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Chalk-steel Interface testing for marine energy foundations

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Abstract:	To aid ease of deployment and recovery of tidal stream generators gravity based foundations rather than fixed foundations are being considered in areas where the foundation may be place directly onto an exposed rock seabed. Horizontal loading is usually critical in such applications, therefore specific knowledge of the interface friction between the foundation and seabed surface is important for design. This paper presents results of an interface testing programme of chalk-steel interfaces carried out utilising a computer controlled interface shear tester under constant normal stress conditions against steel of varying roughness. Results indicate that interface strength is significantly affected by the normal stress applied as interface strength degrades for normal stress levels in excess of 30% of the chalks tensile strength. Large displacement tests revealed a tendency of the ultimate interface frictional resistance to drop to values very similar to that of the basic chalk-chalk interface at normal stresses up to 300 kPa, whereas substantial degradation additional was noticed for normal stresses above 700 kPa. At low normal stresses and displacements the behaviour of the chalk steel interface was captured by an alpha type approach related to the rock UCS which has been developed for other higher strength rock types.
Additional Information:	
Question	**Response**
Please enter the number of total words in your abstract, main text and references.	Number of words Abstract: 200 Main text: 5784 References: 887
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UNIVERSITY OF DUNDEE
Division of Civil Engineering

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Dr Trevor Orr
Editor
CO Editorial Office
ICE Proceedings: Geotechnical Engineering

Dear Dr Orr

ICE Geotechnical Engineering journal - Geotechnics in Energy Provision: Chalk-steel Interface testing for marine energy foundations.

Please find attached our manuscript (Article) to be considered for publication in the ICE Geotechnical Engineering Journal – Geotechnics in Energy Provision themed issue.

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(ii) The authors confirm that all previously published work cited in the manuscript has been fully acknowledged.
(iii) The authors confirm that the manuscript is part of a study and thesis from which other manuscripts may be generated.
(vi) All named authors have contributed substantially to the paper and have approved the final submission.
(iv) The authors do not anticipate any real or perceived conflicts of interest. This research was undertaken at the University of Dundee, funded by the Energy Technology partnership through an Industrial studentship and Lloyd's Register EMEA.

If you require any further information please do not hesitate to contact me by email at a.ziogos@dundee.ac.uk.

Yours sincerely

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RESPONSE TO PEER REVIEW COMMENTS

Paper Title Chalk-steel Interface testing for marine energy foundations

Paper Reference: GE-D-16-00112 R1

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Assessor

General comment

To these, I would suggest expanding the discussion of the relative roughness of the steel and rock and what implications it has to measured/estimated friction and design. In particular, in terms of the results of the experiments, is there a range of relative roughness that enables the authors to consider friction as a function of the roughness of the two materials. For design, how much does it matter and how should designers consider roughness and any possible changes to it during loading.

The authors have not commented on detail on this point is this paper as this has previously been discussed in a conference paper which is referred to (Ziogos et al 2015). This conference paper is based upon initial studies using cement with variable UCS as a rock analogue. It would appear that there is a relative roughness where the shearing resistance becomes independent of increasing steel roughness (for rocks that do not degrade i.e. not chalk) but this relative roughness value varies for different rock types. This is the subject of current research data analysis with a view to publishing a much more detailed paper in Geotechnical Engineering Journal in the future. Therefore the authors would like to reserve comment on this point as it is an ongoing research area where the authors hope to publish a comprehensive discussion of the point and give significantly more detailed information for design.

Reviewer #1:

1-Please define average roughness in the text. Some readers may not be familiar with it. A schematic figure can be helpful.

Explanatory text added as requested**.**

Interface roughness can be quantified by many parameters, but one of the most frequently used is Ra (centreline average roughness) which is the computed average of all deviations of the roughness profile from the median (centre) line over a defined profile length and is defined as in equation 3 (Degarmo et. al. 2003)

“3. $$R_a = 1/L \int_0^L |z(x)|dx$$

Where *L* is profile length and *z(x)* is deviation from the centre line at point x.”

Reference added to further detail (Degarmo et. al. 2003). Definition widely available through web searches.

2-Page 5, line 23: Please clarify the "conditions" that may be encountered in tidal stream. Also, as one of these conditions is the cyclic loading, please add a statement to the text that how that condition can alter the conclusions you drew out of monotonic shearing tests.

Text has been added to page 5 to clarify the conditions that are the focus of this study and that are relevant to tidal stream (which follows on from earlier text in the introduction)

“i.e. non-bonded connection to the seabed under relatively low normal stresses and variable stiffness conditions. It is acknowledged though that tidal stream generator foundations will also be subjected to cyclic loading which will need to be considered when interpreting the results of the monotonic tests presented in this paper”

Text added to last paragraph in section 4.1:

“Similarly in the prototype deployment of tidal stream generator foundations are likely to experience cyclic loading which has the potential to cause degradation at lower stress levels and lower displacements.”

Additional text added in section 4.2 to distinguish between monotonic and cyclic behaviour and:

“……suggests that the approach based upon equation 3 should be used with caution for chalk where large displacements and/or cyclic loading may occur at an interface during installation or service.”

Additional text added Page 15 last paragraph of the conclusions:

“For the particular application of tidal stream generator foundations identified in this paper this maybe further exacerbated by the cyclic nature of loading encountered which was not investigated in this paper.”

3-Please explain how you derived equation 1. The shear-torque relationship is defined by tau = T*r/J where J is the polar moment of inertia of the sample.

Explanatory text added as requested

“The torque measured during IST testing was converted to average shear stress as per equation 1 (Saada and Townsend, 1981).

1. $$\tau = \frac{T}{\int_0^r 2\pi R^2 dR} = \frac{3}{2\pi r^3} T \text{ “}$$

4-What is the initial stiffness (modulus of elasticity) of the Chalk and Sandstone used in your study? This should be added to Table 1.

The modulus of elasticity was added in table 1 as requested.

5-As you mentioned in the text (page 11, lines 26 and 27), there are chalk residues on the steel surface after the tests. It would be helpful if you measured the roughness of the interface surfaces (steel, chalk and sandstone) after the tests to see how interface friction degradation can be linked to the possible reduced roughness of the tested materials. In particular, for large displacement tests, the roughness reduction can be more significant. This is helpful for understanding the interface behavior for applications such as pile installation.

Text added to page 11:

The roughness of the steel interfaces tested was measured before and after testing for the low displacement tests and no significant variation in roughness was noted for either rock type. The roughness of the rock samples was also measured and this remained within the variability of the average values typically measured. A similar procedure was undertaken for the large displacement tests which showed that the steel tested against chalk showed no significant change in roughness after careful removal of the chalk residue. Testing of the steel with the chalk residue in place was not undertaken as the surface was relatively uneven and non-continuous over the steel surface making roughness determination difficult. Visual degradation of the steel surface of the large displacement tests against sandstone was noticed.

6-Please explain in the text why peak and ultimate interface friction angles (Table 3 and Figure 4) reach maximum at some low normal stresses and decrease after that. And what is the consequence of that in practical applications. The consequence can be added in the conclusion part as well.

Figures 3,4 and 5 (and the results in the Tables are explained at some length already). See existing paper text below:

"In IST irrespective of the steel type, the interface resistance exhibits a low value at normal stress of 16 kPa which may indicate poor interlocking between the chalk and steel interface as the applied stress is not adequate to bring the two solid bodies into intimate contact and shearing is occurring on the top of the asperities (steel and chalk). As the normal stress increases, the interface gains higher shear strength, as better interlocking is established between the normal stresses of 79 and 159 kPa (7.2 to 16.6% of the chalk tensile strength, T_0). At these stress levels the shearing is accompanied by observable damage on chalk surface, seen as layer of powder (dry samples) or chalk putty (saturated tests) on the steel interface on post test sample separation. This behaviour is similar to that noted for rock analogues (cement blocks) by Ziogos et al (2015). For normal stresses from 316 kPa to 1000 kPa (i.e., 0.31 to $1.0T_0$) the ultimate interface friction angle reduces to values typically between 30 and 35° and in the majority of cases appears to be approaching the basic chalk-chalk friction angle value noted for the 0.4 µm interface. This suggests that damage at the interface may be filling the rough surface of the rougher steel samples and reducing their apparent interface roughness to that approaching the smoothest interface tested here. Significantly more damage was noticed in some samples tested at 700 kPa and 1000 kPa, where parts of the perimeter of the sample were chipped off (labeled as surface damage, SD in Table 4), or at the highest normal stress level (1000 kPa) resulted in complete tensile failure of the sample (NI) as shown in Figure 6. Therefore in the case of chalk the upper limit to the interface strength appears to be linked to the local surface strength of the material (similar to the grain size of sand exceeding the roughness of steel as discussed earlier) with potential for catastrophic disruption of the interface at higher normal stresses on approaching the tensile strength of the chalk (T_0 = 0.96 to 1.1 MPa). Although, some of the samples tested at the higher stress of 1000 kPa were non intact after removal of the sample from its clamp it is believed that the interface shearing behaviour is valid as the clamping system maintained the integrity of the sample and shearing surface during testing. The reduced shear stress noted during testing at these stresses reflects the increased interface damage."

Other comments:

1-Figure 3a: it seems the labels are not correct as the peak values appear lower than the ultimate values. Please check and correct it.

Labels corrected as requested.

2-Page 7, Line 34: it should be "...a 250 kN..."

Text corrected as proposed.

3-Tables 3 and 4 must be reformatted. It's hard to understand the content in the current form since some headings do not seem to belong to the content underneath.

Tables will be reformatted as requested.

Reviewer #2: The Authors have presented a very useful laboratory study on the interface shear strength of chalk against steel for gravity based foundation applications. The Reviewer would like the Authors to clarify and/or to provide more supporting evidences to following bullet points:

/1/ What is the shear displacement/strain used to define the basic friction angle (phi_b) in the Tilt Table Testing (TTT), and is it of the same order of magnitude to the shear displacement/strain shown in the paper for Interface Shear Testing (IST) with limited displacement (to a maximum of 10 mm)?

The authors do not attempt to define or link the strain levels of the determinations in the tilt table test to those of the IST as it is not possible to quantify the strain levels in the tilt table test. The reason for including the results of the tilt table testing are to allow an attempt for industrial end users to bracket the behaviour of rock-steel interfaces based upon a standard test that does not require specialist laboratory testing (the IST is not commonplace nor are large displacement shear boxes). The title table is used to define the commonly used basic friction angle and has been used here to define a low stress interface friction angle. This is valuable to industry to allow correlation of simple testing to important behaviour as is often done for UCS (and or T0 in this paper).

The reviewer refers to “limited displacement” of 10mm which it is assumed is based upon experience of soil-soil or soil-steel, soil-concrete interface testing where significant displacements are required to mobilise peak or ultimate behaviour due to considerable relative volume change (dilation/contraction). Due to the rigid nature of the materials tested here (and shown in the results) it is not necessary to shear to such displacement/strain levels to mobilise peak and ultimate behaviour as the results show. Therefore the authors disagree that displacement is limited as such a statement/definition should consider the materials under test.

/2/ How the test results and accompanying recommendations to be applied and remained valid in practice, considering the actual wave loading on marine GBS foundation, which is both repeated and reversing (cyclic), accumulated and potential large?

See response to reviewer 1

/3/ Considering points /1/ and /2/, it is important to establish clearly the strain range to be applicable for the quoted interface shearing resistance angle, noting the non-linear attribute of Mohr-Coulomb criterion due to stress range and interface roughness;

See response to point 1 above. The displacement range from IST testing is clearly stated.

/4/ Is this justifiable to use the "ultimate" terminology for delta (Section 3, page 10) where only 10 mm of displacement was reached in IST? In fact, this is even smaller than the failure shear strain in a Direct Shear Test (DST). Suggest using other terminology, and clarify that this value corresponded to a plateau at the end of the limited deformation IST.

No changes made as authors disagree. See response to comment 1 above.

/5/ The interface shear-displacement responses were markedly different between at lower normal stress range (0.3*T_0) and at higher (>0.7*T_0), where T_0 is the rock tensile strength. However, apart from two values shown in Table 1, there is no other description relating to the method of determination for this value and the guidance in GBS foundation design practice relating to this T_0 (commonly the UCS is of interest). Please clarify.

Text modified as requested and additional text added to clarify testing methodology. Tensile strength was measured and used as failure observed in high normal stress appeared to be due to tensile rather than compressive failure. The values of tensile strength are also of the same order of magnitude of the applied normal stress. A reader could use either comparison as both UCS and T0 shown in Table 1.

"The tensile strength T_0 of the rock samples was determined using the Brazilian tensile test (Brazilian Tensile test, ASTM D3967-08). Initially the tensile strength was used as an indirect method to determine unconfined compressive strength (UCS) of the chalk using conversions found in the literature."

In addition, minor corrections are suggested for:

P. 5, para 2: (e.g., Race of Aldernay and Casquets)

Text modified as proposed

P. 6, para 1: Unfortunately due to the working status of the quarry and the required health and safety regulations, the research team...

Text modified as proposed

P. 6, para 1: ... the fresh nature of the chalk (i.e., recently quarried), immediately...

Text modified as proposed

P. 6, para 2: (UCS), tensile strength and interface shear resistance behaviour.

Text modified as proposed

P. 6, para 3: ... saturation levels, generally showing lower strengths...

Text modified as proposed

P. 6, para 3: (... and behaviour of the interface) - please clarify the terminology

Text removed as vague

P. 7, para 1: This area was selected because it is adjacent to...

Text modified as proposed

P. 7, para 1: ... which allows comparison of the behaviour... What does this mean?

Vague terminology "behaviour" replaced with shear resistance.

P. 7, para 2: ... an additional set of tests was...

Text modified as proposed

P. 7, Section 2.3: Add description of tensile strength test (see point #5 above)

Text added to clarify that tensile strength determined by the Brazilian text to ASTM D3967-08.

"The tensile strength T0 of the rock samples was determined using the Brazilian tensile test (Brazilian Tensile test, ASTM D3967-08)"

P. 7, para 3: using conversions found in the literature - please cited exemplary references

Reference already given to Kilic and Teymen, 2008 which are valid for other rock types but not chalk. Authors have modified text to clarify that this method of indirect UCS determination was not appropriate for chalk and direct measurement of UCS was employed.

