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Understanding Rock-Steel interface properties for use in offshore applications

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Abstract

The properties of unbonded rock-steel interfaces and the characteristics that control this behaviour seems to be an under researched area in terms of geotechnical application for example in the design of gravity-based foundation systems or dead weight anchors and the interaction of pipelines on rock. Whilst basic guidance does exist for rock-rock interfaces or pipeline behaviour, this focuses on macro roughness with little consideration of micro roughness, relative roughness of the surfaces or their strengths and hardness. Therefore in order for design and understanding to develop in these areas there is a need for basic interface friction parameters and understanding of the interface characteristics that control the strength of the interface such that correct values can be used but also so that the interface properties can be best manipulated to improve interface interaction. This paper presents interface friction angles for four types of rock sheared against steel interfaces of different roughness at a variety of normal stresses. The rocks themselves have a range of surface roughness, strength and hardness. The results of the testing programme are used to improve a simple analytical approach for predicting the shear strength of rock-steel interfaces that allows input of key controlling parameters.

Keywords: Geotechnical engineering, Strength & testing of materials, Foundations.
Notation list

b fitting constant
c fitting constant
CNS constant normal stiffness
d linear displacement
D_{50} mean particle size of soil
GBS gravity base structure
IST interface shear tester
M relative hardness ratio
M_{\text{rock}} Mohs relative hardness of rock
M_{\text{steel}} Mohs relative hardness of steel
R roughness ratio
R_a average centreline roughness
R_{a,\text{rock}} average centreline roughness of rock interface
R_{a,\text{steel}} average centreline roughness of steel interface
R_{\text{max}} vertical distance between the highest peak and lowest valley of the steel surface profile
R_{n} relative roughness ratio for granular materials
R_{p} radial position in IST test
r sample radius
T torque
T_0 rock tensile strength
UCS unconfined compressive strength
\alpha normalised shear strength (Alpha factor)
\delta interface friction angle
\theta rotational displacement
\mu coefficient of friction
\phi_b basic friction angle
\sigma_n normal stress
\sigma_v vertical stress
\tau shear stress
1 Introduction

Interfaces between construction materials and rock exist in many geotechnical or rock mechanics applications but often these are bonded due to the use of cementitious materials. For example, at the interface between the base of a dam or cast in situ pile rock sockets (Horvath, 1978; Rosenberg and Journeaux, 1976; Williams and Pells, 1981, Ball et al., 2018) and rock–steel interfaces such as rock bolts (Li and Håkansson, 1999) or H-steel piles driven into rock (Yu et al., 2013). These rock–steel interface examples result in constant normal stiffness (CNS) conditions, which lead to high normal stresses where the interface is subject to shear and constraint of dilation. This can result in interface normal stresses that are much higher than in other applications such as lightweight gravity based foundations or dead weight anchors (tidal stream generator foundations, Ziogos et al., 2017, or anchoring for aquaculture) and subsea pipeline installation and operation (e.g. restraint to axial and lateral walking of pipelines, Griffiths et al., 2019). Previous examples are of concrete bonded to rock or dowelled rock-concrete interfaces and there is a dearth of information relevant to certain applications.

One of the few publications relevant to offshore application NAVFAC (1986) suggests a coefficient of friction, $\mu$, of 0.7 (interface friction angle, $\delta = 35^\circ$) for mass concrete on clean, sound rock. However, 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. Investigation of soil-steel interfaces is more common, for example to aid understanding of pile shaft behaviour (Kishida and Uesugi, 1986, Jardine et al., 1993) where it was found that the behaviour of the interface is affected by the surface characteristics of both interface elements (i.e. shape and size of sand grains, roughness of steel etc.). Therefore, taking account of only the surface roughness is not appropriate and a relative roughness ratio was proposed ($R_n = R_{max}/D_{50}$, where $R_{max}$ is the vertical distance between the highest peak and lowest valley of the steel surface profile and $D_{50}$ is the mean particle size of the soil) to investigate the overall effect of the roughness. It might be assumed that greater guidance on rock-interface shearing behaviour could be found in the rock mechanics or engineering geology literature but interface behaviour in these disciplines normally focuses on rock-rock joint interaction (Barton and Choubey, 1977) or faults where relative block movement may occur and interfaces may be infilled with soil materials. Where rock-rock interfaces are investigated these are considered to be controlled by macro roughness or “waviness” (Griffiths et al., 2019) where roughness is measured in terms of centimetres or metres rather than micro metres (unit normally adopted for average centreline steel roughness measurements, $R_a$).

