other geological factors such as presence of weak zones and groundwater conditions.

Table 6 Summary of rock mass classification for studied Chalk

Location	RQD (%)	RMR	ARMR	RMQR	GSI
Sewerby beach	96.75	58–71	57–64	46–51	55–65
Danes dyke	87.33	56–69	57–64	46–51	55–65
South landing	88.64	55–69	54–61	46–51	55–65
Selwicks bay	97.9	71–76	59–66	48	60–70
Rock mass quality/grade	Very good	Good to fair	Slightly to moderate anisotropic	Fair or medium	

Author Contributions CP, CS and AK contributed to the study design; AK and CP contributed to data collection; AK and CP performed data analysis and interpretation; CP, AK and CS wrote and edited the paper.

Funding No funding was received for conducting this study.

Data availability All data presented in this research work and are used and analysed in this study are included in this paper.

Declarations

Conflict of interest The authors declare that they have no conflict of interest regarding the publication of this work.

References

Aydan O, Ulusay R, Tojashiki N (2013) A new rock mass quality rating system: rock mass quality rating (RMQR) and its application to the estimation of geomechanical characteristics of rock masses. Rock Mech Rock Eng 4:1255–1276

Barton N, Lien R, Lunde J (1974) Engineering classification of rock masses for the design of tunnel support. Rock Mech 6(4):189–236

Bell FG (1977) A note on the physical properties of the Chalk. Eng Geol 11:217–225

Bell FG, Culshaw MG (1999) A review of selected engineering geological characteristics of English Chalk. J Eng Geol 54(1990):237–269

Bell FG, Cripps JC, Edmonds CN, Culshaw MG (1990) Chalk fabric and its relation to certain geotechnical properties. In: Burland JB, Mortimore RN, Roberts LD, Jones DL, Corbett BO (eds) Chalk. Proceedings of the international chalk symposium, Brighton polytechnic. Thomas Telford, London, pp 187–194

Bieniawski ZT (1973) Engineering classification of jointed rock masses. Int J Rock Mech Min Sci 15(12):1

CIRIA C574 (2002) Engineering in Chalk

Clayton CRI (1983) The influence of diagenesison some index properties of Chalk in England. Geotechnique 33(3):225–241

Deere D, Miller R (1966) Engineering classification and index properties of intact rock. Tech Report No. AFWL-Tr-65-116, USAF Weapons Lab, Kirtland Air Force Base

Fay-Gomord O et al (2018) Understanding fluid flow during tectonic reactivation: an example from the flamborough head chalk outcrop (UK). Geofluids 2018:17

Flexer A, Honigsrten A (1989) Geology, geotechnical properties and exploitation of Chalk in Israel—an overview. In: Proceedings of the international Chalk symposium, Brighton, pp 63–70

Harris CS, Hart MB, Varley PM, Warren CD (1996) Engineering geology of the channel tunnel. Thomas Telford, London

Higginbottom IE (1965) The engineering geology of Chalk. Proc Symp Chalk Earthw Found Inst Civ Eng 1965:1–13

Hoek E, Brown ET (1980) Empirical strength criterion for rock masses. J Geotech Eng Div ASCE 106(9):1013–1035

Hoek E, Marinos PG (2000) Predicting tunnel squeezing problems in weak heterogeneous rock masses. Tunnels Tunnel Int 132(11):45–51

Hutchinson JN (1972) In stress strain behaviour of soils, field and laboratory studies of a fall in upper Chalk cliffs at Joss Bay, Isle of Thanet, ed Parry R. H. G. (Foulis Henley on Thames), pp 692–706

ISRM (2006) Ulusay R, Hudson JA (2007) The complete ISRM suggested methods for rock characterisation, testing and monitoring: 1974–2006

Lake LM (1990) Underground excavations in chalk. Chalk. In: Proc. int. chalk symp., Brighton polytechnic, 4–7 September, 1989, Thomas Telford, London (1990), pp 461-467