P. 7, para 3: ... with ISRM (2007)...

Text modified as proposed

P. 7, para 3: (see Table 3)

Text modified as proposed

P. 7, para 3: Both the oven dried sandstone and chalk samples...

Text modified as proposed

P. 7, para 4: ... basic friction angles (phi_b) of the chalk and sandstone were determined... Also need to identify the corresponding shear strain/displacement as noted in /1/

See response to comments above

P. 8, para 2: consistency in using abbreviation. Suggest replacing GDSIST with IST (supplied by GDS)

Text modified as proposed

P. 8, para 3: providing a reference to the calibration, verification and data acquisition of the combined dual loadcell and deformation transducers

The text is unmodified as we are unclear what the referee is referring to. The systems were calibrated and verified by the manufacturer and checked regularly in house against standardised calibration equipment as is normal procedure in a testing lab.

P. 8, para 4: explaining the reason for choosing shearing rates of 0.05 mm/s (during 36 mins) and of 1.25 mm/s (lasting 16.5 hours) in two types of IST program

Text added as requested.

"A higher rate was used for these tests in order to allow the execution of each test within a reasonable timeframe."

P. 10, para 2: Figures 2a, 2b and 2c...

Text modified as proposed

P. 10, para 2: ultimate - see comment /4/

No change made see response to comments above

P. 10, para 3: Figures 3, 4 and 5 show...

Text modified as proposed

P. 10, para 3: The IST results are summarized in Table 4. These results suggest that the shear stress - displacement response at the interface is not in proportion with the normal stress. It is possible that a simple constant friction angle based on Mohr-Coulomb failure criterion model for interface shearing may not be appropriate for this chalk.

Text modified as proposed

P. 11, para 1: Are we comparing like with like (similar shear strain/deformation) between TTT and IST? See comment /1/

See response to comments above

P. 11, para 2: In IST, irrespective of the steel type...

Text modified as proposed

P. 11, para 2: For normal stresses between 316 and 1000 kPa (i.e., 0.31 to 1.0*T_0), the post-peak interface resistance angle...

Text modified as proposed. See earlier comments about definition of terms.

P. 11, para 2: This suggests that damages at the interface may be filling the rough surface...

Text unmodified as the use of “damage” is appropriate here.

P. 12, para 1: other studies (Jardine et al, 1993; Barmpopoulos et al, 2010; Ziogos et al, 2015)

Text modified as proposed

P. 12, Section 3.1: adding comparison to earlier studies, (e.g. Barmpopoulos et al, 2010). Note also that for simulation of piling construction in the ring shear tests, large displacement and fast shearing rate was first employed, followed by a much slower shearing rate (pile under loading).

References to similarities to Barmpopoulos et al, 2010 added to section 3.1.

The authors note the comments on rate but unless the test were done under saturated conditions the authors do not see the relevance. Testing done here was done at rate intended to allow fully drained conditions and avoid rate driven pore pressure/effective stress issues.

P. 12, para 2: ... on sandstone shows very...

Text is unmodified as it is unclear what the reviewer is proposing.

P. 13, para 3: up to 700 kPa (i.e., 0.7*T_0). Therefore, it is possible to utilise TTT to estimate the peak friction angle for preliminary design purposes, and using IST (or large displacement direct shear box tests) in detailed design.

Text modified as proposed

P. 14, para 2: ... of whether or not the concrete...

Text modified as proposed

P. 14, Section 5: Summary and Recommendations

Text modified as proposed

P. 14, para 4: up to 159 kPa (i.e., 0.16*T_0).

Text modified as proposed

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Abstract (150-200 words)

To aid ease of deployment and recovery of tidal stream generators gravity based foundations rather than fixed foundation alternatives are being considered in areas where the foundation may be place directly onto an exposed rock seabed. Horizontal loading is usually critical in such applications, therefore specific knowledge of the interface friction between the foundation (made of steel or concrete) and seabed surface is important for design. This paper presents results of an interface testing programme of chalk-steel interfaces carried out utilising a computer controlled interface shear tester under constant normal stress conditions against steel of different roughness. Results indicate that interface strength is significantly affected by the normal stress applied as interface strength degrades for normal stress levels in excess of 30% of the chalks tensile strength (~300 kPa). Large displacement tests revealed a tendency of the ultimate interface frictional resistance to drop to values very similar to that of the basic chalk-chalk interface at normal stresses up to 300 kPa, whereas substantial additional degradation was noticed for normal stresses above 700 kPa. At low normal stresses and displacements the behavior of the chalk steel interface was captured by an alpha type approach related to the rock UCS which has been developed for other higher strength rock types.

Keywords

Renewable energy; Geotechnical engineering; Shallow foundations

List of notation

α	adhesion factor
δ_{peak}	peak interface friction angle
δ_{ult}	ultimate interface friction angle
ϕ_b	basic friction angle
θ	rotational displacement
μ	coefficient of friction
ρ_d	*dry density*
σ_v	normal stress
τ	shear stress
d	linear displacement
D_{50}	mean soil particle size
G_s	specific gravity
m_{sat}	saturated moisture content
n	porosity
r	rock sample radius
R	*radial position*
R_a	average centre line roughness

T	torque
T_0	tensile strength
UCS	unconfined compressive strength of rock

1. Introduction

To allow the design of gravity base foundation systems (GBS) for tidal stream generators it is necessary to have appropriate interface friction parameters for the foundation-seabed interface due to the potential for relatively high lateral loads experienced by these applications. As there are high velocity currents at locations with high tidal stream energy potential, the seabed sediment is likely to be washed out (scoured) resulting in exposed bedrock at the seabed which may form one half of the foundation surface (Small et al. 2014). The determination of interface friction parameters requires laboratory interface testing using the foundation-seabed materials (typically steel or concrete in contact with different rock types) with testing undertaken at appropriate normal stress levels. Currently there is little guidance available to designers on how such parameters should be selected or the appropriate approaches to laboratory testing (Small et al. 2014). What guidance is available is considered conservative based upon simple assumptions of interface behaviour rather than actual laboratory element testing. For example, Fraenkel (2002) estimated that at least 1500 tons of GBS per MW are needed in order to maintain stability, but this value seems very high and conservative where there is significant drive to bring down the foundation costs for marine renewable devices (Carbon trust 2011). NAVFAC (1986) suggest a coefficient of friction,μ of 0.7 (interface friction angle, $\delta = 35^\circ$) for mass concrete on clean-sound rock but the origins of this value are unclear and it is not stated if this refers to a bonded or unbonded surface or the types of rock that were used in its determination.

Existing guidance on rock-concrete and rock-steel interfaces typically relates to very different applications (and interface conditions) such as concrete bonded or cast against rock at high vertical stress levels. Examples of these are found at the interface between the base of a dam or cast insitu pile rock sockets (Horvath 1978, Rosenberg & Journeaux 1976, Williams & Pells 1981) and rock-steel interfaces such as rock bolts (Li and Hakansson 1999) or H-steel piles driven into rock (Yu et al 2013). These rock-steel interface examples result in constant normal stiffness conditions (CNS) which lead to high normal stresses where the interface is subject to shear and constraint of dilation. This can result in normal stresses at the interface that are orders of magnitude higher than those that would be experienced for a tidal stream generator foundation (estimated at some hundreds of kPa, under constant normal stress conditions). This fact along with the potential for concrete bonding between interfaces may limit the relevance of previous interface studies.

Many systematic efforts to investigate the interface shear behaviour between soil and geotechnical structures (rather than rock) have been made. Potyondy (1961) conducted tests between various soil types (e.g. sand, clay and silt) and concrete, steel and wood, while Peterson et al. (1976) conducted tests with sand-steel interfaces. Both studies were carried out using the direct shearbox. In the 1980's significant research was undertaken on sand-steel interfaces by Usegi and Kishida (1986^{a} &1986^{b}) and Kishida and Usegi (1987) utilising the simple shear apparatus. Since these earlier studies research has been continuously undertaken using various devices and laboratory equipment such as the ring shear and curved shearbox (Iscimen and Frost, 2010). Typically it has been found that interface frictional resistance increases as the solid (or the surface representing the structural element) surface roughness increases up to a specific limit defined as critical roughness. At this limit, which approaches the internal friction angle of the sand, a sand-sand slip occurs as a soil-soil shear rather than interface shear predominates. This is because as the surface roughness tends to the diameter of individual sand particles the sand effectively interlocks with the foundation surface forcing the shearing away from the interface and into the soil mass (Peterson et al. 1976, Usegi and Kishida 1986a, Kishida and Uesugi 1987). It has also been shown that as the roughness increases, more displacement is required to mobilise the peak friction angle (Iscimen and Frost, 2010). Where the soil particle diameter exceeds the surface roughness the constant volume interface friction angle decreases significantly with increasing D_{50} with a cut off point of R_a/D_{50}=0.015 for sand (Jardine et al. 1993). For sand-steel interface used in offshore driven piles tan δ_{cv} is often limited to 0.55 (28.8°), (Lehane et al, 2005). Although there have been significant previous studies for soil sheared against common civil engineering materials there is a dearth of information for rock-steel interface testing under the conditions that may be encountered in tidal stream or other renewable energy foundation applications i.e. non-bonded connection to the seabed under relatively low normal stresses and variable stiffness conditions. It is acknowledged though that tidal stream generator foundations will also be subjected to cyclic loading which will need to be considered when interpreting the results of the monotonic tests presented in this paper

This paper presents results of chalk steel interface testing utilising a specially commissioned torsional interface shear tester (IST). This device was used to investigate the interface material properties that influence interface shear strength under stress and displacement levels appropriate to tidal stream GBS foundations. The potential for the use of the equipment in large displacement events has also been explored which may be relevant to driven pile installations which can potentially be used to anchor or support tidal stream generator alternatives. This paper focuses on applications on chalk since it is a rock with extraordinary characteristics (Lord et al 2002) and areas in the south of the UK that have been identified as of significant tidal stream potential may consist of chalk seabeds (e.g. Race of Aldernay and Casquets, which represent around 6% of the total UK tidal resource, Carbon Trust, 2005), or where driven pile solutions may encounter such material types.

This paper aims to provide information regarding the controlling parameters on the foundation-seabed interface sliding resistance and to provide interface properties that can be potentially used during the design process.

2. Laboratory testing

2.1 Description of Chalk samples used for laboratory testing

The samples were collected from the active Imerys Mineral Limited’s Quarry, Westwood, Beverley, HU17 8RQ, UK (501740, 438256). Blocks of chalk typically 350 by 300 by 280 mm were obtained directly after quarrying and prior to crushing for use in the chemical industry. Unfortunately due the working status of the quarry and the required health and safety regulations, the research team were not directly involved with the sampling of the chalk due to health and safety considerations thus making it difficult to comment on the structural setting of the chalk insitu. The chalk is White Chalk from the Flamborough Chalk Formation (Upper Chalk unit, Northern province English Chalk) referred to informally as the Flamborough Sponge Bed (Lord et al 2002, Whitham, 1991 & 1993). This source of material was selected due to the fresh nature of the chalk (i.e. recently quarried), immediately placed under cover and the fact that the chalk was free from flints that may interfere with characterisation and interface testing.

The chalk was characterised using both field and laboratory techniques prior to interface shear testing and the results are summarised in Table 1. These results classify the chalk as of very high density according to CIRIA 574 (Lord et al, 2002). The chalk on return to the laboratory had a very low moisture content of 0.3%. Dry density and saturation moisture content determination (BS 1377-2: 1990) highlighted that the moisture content of the chalk was below the 90% minimum level of saturation recommended for field identification procedures so the chalk was saturated prior to these tests by applying 95 kPa vacuum to submerged samples (in de-aired and de-ionised water) for 24 hours. In order to ascertain the level of saturation, the moisture content after following the aforementioned process was compared to the saturation moisture content w_s=11.49 % of the chalk (calculated according to BS 1377-2:1990) and very high levels of saturation were achieved (99.6-99.7%). Samples were also oven dried in order to investigate the effect of moisture content on the unconfined compressive strength (UCS), tensile strength and interface shear resistance behaviour.

2.2 Scope of testing

Interface testing between chalk-steel interfaces at normal stresses relevant to those anticipated at real tidal stream projects (Ziogos et al 2015), was carried out in order to obtain friction properties necessary for the determination of the sliding resistance of a GBS. The UCS of chalk has previously been found to vary significantly with saturation levels, generally showing lower strengths for saturated samples compared to dry ones (Matthews and Clayton, 1993). Therefore tests using both dry and saturated samples were carried out in order to examine the variation of UCS on the shear resistance. In addition, the effect of steel roughness was investigated (R_a = 0.4-34 μm, Table 2) along with the effect of normal stress (σ_v = 16-1000 kPa) over relatively short displacements of 10mm during shear.

Sandstone-steel interface testing was also undertaken (σ_v = 16-316 kPa) to allow the comparison between the interface behaviour of chalk and a typical sedimentary rock (sandstone) that exhibits more “conventional” behaviour. The samples used for the testing, were sourced from the Caithness area and specifically from a disused quarry located south of John O’ Groats (ND37150 70138). This area was selected because it is adjacent to the Pentland Firth, which exhibits significant tidal resource (Carbon Trust, 2011). The Old Red Sandstone that was recovered for testing is yellow-orange in colour and medium grained (British Geological Survey, 1989). In addition the laboratory determination of UCS revealed a very similar value (Table 1) compared to that of the dry chalk samples which allows comparison of the shear resistance of the two rock types focusing on parameters other than the compressive strength (e.g. the grain size that differs significantly between sandstone and chalk).

In addition to the tests designed to investigate the behaviour of chalk relevant to tidal stream generator GBS foundations (low normal stress and low displacement) an extra set of tests was undertaken to very large cumulative displacements (7.0 m). These tests were to check the potential of the IST device but also may be considered relevant to the displacements that may be encountered in driven piling or underneath a sliding foundation or tow head used in the offshore oil and gas industries.

2.3 Determination of unconfined compressive strength (UCS)

The tensile strength T_0 of the rock samples was determined using the Brazilian tensile test (Brazilian Tensile test, ASTM D3967-08). Initially the tensile strength was used as an indirect method to determine unconfined compressive strength (UCS) of the chalk using conversion factors. The results indicated that the empirical conversion factors used to convert the tensile strength to UCS, found for other sedimentary rocks (e.g. Kilic and Teymen, 2008), were not appropriate for chalk, therefore direct unconfined compression tests were carried out in accordance with ISRM (2007) utilising a 250 kN INSTRON universal testing machine. Direct UCS tests were carried out on cylindrical oven dried and saturated chalk samples with a height to diameter ratio equal to 2 (see Table 3) at a strain rate of 0.1 mm/minute. Dry sandstone samples were also tested for comparison purposes. Both the oven dried sandstone and chalk samples exhibited very similar values of UCS (31.5 and 30.0 MPa, respectively), whereas a 69% decrease in UCS was observed for the chalk when tested in a saturated condition. Deterioration of chalk UCS after saturation has been reported before by Matthews and Clayton (1993), however they noticed a smaller average reduction of 50%. This difference maybe due to the high density of the chalk tested in this study where Matthews and Clayton (1993) report UCS for a variety of chalk densities.