A simplistic analytical approach for predicting the shear resistance of a rock-steel interfaces was previously outlined by Ziogos et al. (2015a) and Ziogos et al. (2017), referred to as an alpha factor approach which was originally derived from shear box testing of steel against grout interfaces (used as rock analogues where unconfined compressive strength, UCS can be varied for the grout, Ziogos, 2020). This has a similar form to the approach outlined in Tomlinson (2001) to predict the shear resistance of cast-in-situ pile rock sockets which recognises the rock strength (UCS) although only rock-steel interfaces at relative low normal stresses are considered here i.e. not those associated with pile driving.

$$\alpha = b \left( \frac{\text{UCS}}{\sigma_n} \right)^c$$

Where $\alpha = \frac{\tau}{\text{UCS}}$ equals the shear stress, $\tau$ divided by the rock strength (UCS)

Equation 1 can be solved for shear stress ($\tau$) leading to:
\[
\tau = b \frac{\text{UCS}^{c+1}}{a_n^c}
\]

Where: \(\tau\) = shear stress, \(\text{UCS}\) = rock unconfined compressive strength, \(\sigma_n\) = normal stress and \(b\) and \(c\) = arithmetic constants.

Although this approach captures the normal stress applied and the rock strength, it does not recognise the roughness or relative roughness of the interface materials and requires further development for rock rather than grout-steel interfaces.

This paper outlines the results of rock-steel interface testing of various rock types from the United Kingdom considering the effects of normal stress, roughness of the interfaces, rock strength and the hardness of the surfaces. This is used to provide a useful database of material parameters for design and further develop a simplistic method for estimating rock-steel interface shear resistance.

2. Laboratory testing

2.1 Description of rock samples used for laboratory testing

The rock samples were originally selected to reflect rock types at areas of tidal stream generation potential (Sandstone, Andesite and Flagstone) in Scotland where gravity based structures may be deployed (Ziogos et al., 2015b). It was then decided to broaden this to include Limestone, which is generally absent in Scotland, and Chalk (Ziogos et al., 2017), to align with the interest in deployment of wind energy foundations in the UK and Europe (Buckley et al., 2020). The Sandstone and Flagstone samples were sourced from the Caithness area of Scotland (North East), UK. The Sandstone came from Warth Hill disused quarry, south of John O’Groats, Scotland (National Grid coordinate: ND37150 70138). The Old Red Sandstone was yellow-orange in colour and medium grained (Johnstone and Mykura, 1989) and described as medium strong. The Flagstone was obtained from an active Caithness Flagstone quarry (Devonian, Spital Flagstone formation) near Achscarbet (National Grid coordinate: ND07829 63333). Caithness Flagstones are laminated siltstones and mudstones (Geological Survey of Scotland, 1914). The samples collected were very strong fine grained and dark-grey in colour. The Limestone samples were obtained from the active Limestone quarry near Dunbar, East Lothian, Scotland, UK (National Grid coordinate: NT71668 76718). The Limestone was a very strong Middle Skateraw Limestone, a fine grained, grey coloured Carboniferous Limestone from the Lower Limestone Group (British Regional Geology, 1971). The Andesite samples were recovered from the active Ardnowie quarry located 8 km north east of Dundee, Scotland, UK (National Grid coordinate: NO48752 33934). The quarry lies in the Devonian, igneous Ochil volcanic formation, and the Andesite consist of a fine grained, very strong dark grey coloured igneous rock (Armstrong et al., 1985). Further details on the sampling and local setting of the rock samples used to prepare the element tests can be found in Ziogos (2020). Images of the saw cut rock samples prepared for testing are shown in Figure 1.