Lautridou JP, Letavernier G, Lindé K, Etlicher B, Ozouf JC (1986) Porosity and frost susceptibility of flints and chalk: laboratory experiments, comparison of scientific study of Flint and Chert. Cambridge University Press, Cambridge, pp 269–282

Lawrence JA, Mortimore RN, Stone KJ, Busby JP (2013) Sea saltwater weakening of chalk and the impact on cliff instability. Geomorphology 191:14–22

Lord JA, Twine D, Yeow H (1994) Foundations in chalk report PR11. CIRIA, London

Matthews MC, Clayton CRI (1993) Influence of intact porosity on the engineering properties of weak rock. In: Geotechnical engineering of hard soils-soft rocks, vol 1. AA Balkema, Rotterdam, pp 693–702

Matthews MC (1993) The mass compressibility of fractured Chalk. PhD thesis. University of Surrey

Mitchell FS (2017) The Chalk group (upper cretaceous) of the Northern Province, eastern England—a review. In: Proceedings of the Yorkshire geological society, vol 62, pp 153–177, 9 August 2018. https://doi.org/10.1144/pygs2017-010

Mortimore RN (2012) Making sense of Chalk: a total-rock approach to its engineering geology. Q J Eng GeolHydrogeol 45:252–334. https://doi.org/10.1144/1470-9236/11-052

Mortimore RN, Duperret A (2004) Coastal Chalk cliff instability. Geol Soc Lond Eng Geol Spec Publ 20:75–88

Mortimore RN, Fielding PM (1990) The relationship between texture, density and strength of chalk. In: Burland JB, Mortimore RN, Roberts LD, Jones DL, Corbett BO (eds) Chalk. Proceedings of the international Chalk symposium, Brighton polytechnic. Thomas Telford, London, pp 109–132

Mortimore RN, Roberts LD, Jones DL (1989) Logging of chalk for engineering purposes. In: Proceedings of the international Chalk symposium, Brighton, 4–7 September 1989, pp 133–152

O'Reilley MP, Tough SG, Pirrie ND, Hignett HJ, Roxborough (1979) Tunnelling trials in chalks. Proc Inst Civ Eng Part 2 67:255–283

Pells PJ, Bieniawski ZT, Hencher SR (2017) Rock quality designation (RQD): time to rest in peace. Can Geotech J 54:825–834

Pettit J, Paraskevopoulou C (2019) Investigating the implications of the geomechanical behaviour of the phosphatic Chalk to the proposed design for the A303 Stonehenge twin-tunnels. In: Proceedings of WTC 2019, word tunnelling congress on tunnels and underground cities: engineering and innovation meet archaeology, architecture and art, May 2019, Naples, Italy

Plinninger RJ, Spaun G, Thuro K (2002) Prediction and classification of tool wear in drill and blast tunnelling. In: Engineering geology for developing countries. Proceedings of the ninth IAEG congress, Durban, South Africa, pp 2226–2236

Polishook B, Flexer A (1998) Assessment of Chalk rock mass in excavation. Bull Eng Geol Env 57(2):145–150

Priest SD, Hudson J (1976) Discontinuity spacing in rock. Int J Rock Mech Min Sci Geomech Abstr 13(5):135–148

Saroglou C, Qi S, Guo S, Faquan Wu (2018) ARMR, a new classification system for the rating of anistropic rock masses. Bull Eng Geol Environ 20019(78):3611–3626

Sissins S, Paraskevopoulou C (2021) Assessing TBM performance in heterogeneous rock masses. Bull Eng Geol Environ 80:6177–6203. https://doi.org/10.1007/s10064-021-02209-2

Twine D, Wright RH (1991) Farmers avenue road crossing, castle mall development, Norwich. In: Proceedings 4th international deep foundation conference Stresa. AA Balkema, Rotterdam, pp 147–155