2.4 Tilt table testing

Prior to the main interface testing the basic friction angle of the chalk (ϕ_b=30.5º) and sandstone was determined using simple tilt table testing in line with the methodology outlined in USBR 6258. This involves tilt table testing of two 54 mm diameter samples of 27 mm thickness placed on top of each other. The samples were prepared by coring of a block of chalk (54 mm nominal diameter) and then dry cross cutting of the core using a diamond saw. The interface frictional resistance was determined on this saw cut surface (as per USBR 6258). The ϕ_b was 30.5° and 38.5° for chalk and sandstone respectively. Previous experience of the results from the low normal stress tilt table tests show good correlation with the more advanced testing techniques at elevated stress levels (Table 3). Therefore, apart from using the tilt table test to determine the basic friction angle, the simple test was also used to test the chalk samples against the steel interfaces used in the main study.

2.5 Description of the Interface Shear Testing device (IST)

A computer controlled torsional interface shear tester IST (supplied by GDS) was utilised for the execution of the main part of the interface shear testing program (Figure 1). This device consists of an axial actuator at the top of the rig which can apply up to 5 kN of vertical load. Below the actuator is a combined torque load cell arrangement with a capacity of 5 kN and 200 Nm respectively. At the base of the rig is a rotational actuation system capable of applying torque up to 200 Nm and rotating at rates up to 0.05 degrees/s. The axial actuator applies the normal load to the samples under test and is fixed against rotation, whereas the rotational actuator applies the torque from below.

A special clamping system was developed to allow rectangular interchangeable foundation interface elements of 65 x 90 mm with a thickness of 8 mm to be clamped at the base of the rig above the rotational actuator (Figure 1b). Similarly, below the load/torque load cell a clamping device was developed to clamp short round rock samples (54 mm diameter and 25 mm high). During the test, the upper rock sample was fixed whilst the lower steel sample rotated at a predetermined rate. The IST used here is an evolution of that previously used by Kuo et. al (2015) for the low stress interface testing of pipelines (referred to as the CAMTOR device). This previous device incorporated an outer pressure cell and allowed the testing of soil samples up to 70 mm in diameter and 20 mm thickness against pipeline surface elements. During the tests torque and normal load were measured using a calibrated torque/load cell and vertical and rotational deformation measurements were provided by a calibrated encoder attached to the stepper motor.

The tests were conducted under constant normal stress conditions on both dry and saturated samples under six different normal stress levels of 16, 79, 159, 316, 700 and 1000 kPa. In order to conduct testing of submerged interfaces for saturated samples, a custom made perspex box (bath) was attached to the lower rotation platen, Figure1c. The saturated rock sample was clamped using the top holder and the bath was filled with de-ionised water, in order to prevent drying of the saturated sample. For saturated tests, the interface was kept under constant normal stress for 15 minutes before the initiation of shearing in order to allow any excess water pressure dissipation at the interface, for the same reason the shearing rate was kept at a low level at 0.05 mm/s of equivalent horizontal displacement. Every test lasted approximately 36 minutes and was terminated when an equivalent horizontal displacement of 10 mm was reached (corresponding to 42.5° rotational displacement). In addition to the aforementioned tests, three tests up to a horizontal displacement of 7.0 m (29750 degrees rotational displacement) were carried out under three different stress levels (100, 300 and 700 kPa) using saturated samples. The shearing rate for these tests was 1.25 mm/s and each test lasted 16.5 hours. A higher rate was used for these tests in order to allow the execution of each test within a reasonable timeframe. The scope of these tests was to investigate any possible degradation on the chalk surface (and consequently to the shear strength of the interface) at very high shear deformations that can potentially occur for applications such as pile driving. Therefore the steel plate with R_a=7.2 μm was selected as the roughness lies in the middle of the roughness range of steel piles used in practice (R_a=5-10 μm for steel piles, Barmpopoulos et. al. 2010).

The torque measured during IST testing was converted to average shear stress as per equation 1 after considering Saada and Townsend (1981) for ring shear testing.

1.
$$\tau = \frac{T}{\int_0^r 2\pi R^2 dR} = \frac{3}{2\pi r^3} T$$

The radial deformation was converted to a linear displacement at a reference point considered at a distance equal half of the radial length of the circular rock sample as per equation 2.

2.
$$d = \theta \frac{r\pi}{360}$$

Where θ is rotational displacement, τ is shear stress, d is linear displacement, r is rock sample radius, R is radial position and T is torque.

2.6 Description of steel samples (foundation analogues)

Mild steel was used to prepare rectangular (65 x 95 x 8 mm) plates that represented foundation analogues for the interface testing. As discussed in the introduction and found in the literature (Ziogos et al 2015), roughness has a major effect on the interface behaviour, therefore different preparation techniques (polishing and machining) were applied and resulted in three different foundation analogues with a wide range of surface roughness (R_a between 0.4 and 34 μm).

Polishing with a surface grinder using a BAA60 – K7V wheel resulted in surface roughness average R_a=0.4 µm. Machining, using a shaping machine and an appropriately adjusted shaping tool, resulted in R_a values of 7.2 and 34 µm. The range of roughness obtained covers the roughness of some of the steel elements commonly found in geotechnical applications (for example, R_a=5-10 µm, for steel piles, Barmpopoulos et. al. 2010), allowing the utilisation of the results to other applications.

2.7 Surface roughness characterisation

Interface roughness can be quantified by many parameters, but one of the most frequently used is R_a (centreline average roughness) which is the computed average of all deviations of the roughness profile from the median (centre) line over a defined profile length and is defined in equation 3 (Degarmo et. al. 2003). A hand held Taylor Hobson Surtronic Duo stylus contact profilometer was used to determine the average centreline roughness (R_a) of all of the samples used for interface testing (rock and steel). The profilometer has a range of measurement up to 40 µm and a traverse length of 5 mm. For each sample, five R_a measurements were taken and the mean value was selected. Calibration of the device was carried out periodically against a standard roughness profile with R_a=5.81 µm and R_z=21.5 µm (supplied with the device). The interface face properties of all the materials used for testing (rock and steel samples) are summarised in Table 3.

3. $$R_a = 1/L \int_0^L |z(x)| dx$$

Where L is profile length and $z(x)$ is deviation from the centre line at point x..

3. Results

Figure 2a, 2b and 2c show the normalised shear stress-displacement curves from saturated chalk-steel interface tests on steel of increasing roughness. A typical result shows a slightly elevated initial shear stress followed by a slight reduction in shear stress post peak (or yield) and then remaining relatively constant until the end of the test. It is apparent that yielding or peak shear stress is observed at increasing displacement levels as the normal stress on the chalk increases, as seen in Figure 2a for normal stresses above 159 kPa. It is also noticeable that as the normal stress increases there is an increase in shear resistance up to a normal stress of 79-159 kPa and then a reduction in the shear resistance with the lowest shear resistances associated with the highest normal stress of 1000 kPa. Table 4 shows the summarised results of testing where δ_{peak} is defined as the maximum value at a shear displacement up to 4mm and δ_{ult} is defined as the minimum value in the region of 8-10 mm. The results in Figure 2d show the tests for sandstone sheared against steel of R_a= 7.2 µm where the curves are more “noisy” because sandstone is rougher and harder, whereas it is apparent that higher interface shear stresses are mobilised in the softer chalk.

Figures 3, 4 and 5 show the results of IST testing of the saturated and dry chalk against the various steel interfaces in terms of the different normal stresses. For the dry tests the peak interface friction angles δ_{peak} range from 35º to 45º and δ_{ult} from 22.5º to 40º. For saturated tests, δ_{peak} ranges from 27º to 42º and δ_{ult} from 22 º to 40º. All of the results from IST testing are summarised in Table 4. The IST results are summarised in Table 4. These results suggest that the shear stress - displacement response at the interface is not proportional to the normal stress. It is possible that a simple constant friction angle based on Mohr-Coulomb failure criterion model for interface shearing may not be appropriate for chalk. The peak interface friction angles noted do not seem significantly affected by the degree of saturation although the values are higher for the dry tests. They do not seem to reflect the variation of UCS change noted between dry and saturated chalk samples (69% reduction in UCS from dry to saturated).

All of the figures have been annotated with the value of the interface friction angle derived from the low stress tilt table testing (Table 3) and the basic chalk-chalk friction angle (again obtained from tilt table testing as described earlier). The derived interface friction angles from IST testing tend to exceed these values for the lowest and highest steel roughness (0.4 µm and 34 µm) whereas the results for the dry and saturated tests against 7.2 µm steel only appear to exceed this at the highest interface angles. This suggests that in the case of chalk, the normal stress level effects the results obtained from the IST when compared to tilt table testing, although, this is not the case for other higher strength rocks. This variation in behaviour suggests a transition in moving from 0.4 µm to 7.2 µm steel interface which is reflected in both the IST and tilt table testing.

In the IST irrespective of the steel type, the interface resistance exhibits a low value at normal stress of 16 kPa which may indicate poor interlocking between the chalk and steel interface as the applied stress is not adequate to bring the two solid bodies into intimate contact and shearing is occurring on the top of the asperities (steel and chalk). As the normal stress increases, the interface gains higher shear strength, as better interlocking is established between the normal stresses of 79 and 159 kPa (7.2 to 16.6% of the chalk tensile strength, T_0). At these stress levels the shearing is accompanied by observable damage on chalk surface, seen as layer of powder (dry samples) or chalk putty (saturated tests) on the steel interface on post test sample separation. This behaviour is similar to that noted for rock analogues (cement blocks) by Ziogos et al (2015). For normal stresses from 316 kPa to 1000 kPa (i.e., 0.31 to $1.0T_0$) the ultimate interface friction angle reduces to values typically between 30 and 35° and in the majority of cases appears to be approaching the basic chalk-chalk friction angle value noted for the 0.4 µm interface. This suggests that damage at the interface may be filling the rough surface of the rougher steel samples and reducing their apparent interface roughness to that approaching the smoothest interface tested here. Significantly more damage was noticed in some samples tested at 700 kPa and 1000 kPa, where parts of the perimeter of the sample were chipped off (labeled as surface damage, SD in Table 4), or at the highest normal stress level (1000 kPa) resulted in complete tensile failure of the sample (NI) as shown in Figure 6. Therefore in the case of chalk the upper limit to the interface strength appears to be linked to the local surface strength of the material (similar to the grain size of sand exceeding the roughness of steel as discussed earlier) with potential for catastrophic disruption of the interface at higher normal stresses on approaching the tensile strength of the chalk (T_0 = 0.96 to 1.1 MPa). Although, some of the samples tested at the higher stress of 1000 kPa were non intact after removal of the sample from its clamp it is believed that the interface shearing behaviour is valid as the clamping system maintained the integrity of the sample and shearing surface during testing. The reduced shear stress noted during testing at these stresses reflects the increased interface damage. The roughness of the steel interfaces tested was measured before and after testing for the low displacement tests and no significant variation in roughness was noted for either rock type. The roughness of the rock samples was also measured and this remained within the variability of the average values typically measured. A similar procedure was undertaken for the large displacement tests which showed that the steel tested against chalk showed no significant change in roughness after careful removal of the chalk residue. Testing of the steel with the chalk residue in place was not undertaken as the surface was relatively uneven and non-continuous over the steel surface making roughness determination difficult. Visual degradation of the steel surface of the large displacement tests against sandstone was noticed.

As mentioned earlier, the adoption of a linear failure envelope for chalk does not seem appropriate for design purposes, since the interface friction angle is affected by the normal stress level. Although, in order to allow comparison, linear failure envelopes for peak and ultimate interface resistance were calculated. These are based upon the average peak or ultimate resistance determined over the range of effective stresses tested. To allow the effect of normal stress and potential for surface degradation and damage to be represented the range of normalised friction angles obtained are denoted by vertical error bars as shown in Figure 7 (shown for chalk peak values only for clarity). The results suggest that over the steel roughness range investigated (R_a=0.4-34 μm), that on average interface becomes stronger as the steel roughness increases, without reaching a “plateau” as seen in other studies (Jardine et al, 1993; Barmpopoulos et al, 2010; Ziogos et al, 2015) and as shown for sandstone. Although when increasing normal stress is considered there appears to be a tendency for the chalk-steel interfaces to lean towards the basic chalk-chalk interface properties.

3.1 Large displacement interface testing

Results from the large displacement tests can be seen in figure 8 compared with the result from a similar test undertake on sandstone for comparison. It is clear from the tests on chalk at all normal stress levels that there is continuous degradation of the shear surface throughout the test. This is similar to the behavior observed by Barmpopoulos et al, (2010) testing sand against concrete to large displacements which was attributed to observed sand particle crushing and generation of fines. At the lowest stress of 100 kPa the friction angle has fallen from an initial peak of 43 degrees to 37 degrees at 7.0 m with the rate of degradation appearing to reduce. This value is similar to that noted from the low stress tilt table testing of chalk-steel (Table 3). At 300 kPa normal stress, reduced initial degradation is observed with a relatively constant interface friction angle of 30-31 degrees being reached after 2.4 m of displacement which tends to the basic chalk-chalk interface friction angle which may be explained by the degradation behaviour described above for the low displacement tests. In contrast at a normal stress of 700 kPa there is a significant reduction in the interface friction angle below the basic chalk-chalk interface friction angle until reaching a relatively constant value of 17° ($0.56\phi_b$) at 6.5 m. Previous low displacement testing results shown earlier may have led to the recommendation of a lower safe bound design interface friction angle of approximately 29° ($0.95\phi_b$) which could be determined from the basic chalk-chalk interface friction angle. In the case of large displacement events this may be a suitable approach where the normal stresses do not exceed 300 kPa ($0.31T_0$). Where this value is exceeded then a more conservative interface resistance must be assumed. The behaviour observed in Figure 7 for the large displacement test on sandstone shows very different behaviour with increasing resistance with increasing displacement up to 1.7 m displacement and then a more gradual increase with increasing displacement which again appears to be tending to the sandstone-sandstone basic interface friction angle. This maybe due to the removal of weak exposed sandstone asperities (individual weakly cemented grains) but this behaviour requires further investigation. What is apparent from the testing is that, unless normal stresses are high enough to cause significant interface and sample damage, that large deformation tests on steel (R_a = 7.2μm) rock interfaces result in interface behaviour that tends to the basic low stress rock-rock interface behavior (for both chalk and sandstone-steel interfaces).