2.2 Scope of testing

Interface testing between rock–steel interfaces at normal stresses relevant to those anticipated in real tidal stream projects (Ziogos et al., 2015b) had previously been used in order to obtain the friction properties necessary for the determination of the sliding resistance of a gravity based structure (GBS). The same level of normal stresses was used here. In addition, the effect of steel roughness was investigated \((R_s =0.4, 7.2 \text{ and } 34 \text{ \mu m})\), Table 1, \(R_s\) refers to centre-line average roughness, as outlined in section 2.6) along with the effect of normal stress \((\sigma_v \text{ or } \sigma_n = 16, 79, 159 \text{ and } 316 \text{ kN/m}^2)\) over displacements of 10 mm during shear. The range of steel roughness investigated covers the roughness of some of the steel elements commonly found in geotechnical applications (for example, \(R_s = 5–10\))
μm for steel piles, Barmpopoulous et al., 2010). Initially, tilt table testing of rock-rock interfaces was undertaken to define the rock-rock basic friction angle (φb) which is a common parameter in rock mechanics. This was followed by rock-steel interface testing to allow comparison of the interface measurement using this simplistic equipment with that of the more advanced IST testing (Interface shear tester, as introduced in section 2.4). This was then followed by the use of the IST to test rock-steel interfaces over a range of normal stresses. IST testing and tilt table testing were undertaken in parallel to see if the results of the low-cost tilt table could be used to derive useful interface characterisation without the requirement for more specialised equipment.

2.3 Tilt table testing

Prior to the main interface testing the basic friction angle (rock-rock) of the rock samples (e.g. Sandstone, φb =30-5°) was determined using the tilt table test in line with the methodology outlined in USBR 6258 (USBR, 2009). This involves tilt table testing of two 54 mm diameter rock samples of 27 mm thickness placed on top of each other (this size of sample was used for all testing). The samples were prepared by coring of a block of the sampled rock and then dry crosscutting of the core using a diamond saw. The interface frictional resistance was determined on this saw-cut surface (as per USBR 6258) for all tilt table and IST testing. The φb determined for the various rock types is summarised in Table 2. Previous results from the low normal stress tilt table tests show good correlation with the more advanced testing techniques at elevated stress levels (Ziogos et al., 2017, Ziogos, 2020). Apart from using the tilt table test to determine the basic friction angle, this simple test was also used to test the rock samples against the steel interfaces (Figure 2) to see how the more advanced testing compared with the basic tilt table test. All samples tested in this study were dry. The tilt table consisted of a Controls joint roughness coefficient test device (32-B0096) capable of inclination of up to 50 degrees with a top surface plate of square area 265 mm by 170 mm.

2.4 Description of the Interface shear tester (IST) device

A computer-controlled torsional interface shear tester (IST, GDS Instruments, UK) was used for interface shear testing (Figure 3). This device consists of an axial actuator at the top of the rig, which can apply up to 5 kN of vertical load, and a rotational actuation system at the base, capable of applying torque up to 200 Nm. Below the axial actuator is a combined load/torque cell arrangement with capacities of 5 kN and 200 Nm, respectively. The axial actuator applies the normal load to the samples under test and is fixed against rotation, whereas the rotational actuator applies the torque/rotation from below. Images and a more detailed description of this equipment can be found in Ziogos et al. (2017) and Ziogos (2020).

A clamping system was developed to allow rectangular interchangeable steel interface elements of 65x90 mm with a thickness of 8 mm to be clamped at the base of the rig above the rotational actuator. Similarly, below the load/torque load cell a clamping device was developed to clamp the rock samples. During the test, the upper rock sample was fixed while the lower steel sample rotated. During the tests torque and normal load were measured using the calibrated torque/load cell and vertical and rotational deformation measurements were automatically calculated by the counts of the stepper motor driving the low rotational actuation.

The tests were conducted under constant normal stress conditions on dry samples under four different normal stress levels of 16, 79, 159, 316 kPa. The shearing rate was 0-005 mm/s of equivalent horizontal displacement. Each test was terminated at an equivalent horizontal displacement of 10 mm (42.5° rotational displacement). The torque measured was converted to average shear stress as per Equation 3 after Saada and Townsend (1981) for ring shear testing.
\[
\tau = \frac{\tau}{\int_0^r \frac{r}{2\pi r^2} dr} = \frac{2}{2\pi r^2} \frac{\tau}{r}
\]

The radial deformation was converted to a linear displacement at a reference point considered at a
distance equal to half of the radial length of the circular rock sample, as per Equation 4.

\[
d = \frac{\theta \pi}{360}
\]

where \(\theta\) is rotational displacement, \(\tau\) is shear stress, \(d\) is linear displacement, \(r\) is the rock sample
radius, \(R_p\) is radial position and \(T\) is torque.

2.5 Description of steel interface samples

Mild steel (EN24T) was used to prepare the rectangular (65×95×8 mm) steel plates. As discussed in
the introduction (Ziogos et al., 2015a, 2015b), roughness has a major effect on the interface behaviour,
therefore different preparation techniques (polishing and machining) were applied and resulted in
plates with a wide range of surface roughness (\(R_s\) between 0·4 and 34 μm). Polishing with a surface
grinder using a BAA60 – K7V wheel resulted in surface roughness average \(R_s\) = 0·4 μm. Machining,
using a shaping machine and an appropriately adjusted shaping tool, resulted in \(R_s\) values of 7·2 and
34 μm.

2.6 Rock and steel characterisation

The Interface roughness parameter selected to reflect the rock and steel roughness was \(R_s\) (centre-
line average roughness), which is the average of all deviations of the roughness profile from the
median (centre) line over a defined profile length (Degarmo et al., 2003). A Taylor Hobson Surtronic
Duo stylus contact profilometer was used to determine \(R_s\). For each sample and interface, five \(R_s\)
measurements were taken and the mean value was selected. The average interface properties of the
materials used for testing (rock and steel samples) are summarised in Table 1 and 2. In line with similar
approaches for sand-steel interfaces a relative roughness (\(R\)) approach was used in this study:

\[
R = \frac{R_{a,steel}}{R_{a,rock}}
\]

Steel plates with \(R_s = 0.4, 7.2\) and 34.0 μm were used, leading to values of roughness ratio (\(R\)) between
0·021 (rock significantly rougher than steel) and 12.592 (steel significantly rougher than rock).

The hardness of both the rock and steel interfaces (Table 3) was determined by the relative scratch
test using hardness picks manufactured from different materials and hardness with each pick designed
to reflect a particular Mohs hardness (between 2 to 9). The process of determining Mohs hardness is
to attempt to scratch the surface of interest with a pick. The pick will either scratch the surface (if pick
is harder than the surface), slide across it (indication of equal Mohs hardness) or leave behind a streak
of the material of the pick (is softer than the surface). Based upon a trial an error process and varying
the picks is it possible to determine an approximate material hardness. Although the methodology
seems relatively simplistic the Mohs Hardness for the mild steel used is equal to 4 which converts to
a Vickers Hardness of 315 kg/mm² (Vickers Hardness was not measured directly and is only given as
an indicative value based upon conversion outlined in Petrescu, 1999). This is consistent with the
manufacturer’s upper hardness values specified for the mild steel (252-303 kg/mm²).