It should be noted that the testing regime here is constant normal stress (similar to that adopted by Barmpopoulos et al, (2010) for ring shear tests on sand-steel and sand-concrete interfaces) and in the case of driven piles a constant normal stiffness regime may more adequately represent insitu conditions leading to a reduced potential for tensile strength linked degradation. This assumes though that the chalk insitu is intact and well confined without faults or voids/low strength zones. In addition constant normal stiffness conditions may lead to significantly higher insitu stresses than those tested here which could result in a more rapid degradation with displacement.

4.0 Implications for testing and design

4.1 Utilisation of tilt table for simple interface characterization

Table 3 compares the results of interface testing using the tilt table to those obtained from IST testing. It can be seen that there is good agreement between the peak interface friction angle measured in both types of test, especially for the rougher steel plates (R_a=7.2 and 34 µm) and for σ_v up to 700 kPa (i.e., $0.7T_0$). Therefore, it is possible to utilise tilt table test to estimate the peak friction angle for preliminary design purposes, and using IST (or large displacement direct shear box tests) in detailed design.. Based upon the IST tests here for chalk (Figures 3, 4, 5), and the apparent tendency to degrade to low friction angles with increasing normal stress levels and interface degradation, tilt tables tests for chalk against a relatively smooth interface may give a useful lower bound for design. For both the low and high displacements it would seem that the normal lower bound interface friction angle should be taken as the basic chalk-chalk friction angle from tilt table testing irrespective of the foundation material or roughness. For higher displacement tests though some caution has to be exercised when normal stress levels exceed $0.31T_0$. Similarly in the prototype deployment of tidal stream generator foundations are likely to experience cyclic loading which has the potential to cause degradation at lower stress levels and lower displacements.

4.2 Potential Design approaches

Previously Ziogos et al (2015) have proposed an adhesion factor (α) (shear stress normalised by UCS) type approach for monotonic rock-steel and cement-steel interface strength prediction similar to that developed for rock socket pile adhesion factors (Tomlinson 2001). In this case though the magnitude of shear stress is lower by several orders of magnitude compared to pile applications, due to the unbonded nature of the interface and CNS conditions for rock socketed piles. UCS was also normalised by the vertical stress during interface testing as this was seen to have a significant effect over the relatively low stresses likely to be encountered at the rock-steel interface (as also observed in this study). It is assumed such a normalisation is not applied for rock socket piles due to the high confining stresses and difficulty in determining the actual in situ stress at the bonded interface. Figure 9 shows lines which represent the adhesion factor values obtained from previous monotonic interface testing of various rock-steel interface combinations. The lines are described by equation 4 and allow the calculation of the maximum shear stress capacity of the interface, for a given rock type (UCS), foundation footing (steel R_a) and the anticipated applied average normal stress (σ_v).

4.
$$a = \mathrm{a}\left(\frac{UCS}{\sigma_v}\right)^b$$

The lines previously determined for various steel roughness levels (R_a from 0.4 to 7.2 µm and UCS from 45 to 157.2 MPa) have been extrapolated to cover the range of testing undertaken in this study. For steel R_a=0.4µm, *a* and *b* may be taken as 1.78 and -1.26 respectively, whereas for

R_a=7.2 µm, *a* = 1.25 and *b* = -1.16. Specific data points are also shown for the IST testing of Old Red Sandstone as way of comparison. It can be seen that the previously determined relationship for rocks of much higher UCS seems applicable for the much lower strength chalk and offers an alternative design approach to an interface friction angle based approach to design where low monotonic displacements occur (which could be attempted from the results in Table 4 or the lower bound basic friction angle). Additionally, the results are shown for the large displacement tests on chalk (Figure 7) which suggests that the approach based upon equation 3 should be used with caution for chalk where large displacements and/or cyclic loading may occur at an interface during installation or service. Adhesion factor ranges from 0.001 (σ_v=16 kPa) to 0.07 (σ_v=1000 kPa) for saturated chalk samples are similar to the cohesion intercept/UCS ratio (ranges from 0.02 to 0.13) defined by Clayton and Saffari-Shooshtari (1990) from interface tests on bonded planar chalk-concrete interfaces. This suggest that the strength of the material is potentially controlling behavior irrespective of whether or not the concrete is bonded or unbonded.

5 Summary and Recommendations

Interface shear testing between a very high density chalk and steel of varying roughness was undertaken to gain insights for tidal stream generator GBS foundation design. In addition interface testing using Old Red Sandstone samples was undertaken for comparison purposes.

Low displacement interface shear testing of chalk-steel interfaces at low normal stresses showed a tendency for increasing shear resistance up 159 kPa (i.e. 0.16T_0). At stress levels above this and in particular between 316 kPa (0.33T_0) the interface shear resistance begins to degrade and tends to the basic chalk-chalk interface behaviour (with increasing normal stress) determined at low stress from tilt table testing. This suggests damage at the chalk still interface which was observed as chalk dust or putty on the steel interfaces after testing. As the normal stress was increased further the chalk displayed surface damage (σ_v = 700 kPa, 0.76T_0) and fracturing (σ_v = 1000 kPa, 1.10T_0). The average chalk-steel interface shear strength appears to increase linearly with increasing roughness of the steel which is in contrast to the results of sandstone-steel interfaces, which reaches a “plateau” at an average steel roughness of 7.2 µm but this behavior is highly dependent on the normal stress levels.

Large displacement monotonic tests of saturated chalk samples (up to 7.0 m) revealed a degradation of interface strength for increasing displacement with a tendency for resistance towards the basic chalk-chalk interface behavior measured from tilt table testing (ϕ_b=30.5°) at normal stress levels up to 300 kPa (0.33T_0). At normal stress levels above this (σ_v=700 kPa) degradation of the chalk-steel interface was more severe tending towards half of the resistance at lower stress levels.

Tilt table interface tests were undertaken on chalk-steel interfaces with resulting very low normal stresses (less than 1 kPa), and showed good agreement with the IST results at low normal stresses (σ_v=16 kPa), especially for the rougher steel plates used during this study (R_a= 7.2 and 34 µm). The tilt table test was also used to determine the basic chalk-chalk interface friction angle which seems to be a key indicator of behavior for degraded chalk behavior which in some cases may be used a lower bound design approach. Results would suggest that the tilt table test is useful inexpensive method of charactering rock-steel interfaces that may give useful insights to behavior for preliminary design.

Comparison of the results from this study with those of other higher UCS rocks would suggest that a previously developed alpha versus normalised UCS based design approach to predicting chalk-steel interface resistance may be adopted but that some care needs to be exercised when crushing or degradation of chalk may occur. For the particular application of tidal stream generator foundations identified in this paper this maybe further exacerbated by the cyclic nature of loading encountered which was not investigated in this paper.

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Figure captions

Figure 1. (a) Interface Shear Tester apparatus, (b) detailed view of the Interface Shear Tester sample mounting arrangement, (c) detailed view of perspex bath used for saturated testing.

Figure 2. Normalised shear stress vs horizontal displacement for saturated chalk samples against (a) steel Ra=0.4µm, (b) Ra=7.2µm, (c) Ra=34µm and (d) dry sandstone samples against steel Ra=7.2µm.

Figure 3. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with R_a=0.4µm against (a) dry and (b) saturated chalk.

Figure 4. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with R_a=7.2µm against (a) dry and (b) saturated chalk.

Figure 5. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with R_a=34µm against (a) dry and (b) saturated chalk.

Figure 6. Tensile failure of a dry chalk sample sheared at 1000kPa.

Figure 7. Variation of normalised friction angle with increasing steel roughness, for saturated chalk samples and dry Old Red Sandstone.

Figure 8. Interface friction angle vs horizontal displacement for saturated chalk samples.

Figure 9. Adhesion factor values for chalk and sandstone compared to contours from Ziogos et al 2015 (steel Ra=7.2µm).

Table captions

Table 1. Summary of key Index properties for the Chalk and Sandstone samples.

Table 2. Summary of the interface properties of the materials tested.

Table 3. Comparison of results of chalk-steel interface testing utilising the tilt table and the IST device.

Table 4. Summary of results from interface testing of chalk-steel interface utilising the IST device.

Figure 1a. Interface Shear Tester apparatus.

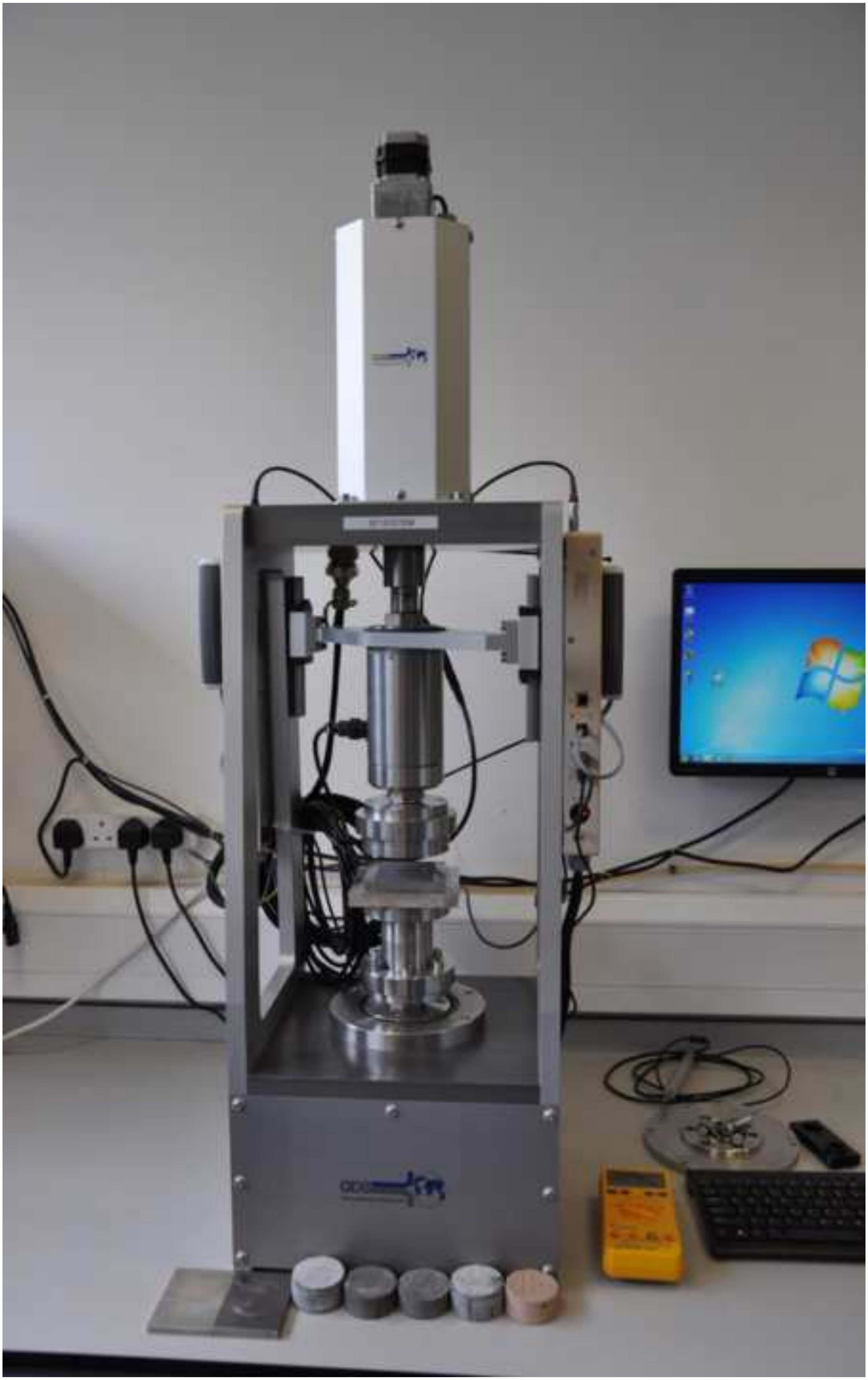


Figure 1b. detailed view of the Interface Shear Tester sample mounting arrangement.

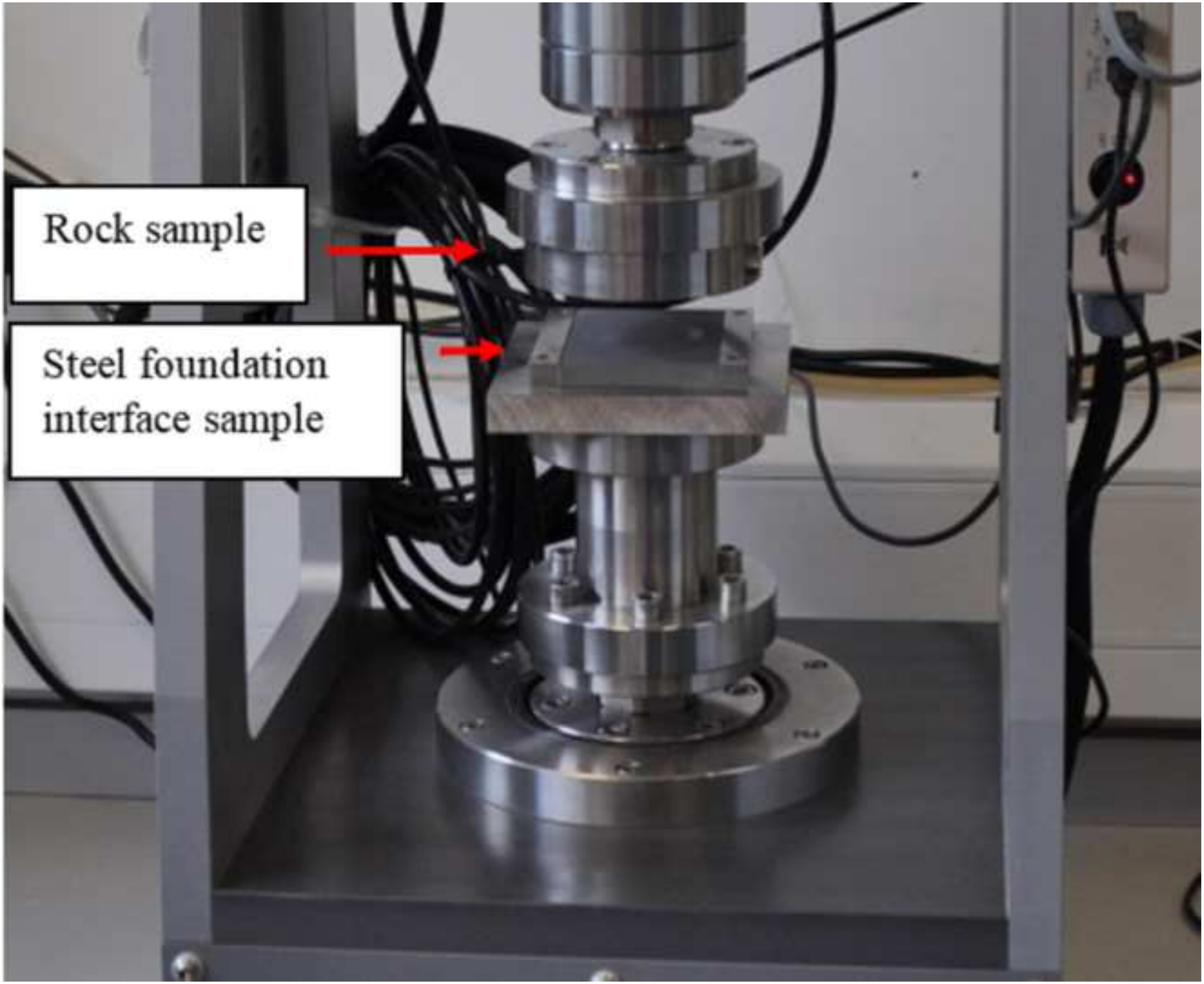


Figure 1c. detailed view of perspex bath used for saturated testing.