Unconfined compression (direct method) to determine the unconfined compressive strength (UCS)
normally consists of crushing rock cylinders. According to ISRM (2007), the cylinder should have height
to diameter ratio equal to 2. For this research, 54 mm diameter samples were used, suggesting 108
mm high samples would be needed for standard UCS testing. Due to the inconvenient dimensions of
the rock blocks retrieved from the field (not thick enough), cores appropriate for crushing in this
manner were only obtained from Sandstone samples. Thus, for the rest of the rock types, it was necessary to correlate the UCS to the tensile strength ($T_0$) using the Brazilian test. Equation 6 was used to correlate tensile strength to UCS and was proposed by Altindag and Guney (2010), after analysing experimental data from various rock types.

$$UCS = 12.308T_0^{1.0725}$$

Three tests per rock type were carried out and the mean value was used to calculate UCS. The results are summarised in Table 2.

### 3 Results and discussion

#### 3.1 Effects of surface roughness and normal stress

Typical data from IST testing is shown in Figure 4 for the Flagstone. A summary of all test data is provided in Table 4. The various interface combinations indicate a relatively similar response to that in Figure 4 with a slightly elevated initial shear stress (peak) followed by a reduction in shear stress post peak (or ultimate) and then remaining relatively constant until the end of the test. Typically, peak shear stress is observed at increasing displacement levels as normal stress increases though it is noted that peak shear stresses are reached at displacements typically less than 0.5mm suggesting that in-service design of such interfaces should be based upon ultimate rather than peak resistance. The data is generally rather “noisy” compared to conventional interface testing (sand – steel interfaces) due to the solid nature of the rock-interface. The asperities on a conventional steel surface apply stress to the grains of the sand during shearing resulting in displacement of the grains and the sand element is deformed (compliant interface). When two solid samples are sheared (i.e. steel and rock), the asperities of both elements of the interface are interacting, however the shear stress generated may not be adequate to cause significant deformation of the samples (i.e. non-compliant interface, especially under low normal stress levels). As a result, the shear stress generated fluctuates due to the surface topography of the elements.

Comparison of the relative behaviour of the different rock types against a steel interface with the same roughness for all rock types is shown in Figure 5. The Sandstone interface (the roughest of the rock types tested) exhibits the highest interface friction angle values ($\delta$). Flagstone and Andesite have very similar $R_s$ values (Table 4) and broadly similar interface friction behaviour albeit with lower friction angles for the Flagstone (Figure 5). Limestone is significantly smoother resulting in the weakest interface especially for smoothest steel interface ($R_s = 0.4 \, \mu m$).

Figure 6 shows how the peak and ultimate interface friction angles of the various rock types tested against the steel interfaces varies with respect to applied normal stresses. The basic friction angle ($\phi_b$) is also shown (rock-rock). In addition to the basic friction angle, the figure shows the range of tilt table results for the different steel surface roughness ($R_s = 0.4$ and $34 \, \mu m$, rock-steel). The results are also annotated with the relative roughness ratio, $R$. Figure 6 shows that irrespective of the rock type, the interfaces typically exhibit the highest friction angle at the low normal stress of 16 kPa. The interface friction angle decreases with increasing normal stress up to 159 kPa and tends to a lower value between 159 and 316 kPa where little variation is noticed. This decrease of interface friction angle with increasing normal stress is in accordance with the findings of Abuel-Naga et al., (2018). They investigated the effect of the surface properties (roughness and hardness) of glass fibre reinforced polymer, copper, mild steel and high carbon steel on the shear behaviour of continuum – granular material interfaces and found that the interface friction angle reduced with increasing normal stress. They conducted interface shear box tests at normal stresses of 56, 97 and 184 kPa and a reduction of
up to 25% was observed when the normal stress increased from 56 to 184 kPa, however the mechanism was not discussed further.

Based on Figure 4, and also by comparing the peak and ultimate values for each individual rock – steel combination (Figure 6), it can be seen that all the interfaces exhibit a “brittle” type behaviour where in general the ultimate friction angles are significantly lower than the peak values (by over 50% in some cases). At low normal stress levels (16 kPa), peak interface friction angle values (Figure 6a, c, e, g) tend to the basic friction angle (\(\phi_b\)) which is usually (apart from Limestone) higher than tilt table results for the rock – steel interface tests. Thus, this could be proposed as a method to determine the upper bound shear resistance using a simple tilt table and at low stress suggests the rock interface is dominating the interface behaviour. This though is not clear in the case of limestone. It would also appear that for the rougher rock samples (Sandstone and Andesite) that the tilt table testing could be used to bracket the complete behaviour (Figure 6a, b, e, f) over a range of rock–steel relative roughness.

When the smoothest steel interface is considered (\(R_s = 0.4 \mu m\)), the roughness ratio (R) values vary between 0.021 (Sandstone) and 0.148 (Limestone) (Table 1). The Sandstone which has the roughest surface (\(R_s = 19 \mu m\)) – polished steel interface is the strongest (Figure 5), exhibiting \(\delta_{peak}\) between 38° and 29° (Figure 6a) and \(\delta_{ultimate}\) between 29° and 24° (Figure 6b) depending on the applied normal stress (Table 4). In the case of Flagstone (\(R_s = 5.5 \mu m\)), the interface yields lower peak (\(\delta_{peak} = 33° - 18°\)) and ultimate values (\(\delta_{ultimate} = 25° - 13°\)) depending on normal stress (Figure 6c, d). Whereas, for Andesite (\(R_s = 5.8 \mu m\)), \(\delta_{peak}\) ranges between 27° and 25° and \(\delta_{ultimate}\) is remarkably consistent around 21° irrespective of normal stress (Figure 6e, f). For Limestone (\(R_s = 2.7 \mu m\)), which is the smoothest rock tested, the interface becomes significantly weaker, exhibiting \(\delta_{peak}\) between 17° and 10° and \(\delta_{ultimate}\) between 13° and 7° (Figure 6g, h). It would appear that these lower values are a result of very low surface roughness of both interacting materials (i.e. Limestone and steel, \(R=0.148\)). The effect of relative roughness, R, is considered separately in Figure 7.

The average interface friction angle of the tests at 159 and 316 kPa (where the interface behaviour seems to be more consistent) is shown for each individual rock – steel combination (Figure 7). Although it might be expected that relative roughness, R may dominate behaviour it is apparent that the variation of R doesn’t have the same effect on all the interfaces. Sandstone and Andesite don’t appear to be significantly affected by R (over the range studied) whereas the interface friction angle for Flagstone and Limestone interfaces appear to increase significantly. This behaviour is different to that exhibited for continuum material – sand interfaces (Jardine et al., 1993, Abuel-Naga et al., 2018), where the upper limit of the interface shear strength is defined by the internal friction angle of the granular material where the solid interface becomes so rough that it effectively grabs soil particles and induces full soil-soil shear. The apparent variation of the effect of R suggests that although roughness influences, other interface properties are also having an effect.