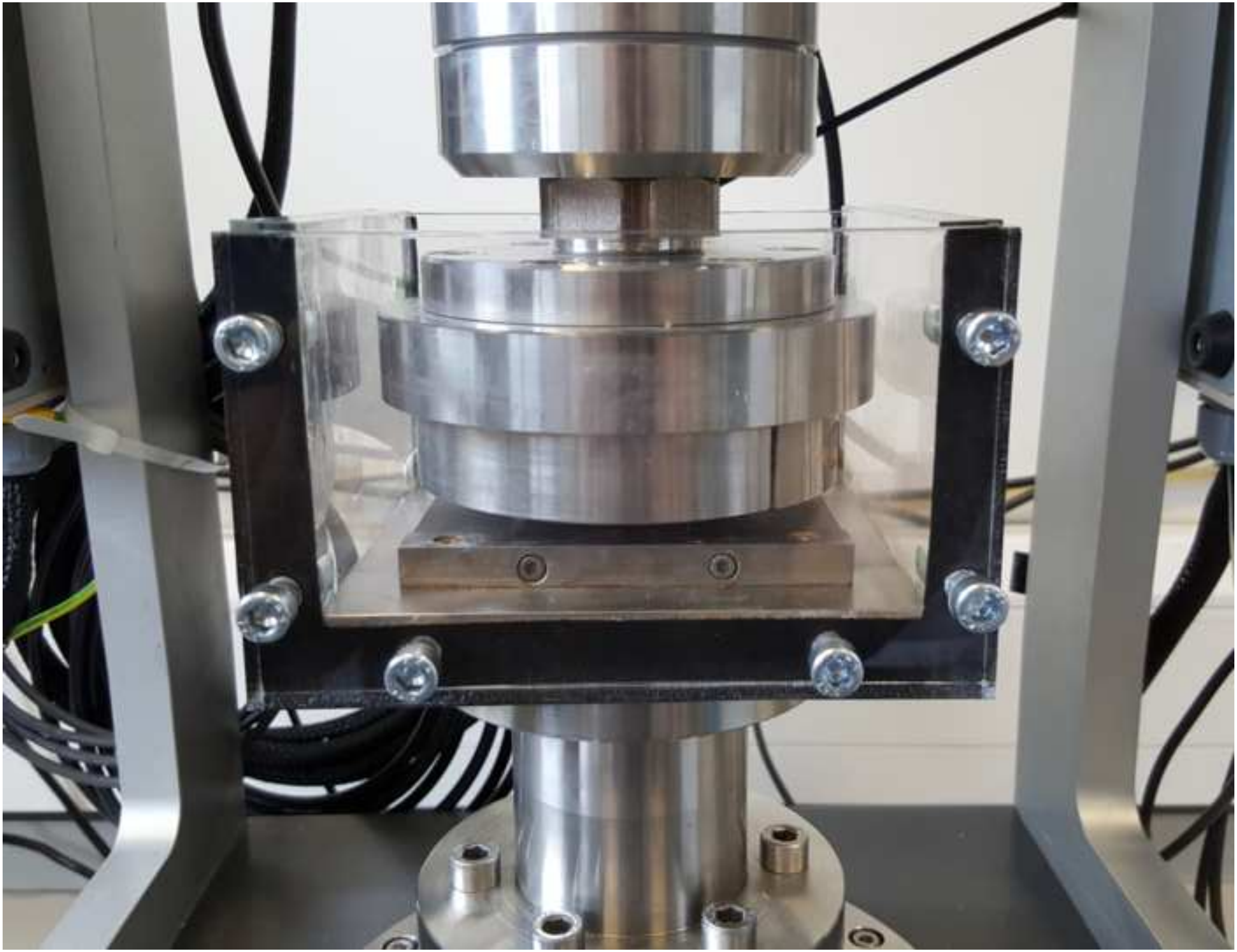


Figure 2a. Normalised shear stress vs horizontal displacement for saturated chalk samples against steel Ra=0.4μm.

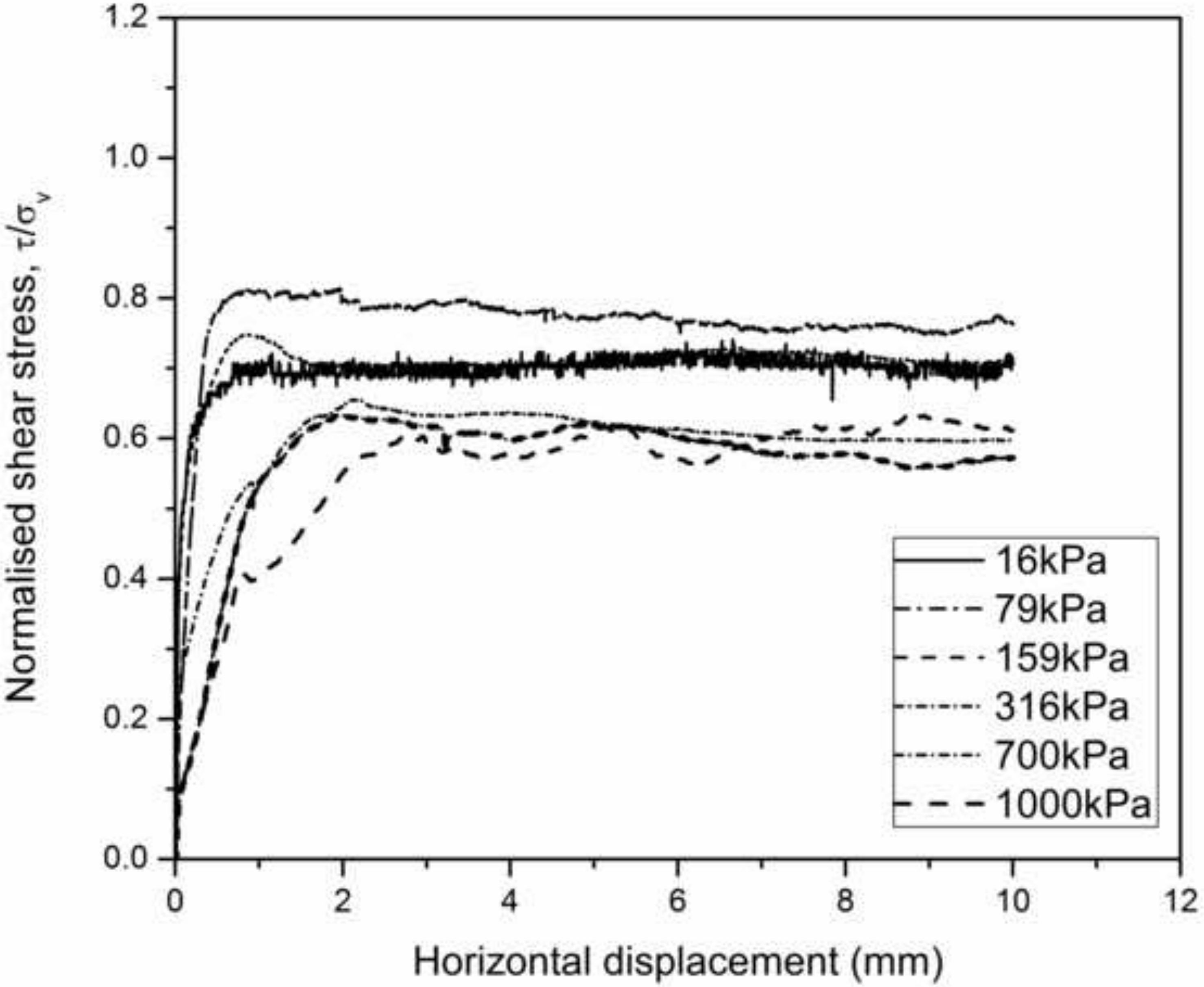


Figure 2b. Normalised shear stress vs horizontal displacement for saturated chalk samples against steel Ra=7.2µm.

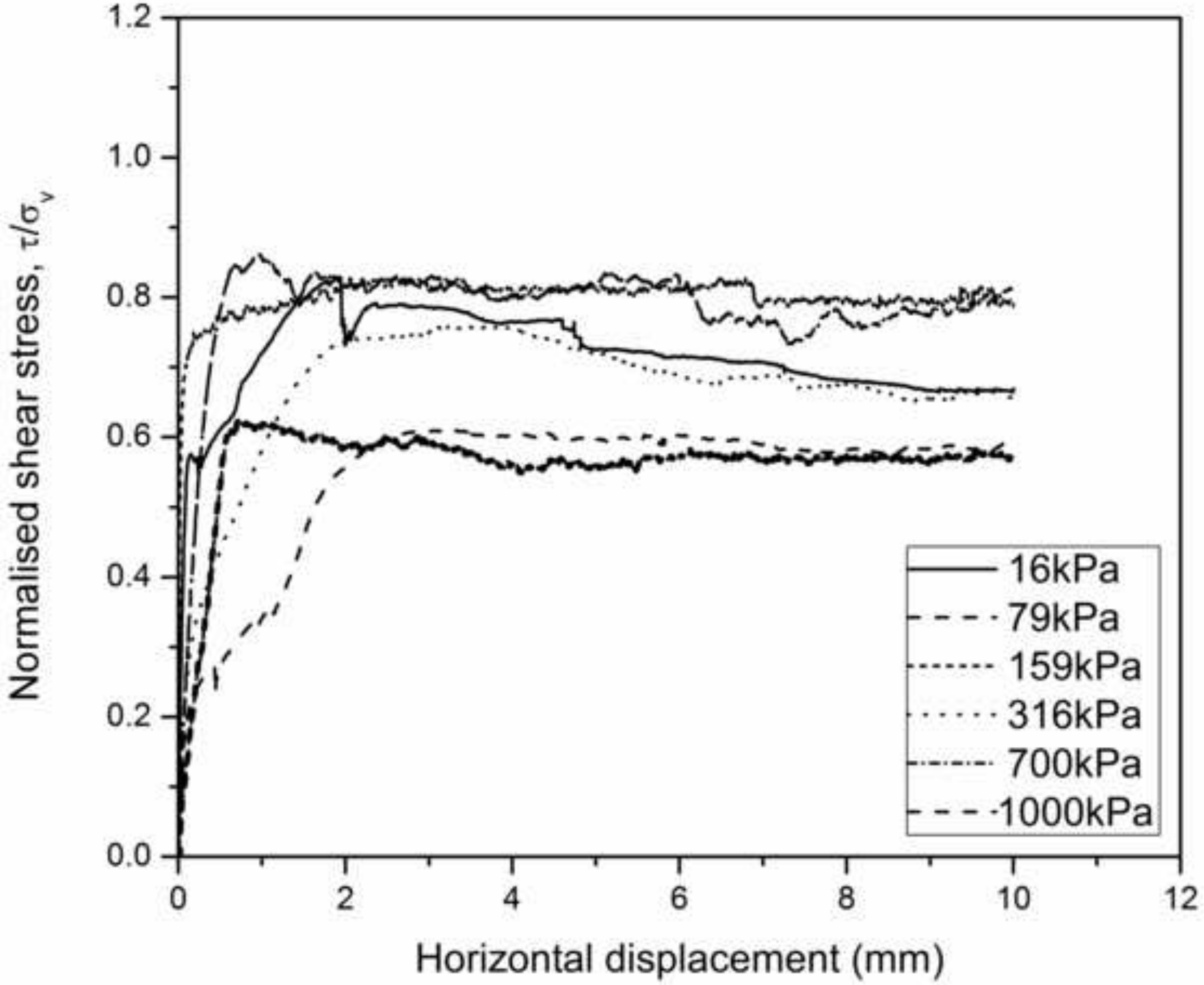


Figure 2c. Normalised shear stress vs horizontal displacement for saturated chalk samples against steel Ra=34μm.