3.2 Considering surface hardness

To further investigate this behaviour, it was decided to consider interface relative hardness (Table 3, Equation 7). This is not something a geotechnical engineer dealing with soil-structure interfaces would normally consider due to the relative stiffness of construction material where soil deformation would normally occur well before any interface damage. The relative scratch hardness has been identified in the literature as a factor that affects the shear deformation of continuum – continuum (Engelder and Scholz, 1976) and continuum – granular material interfaces (Abuel-Naga et al., 2018). When one of the two counter faces is harder, then ploughing occurs (harder surface into the softer surface) during shear (Engelder and Scholz, 1976). In this study, a relative hardness ratio M has been defined:
The Mohs hardness value for the Sandstone is 7, for Andesite 6 (Table 3) and for the steel 4, resulting in $M$ values of 0.57 and 0.67 for Sandstone and Andesite interfaces respectively (i.e. the rock is harder than the steel). This suggests that no ploughing of the steel into the rock surface occurs, although rock asperities could plough into the steel surface. This also explains the consistency between the behaviour in these two rock types (Figure 7) where the rocks have similar hardness and plough into the steel, which although had different roughness between tests, was fabricated consistently from Grade EN24T steel. Thus, in this case (Sandstone and Andesite) the steel interface is the one that may be more influential in terms of variability or relative behaviour than the rock. As seen in Figure 6a and 3e the peak interface friction angle values are higher for low normal stresses (up to 79 kPa) and increase with increasing steel roughness. As normal stress increases (159 and 316 kPa), peak interface friction angles reduce, and the effect of steel roughness becomes less apparent (Figure 7). This suggests that as the stress increases there is an increase in ploughing occurring into the steel and at low stress the asperities of the rock are riding over the peaks in roughness of the steel with limited damage to either surface. This is supported by measurement of small deflections that occur between the platens of the IST interfaces (Figure 8). The displacement is dilatant (positive) for normal stress of 16 kPa and contractive (negative) for normal stress of 316 kPa. In addition, dilation seems to be greater for increasing steel $R_s$ and roughness ratio $R$ (at normal stress of 16kPa), whereas at normal stress of 316 kPa the contraction is similar irrespective of steel roughness thus roughness plays a greater role at lower stress.

Ultimate friction angle observations also support this assumption in that the effect of both normal stress and steel $R_s$ is rather minimal at larger strains or displacements as can be seen in Figure 6b and Figure 6f. Therefore, once the initial low stress dilation has occurred or the surface has been damaged the shearing behaviour on the interface for the harder Sandstone and Andesite becomes independent of the initial surface steel roughness or normal stress. The tilt table tests using steel $R_s = 0.4$ μm lie below the lower values observed from IST testing (typically for steel $R_s = 0.4$ μm) as far as peak and ultimate values are concerned (Figure 6a, b, e, f). Thus, tilt table test of the smoother interfaces seems to be able to provide a lower bound value for Sandstone – steel and Andesite – steel interfaces at higher stresses. Whereas at lower stresses the basic friction angle could be used to estimate upper bound resistances especially for the rougher interfaces.

Considering the Flagstone – steel and Limestone – steel interfaces as exhibiting similar behaviour to each other, albeit Flagstone interfaces yield higher interface friction angles, both rock types have a Mohs hardness value similar to that of mild steel (Table 3). Limestone has a value of 4.5 and Flagstone has a value of 3 on the Mohs scale (Limestone is slightly harder, and Flagstone is softer). The interfaces exhibit the highest $\delta$ peak values for $\sigma_n = 16$ kPa because dilation is taking place and consequently $\delta$ peak increases with increasing steel $R_s$ (Figure 6c, 6g and Figure 8b). As $\sigma_n$ increases (159 and 316 kPa), dilation is suppressed (Figure 8a) however the effect of steel $R_s$ is still apparent ($\delta_{\text{peak}}$ is higher for steel $R_s = 34$ μm) in contrast to what was shown before for Sandstone and Andesite interfaces (Figure 8a). This happens because Flagstone and Limestone exhibit hardness values very close to that of the steel element. Therefore, it is believed that higher localised normal stress at the point of contact is required for ploughing to occur. As the normal stress increases, ploughing of the steel asperities into the rock surface (or vice versa depending on which material is harder) takes place during shearing. It is also apparent, that contraction (i.e. indicating ploughing) for Sandstone and Andesite interfaces is almost double that observed for Flagstone and Limestone interfaces (Figure 8b). This behaviour is in accordance with Engelder (1978), who showed that the mode of shearing depends on the applied normal stress and the hardness of the counter face materials. This phenomenon is more pronounced
as steel \( R_s \) increases (for a given \( \alpha_n \)), because actual applied normal stress at the contact points is potentially much higher compared to the nominal \( \sigma_n \) which is calculated as an average value (i.e. the applied normal force divide by the plan area of the rock surface). This seems to affect both the peak and ultimate interface friction angles. As shown in Figure 6c the tilt table test provides a lower bound value of peak shear resistance for the Flagstone – steel interfaces, irrespective of steel \( R_s \). The tilt table tests seem to overestimate the ultimate values of shear resistance for steel \( R_s = 0.4 \) and 7.4 \( \mu \)m, thus a lower bound value can only be provided for the steel \( R_s = 34 \mu \)m results when the ultimate values are considered (Figure 6d). The tilt table seems to overestimate the interface friction angles for the Limestone – steel interfaces irrespective of the steel roughness, with only the peak interface behaviour showing any correlation at lower stresses to the basic friction angle or that for the roughest steel.