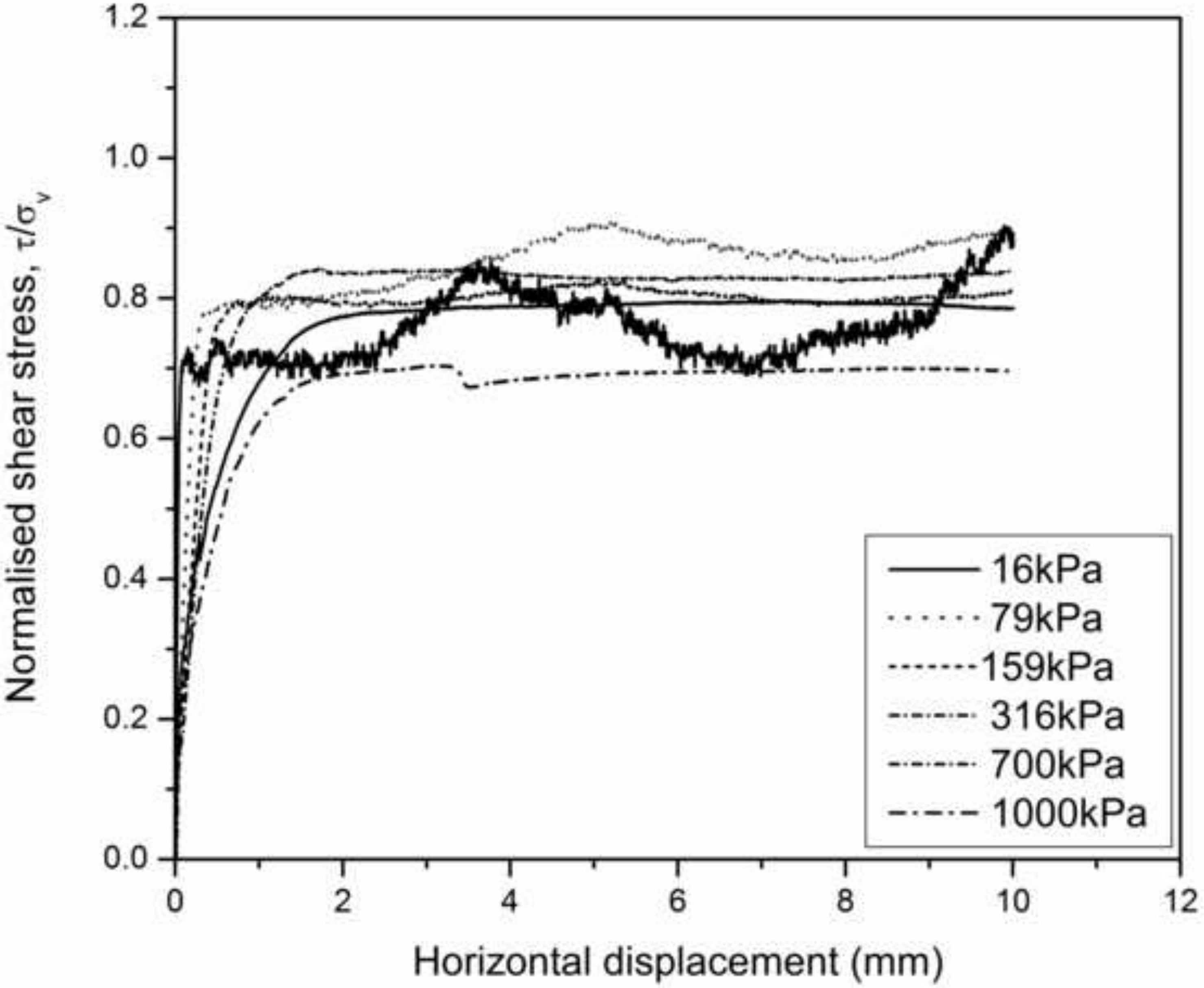


Figure 2d. Normalised shear stress vs horizontal displacement for dry sandstone samples against steel Ra=7.2μm.

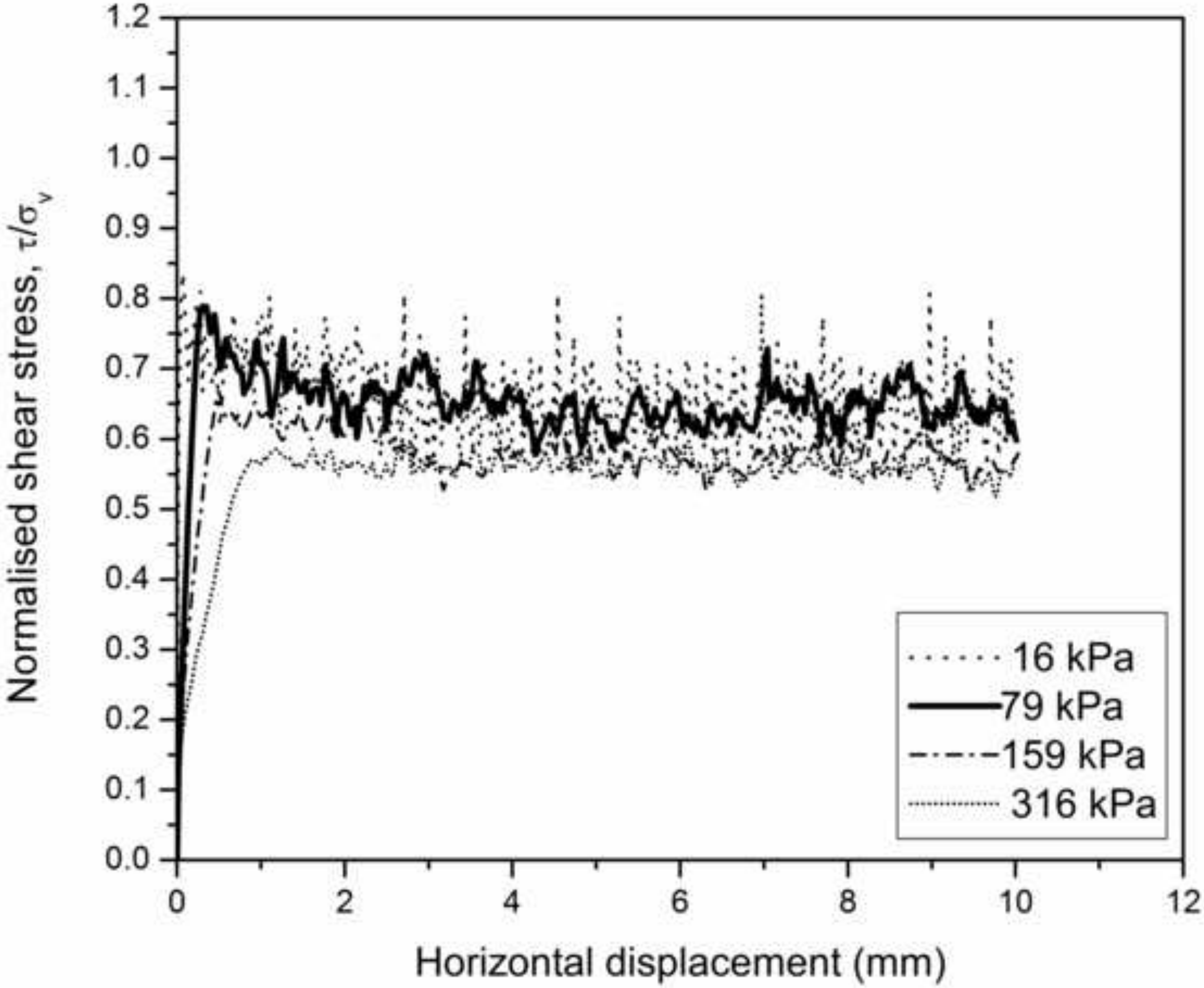


Figure 3. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with Ra=0.4μm against dry chalk.

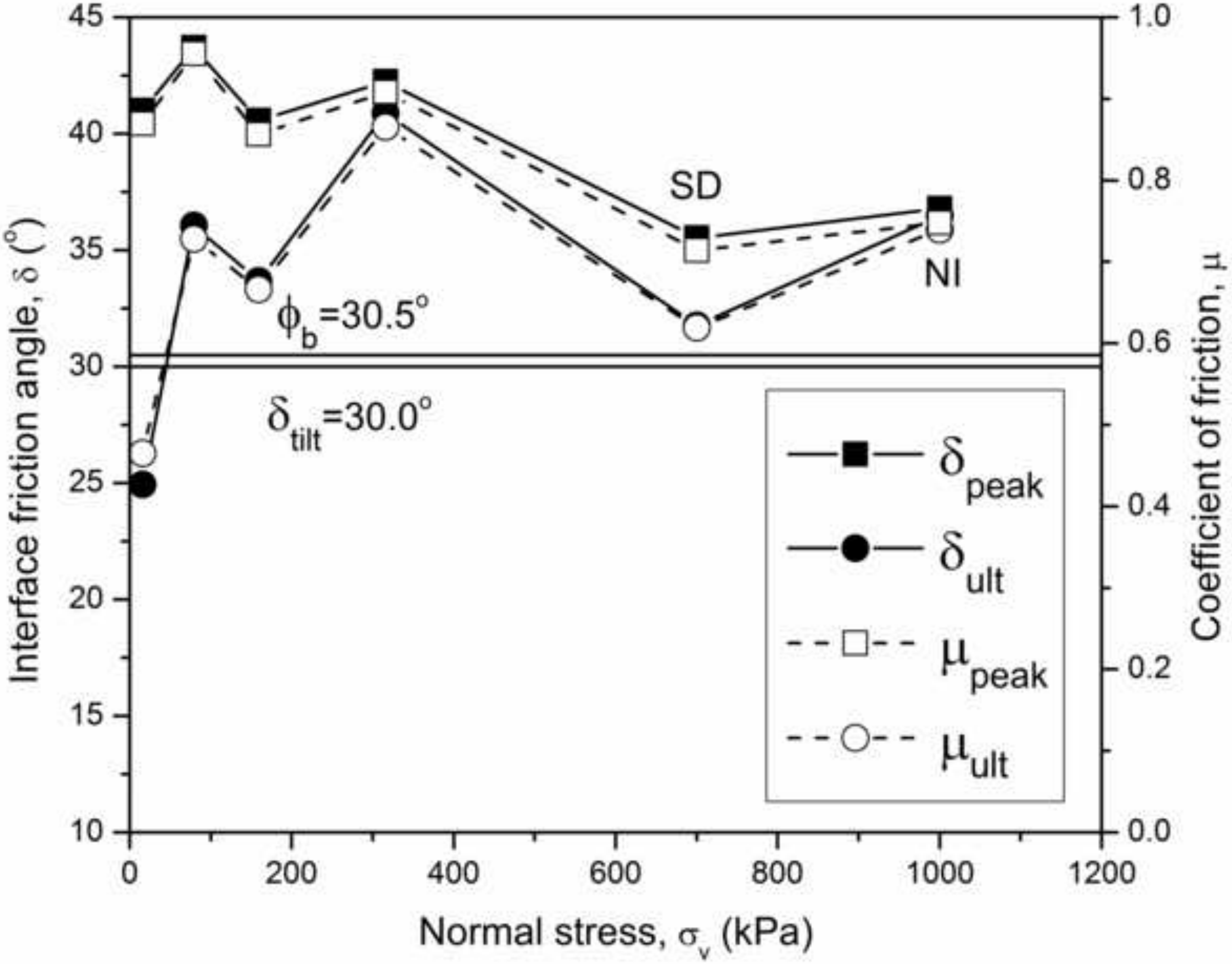


Figure 3b. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with Ra=0.4μm against saturated chalk.

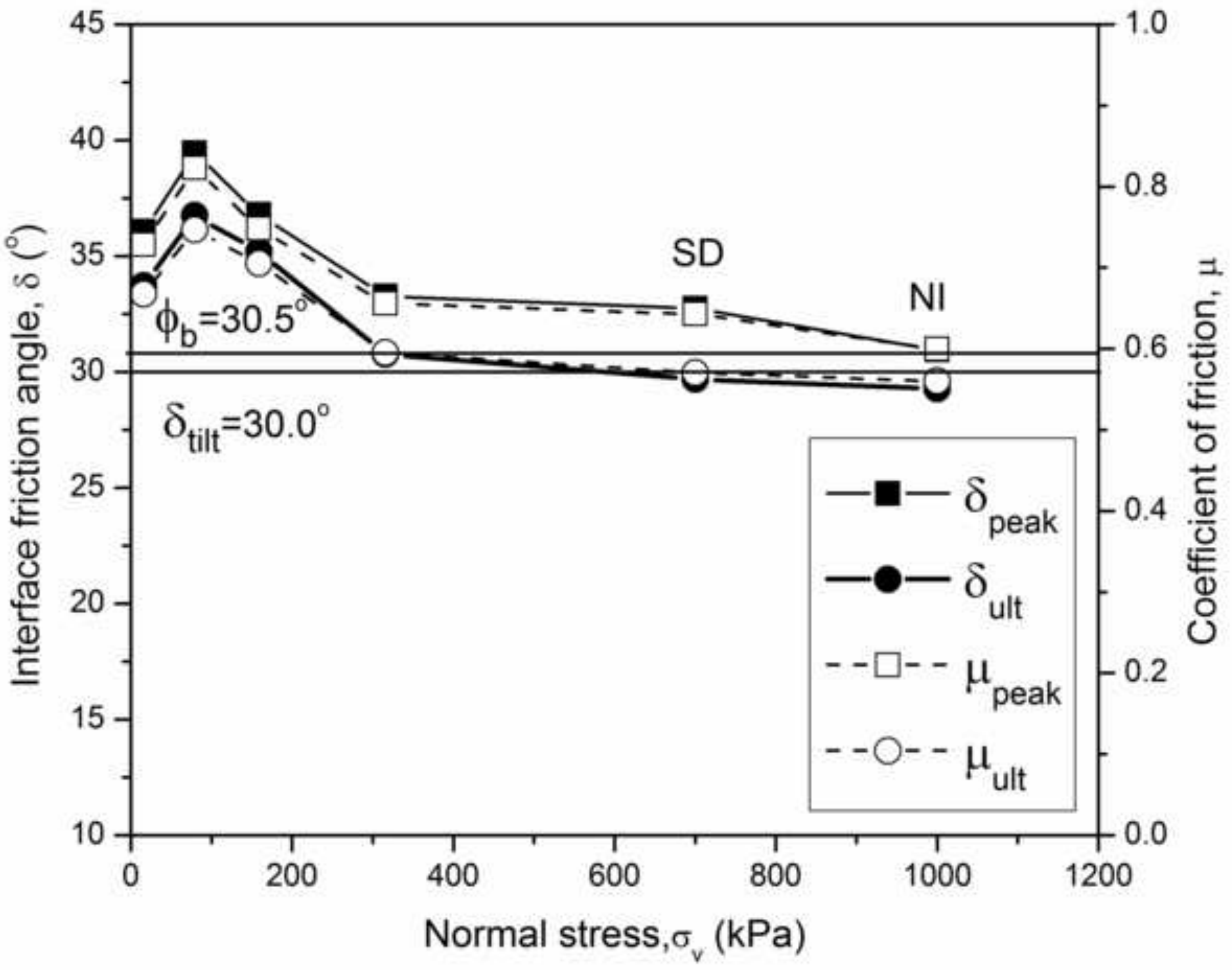


Figure 4a. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with Ra=7.2μm against dry chalk.

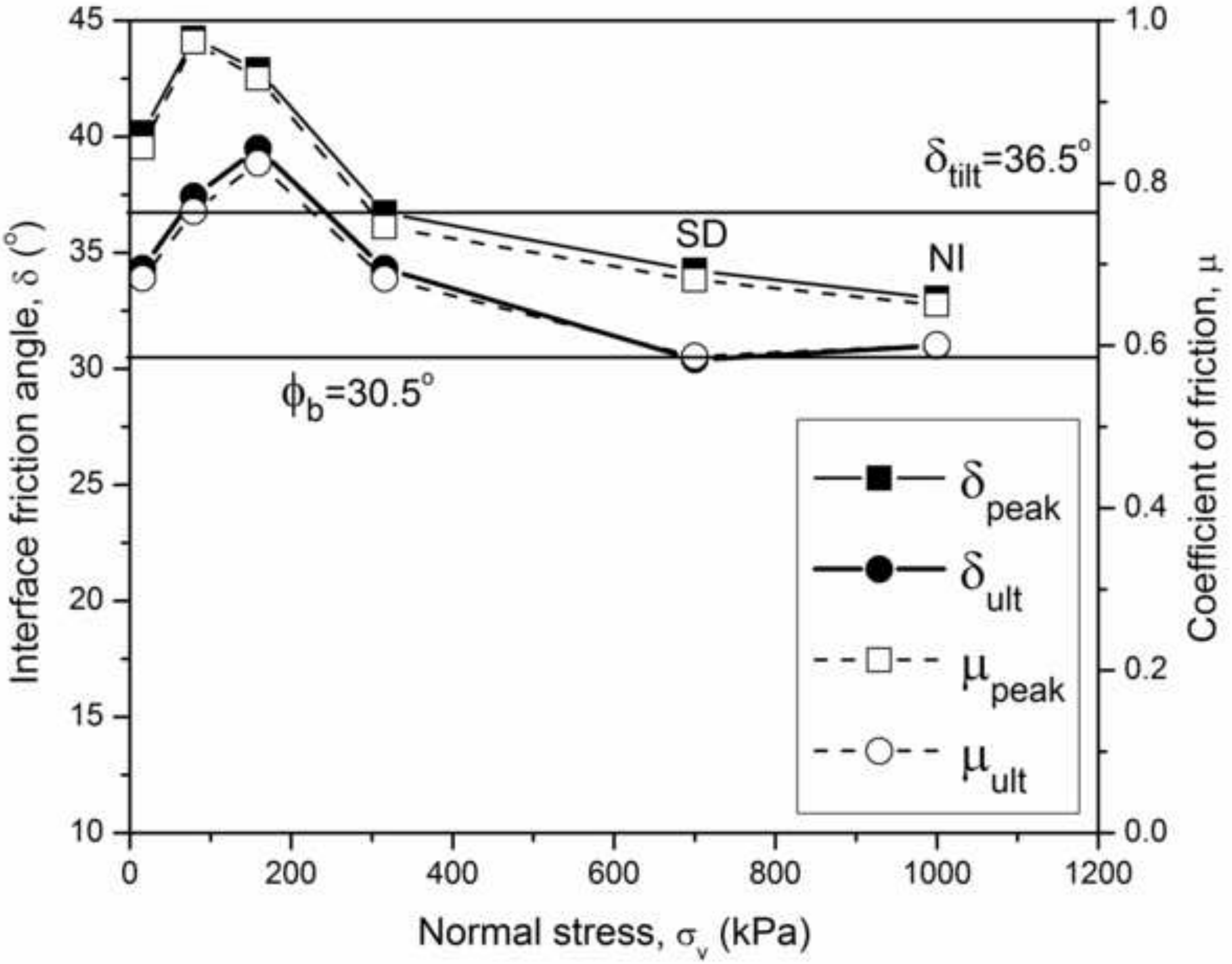


Figure 4b. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with Ra=7.2μm against saturated chalk.

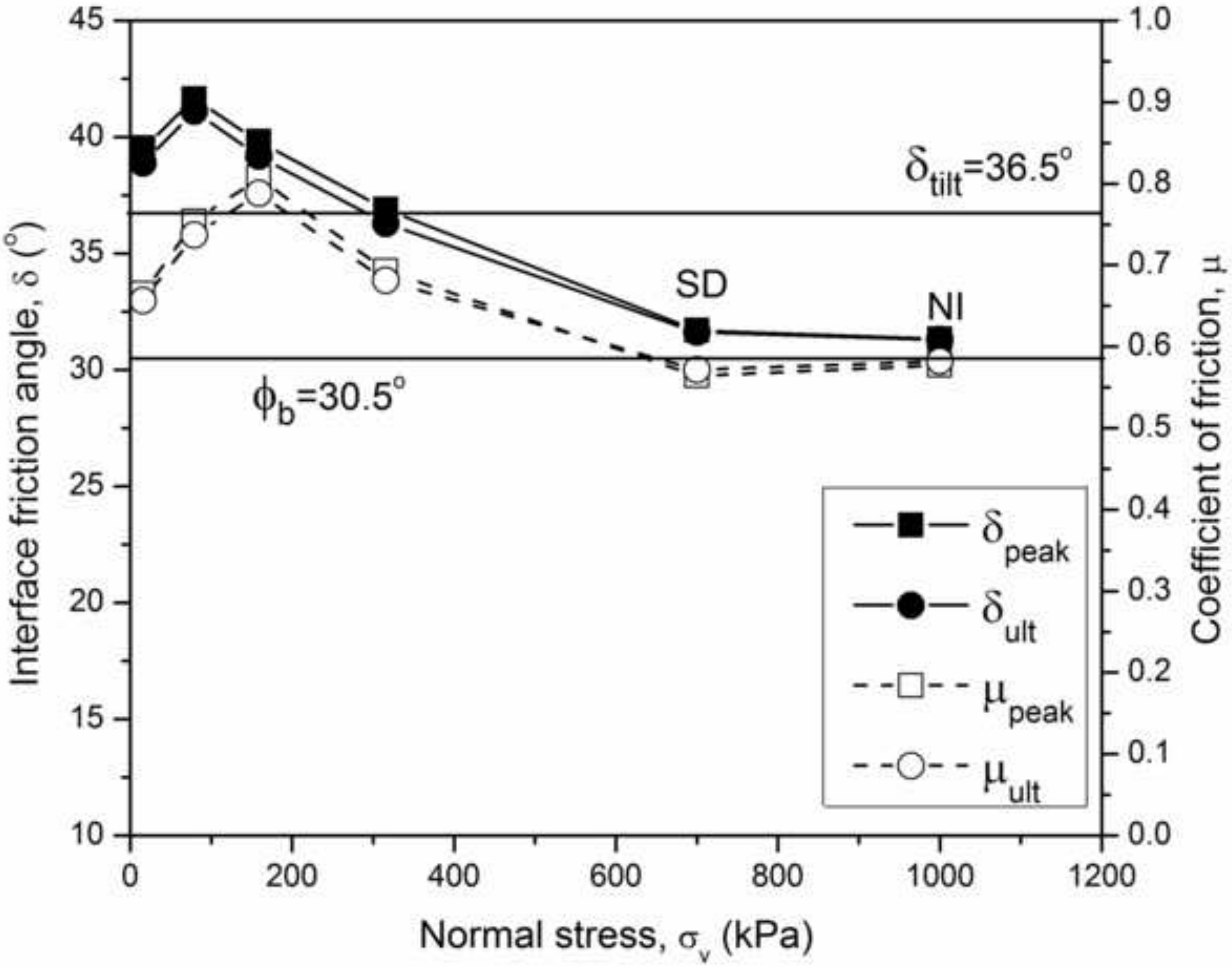


Figure 5a. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with Ra=34μm against dry chalk.

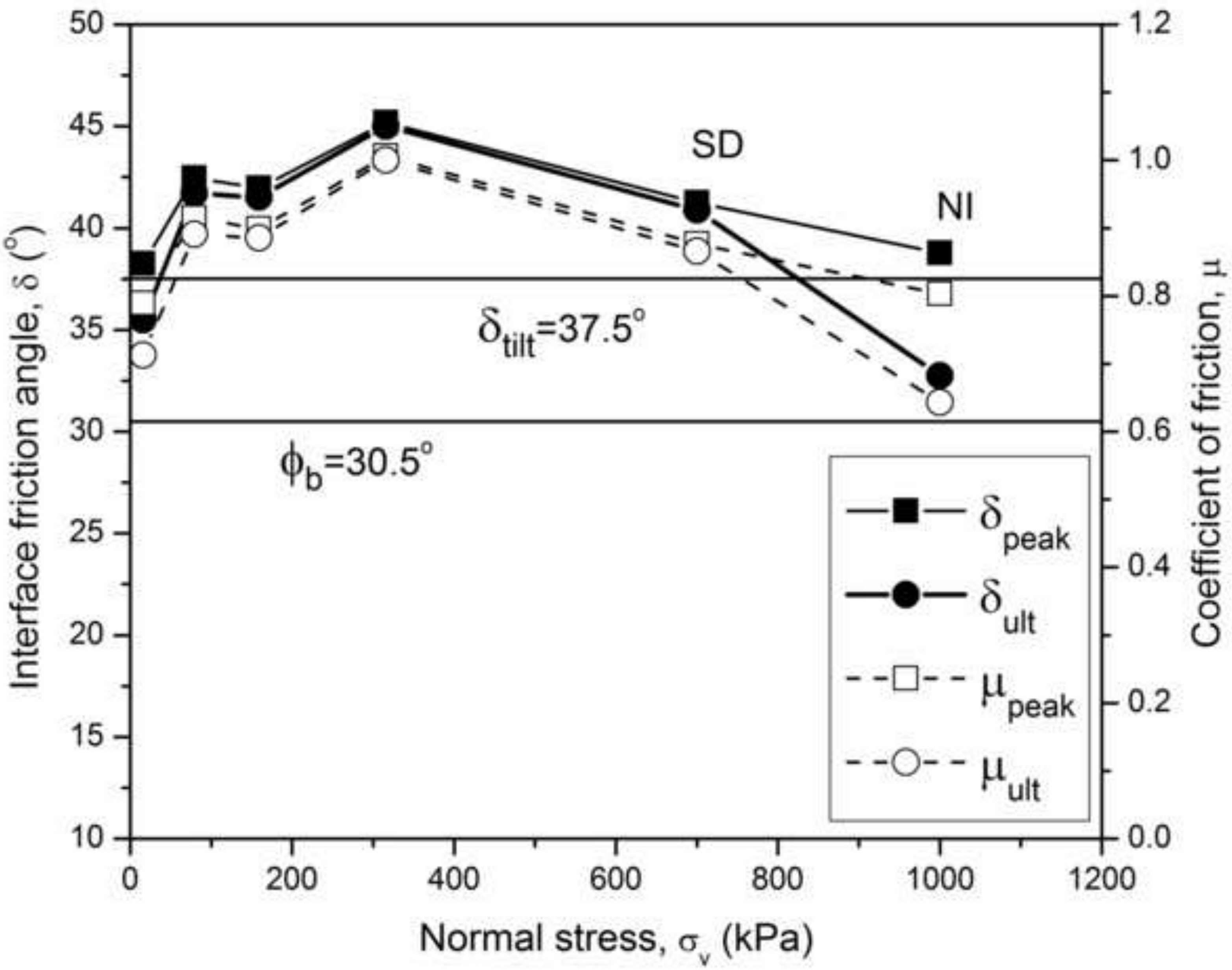


Figure 5b. Variation of interface friction angle and coefficient of friction for chalk-steel interface test for steel with Ra=34μm against saturated chalk.

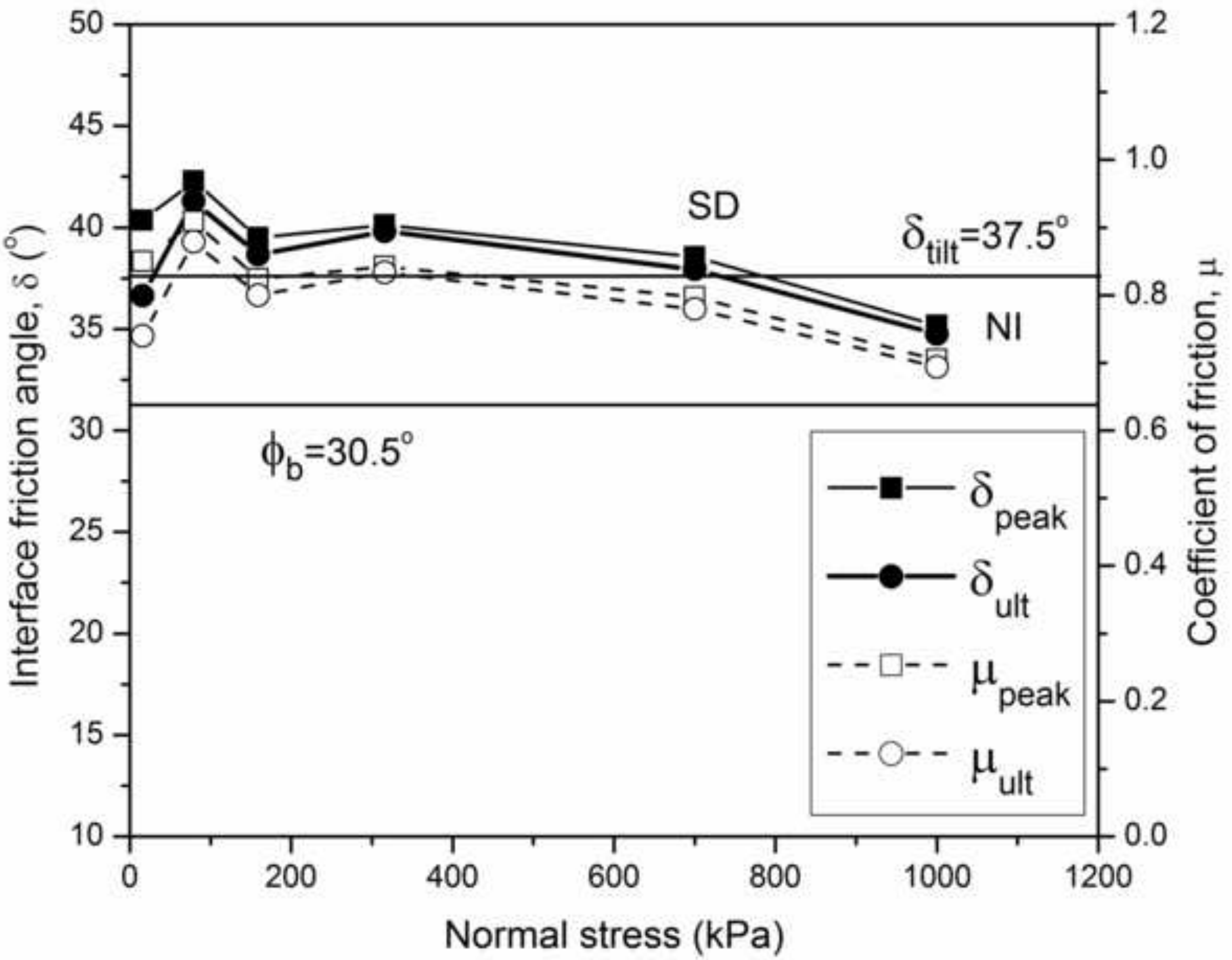
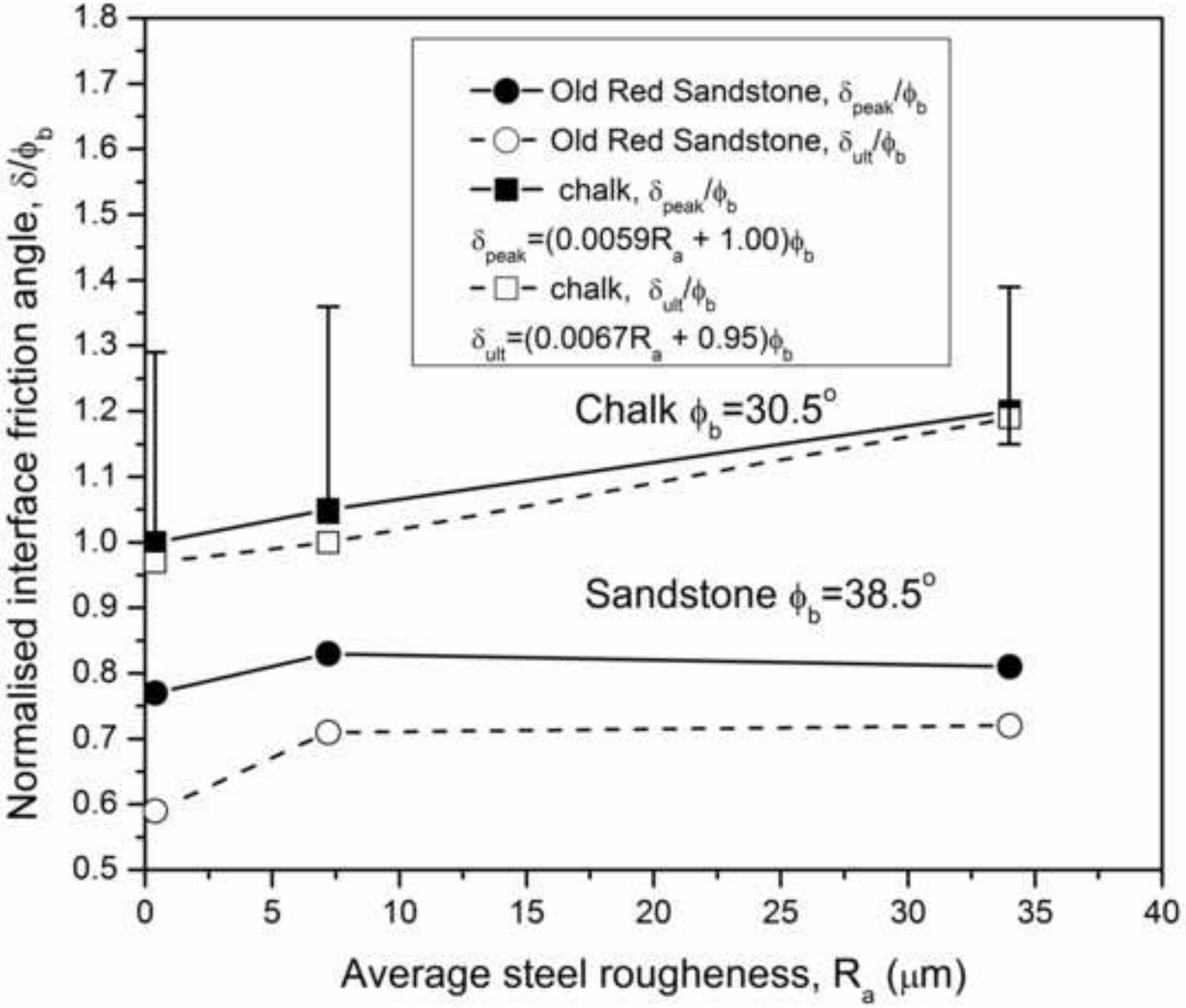
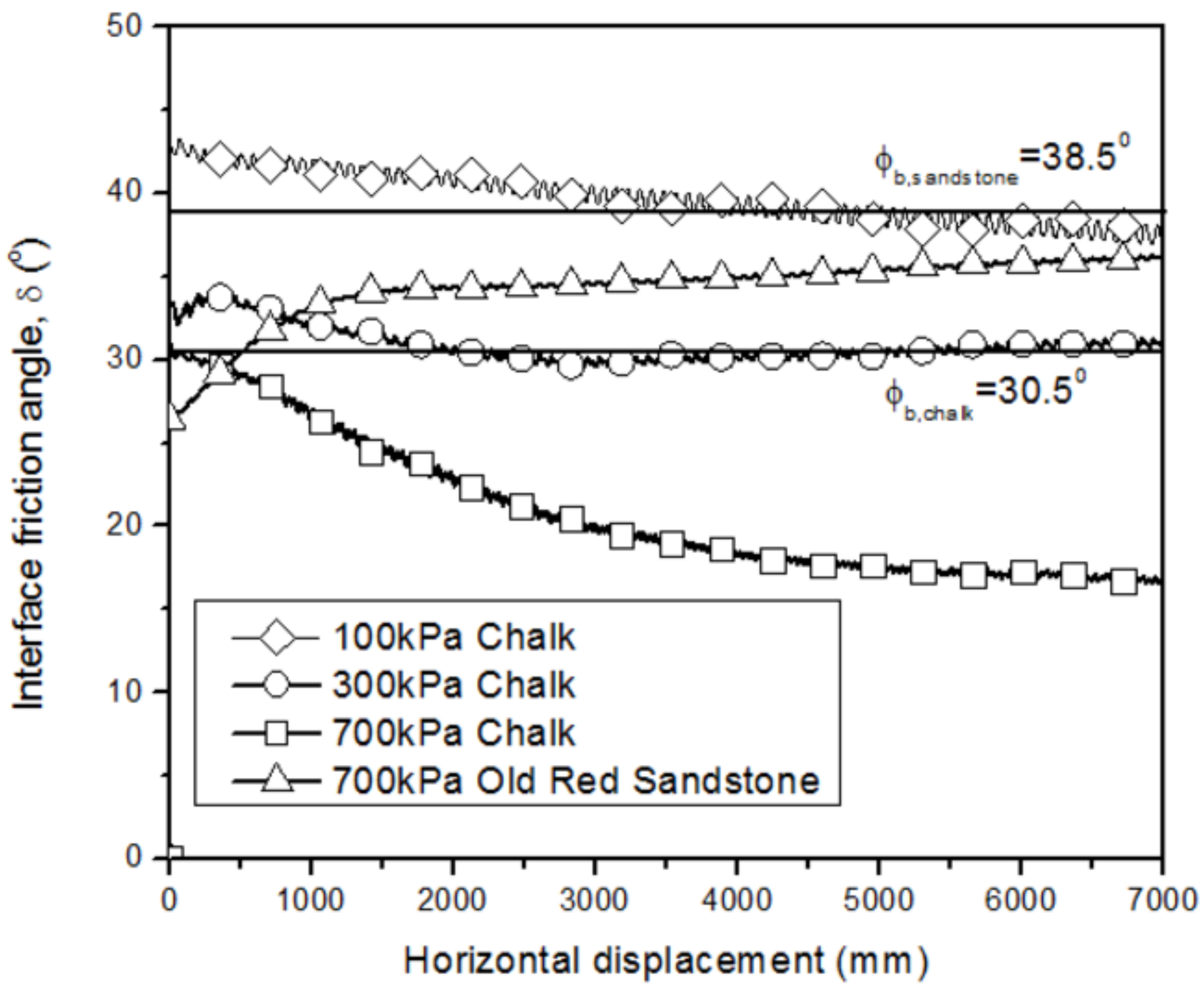


Figure 6. Tensile failure of a dry chalk sample sheared at 1000kPa.

Figure 7. Variation of normalised interface friction angle with increasing steel roughness, for saturated chalk samples and dry Old Red Sandstone.



Interface friction angle vs horizontal displacement for saturated chalk samples



ure 9. Adhesion factor values for chalk and sandstone compared to contours from Ziogos et al (2015).

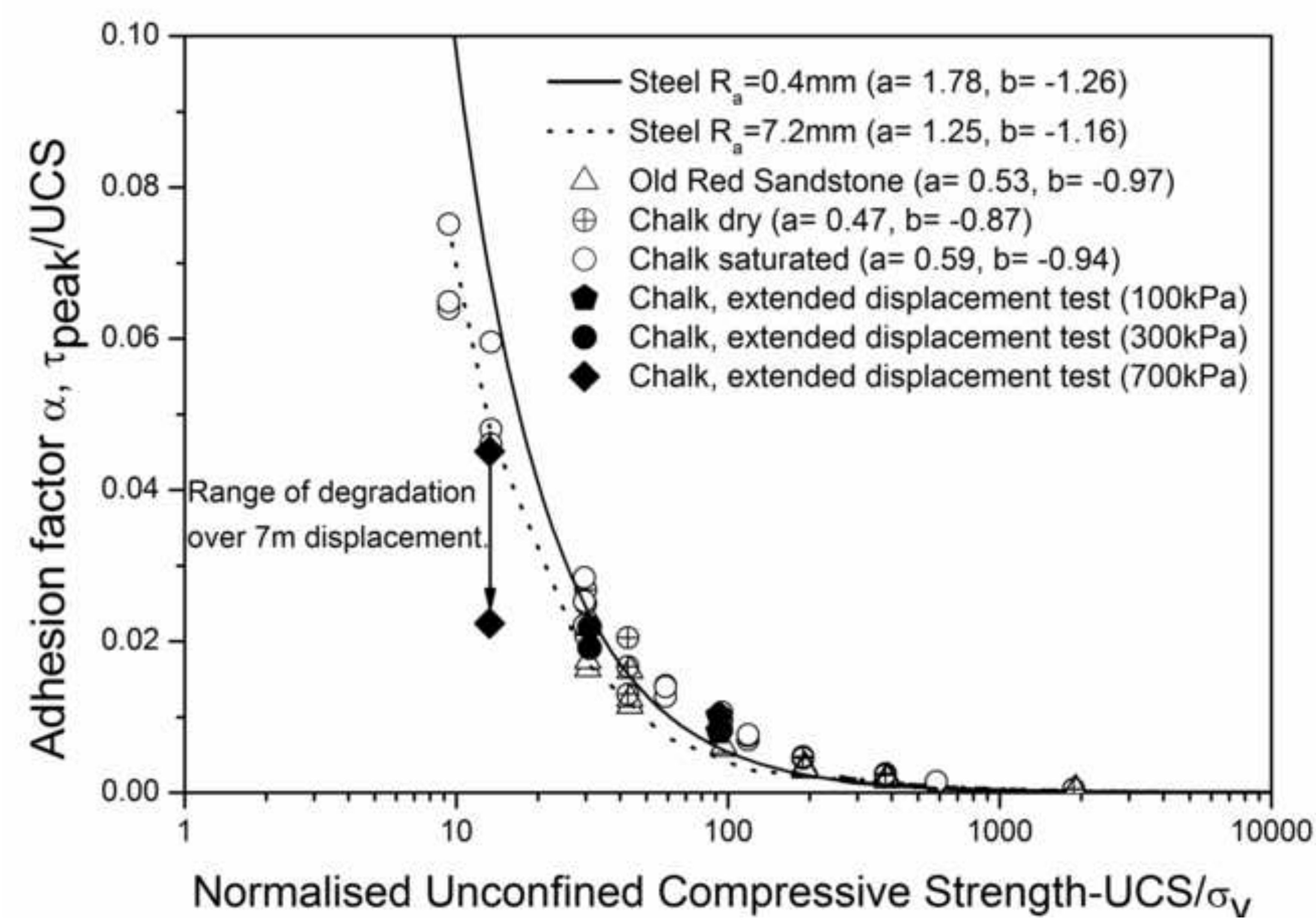


Table 1. Summary of key Index properties for the Chalk and Sandstone samples

Property	Chalk	Sandstone
Dry density, ρ_d (Mg/m^3)	2.06	2.23
Porosity, n (%)	23	13
Voids ratio, e	0.3	0.15
Saturated moisture content, m_{sat} (%)	11.4	6
Specific gravity, G_s	2.7	2.57
UCS, dry samples (MPa)	30.00	31.50
UCS, saturated samples (MPa)	9.30	-
Tensile strength, $T_{0,}$ dry samples (MPa)	1.10	2.60
Tensile strength, $T_{0,}$ saturated samples (MPa)	0.96	-
Young's Modulus, dry samples (GPa)	8.60	10.20
Young's Modulus, saturated samples (GPa)	2.85	-

Table 2. Summary of the interface properties of the materials tested

Material	Average roughness, R_a (μm)
Chalk (saw cut)	3.1
Sandstone (saw cut)	19.0
Polished steel	0.4
Machined steel 1	7.2
Machined steel 2	34.0

Table 3. Comparison of results of chalk-steel interface testing utilising the tilt table and the IST device.

		Interface		
		Chalk-steel R_a=0.4μm	Chalk-steel R_a=7.2μm	Chalk-steel R_a=34μm
	σ_v (kPa)	Measured peak interface friction angle, δ_{peak} (^{o})		
Tilt table	~0.6	30.0	36.5	37.5
IST	16	36.0	39.5	40.5
IST	79	39.5	41.5	42.5
IST	159	37.0	40.0	39.5
IST	316	33.5	37.0	40.0
IST	700	32.5	31.5	38.5
IST	1000	31.0	31.5	35.0

Table 4. Summary of results from interface testing of chalk-steel interface utilising the IST device.

Normal stress (kPa)	Initial sample State*	Post test sample condition[$]	R_a (μm)					
			0.4		7.2		34.0	
			Peak shear stress (kPa)	Ultimate shear stress (kPa)	Peak shear stress (kPa)	Ultimate shear stress (kPa)	Peak shear stress (kPa)	Ultimate shear stress (kPa)
16	D	I	13.9	7.5	13.5	11.0	12.62	11.5
16	S	I	11.5	10.5	13.0	10.5	13.5	12.0
79	D	I	75.5	57.5	76.9	60.5	72.5	70.5
79	S	I	65.0	59.0	70.2	58.0	72.0	69.5
159	D	I	136.0	106.0	147.5	131.0	143.0	141.0
159	S	I	119.0	112.0	132.5	125.5	131.0	127.0
316	D	I	287.0	273.5	235.6	215.5	318.0	316.0
316	S	I	207.5	188.0	237.2	215.0	266.0	263.5
700	D	SD	500.0	433.5	476.3	410.6	614.0	606.5
700	S	SD	450.0	399.0	432.5	400.0	558.0	546.0
1000	D	NI	748.0	739.5	650.3	600.5	803.5	643.0
1000	S	NI	600.0	560.5	608.5	582.0	705.0	694.0

* S = saturated, D = dry samples

[$] I =intact, SD = surface damage, NI = non-intact samples

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