The effect of relative Mohs Hardness on the test results are summarised in Figure 6a and b. Each figure contains three interface friction angle values per rock type (one per steel \( R_s \)) and a line that groups the data points for each steel \( R_s \) value. As shown previously (Figure 6a to 6h), \( \delta \) varies significantly between 16 and 159 kPa, whereas it seems to settle between 159 and 316 kPa. Therefore, the average value of \( \delta \) from the tests at 159 and 316 kPa normal stress are considered in Figure 9.

Sandstone – steel interfaces (\( M = 0.57 \)) exhibit the highest values of interface friction and Limestone – steel interfaces (\( M = 0.89 \)) exhibit the lowest values. For steel \( R_s = 0.4 \) and 7.2 \( \mu \)m, interface friction angle values drop significantly between \( M = 0.57 \) and \( M = 0.89 \) and then delta increases again for \( M = 1.33 \) (Flagstone – steel). For steel \( R_s = 34 \mu \)m a similar pattern is followed, where the Limestone – steel interface again exhibits the lower values of \( \delta \), although the difference to the \( \delta \) values of Andesite – steel and Flagstone – steel interfaces is not as significant as for steel \( R_s = 0.4 \) and 7.2 \( \mu \)m. In other words, it seems that the interface shear strength exhibits the lowest value when \( M \) is close to 1, whereas it increases as \( M \) displays values significantly different to 1 (i.e. where the rock interface is much harder or weaker than the steel). The Mohs hardness ratio \( M \) gives values close to 1, when the hardness of the steel and the rock are similar (e.g. 0.89 for Limestone – steel). In this case, it is believed that ploughing (of the harder material into the softer) is reduced during shearing (tending to sliding behaviour), thus leading to lower \( \delta \) values. This is supported by the reduced contraction seen in Figure 8b. As the steel roughness increases, the localised stress at the points of contact is higher (fewer contact points) and ploughing becomes more apparent (i.e. \( \delta \) is similar for all rock types for the roughest steel interface and the effect of roughness is more important). If the rock is significantly harder than the steel, then ploughing of the rock into the steel takes place even under lower normal stress levels, leading to an increase in the interface shear strength. In a similar manner, when the steel is significantly harder than the rock, ploughing (scratching) of the steel into the rock takes place. However, taking into account the data in Figure 9, it is believed that \( \delta \) is higher when \( M \) tends to 0.5 (i.e. rock harder than the steel), because steel is more ductile than rock. Therefore, it is felt that more energy is dissipated when rock ploughs (causing scratches) into the steel compared to when the steel ploughs into the rock surface. In terms of design optimisation this would suggest that it doesn’t matter how hard the steel is if it is rough enough but where the steel is relatively smooth then it should ideally be softer than the rock.

3.3 Analytical approach to determine shear resistance of rock-steel interfaces

The results of this study are shown in Figures 10 as per the previous proposed alpha method as outlined in Equation 1 and 2. Contours have been plotted for the \( \alpha \) values of all the rock types for each value of steel \( R_s \) (i.e. 3 contours) and the fitting constants \( b, c \) for each contour are listed in Table 5.
Equation 2 can be used to estimate the shear strength of a steel interface in the field. Arithmetic constants $b$ and $c$ can be selected in a simple fashion to reflect the roughness of the final steel interface or to select an appropriate roughness if the surface can take additional preparation (i.e. roughened). It is suggested that this equation is used only for the range of UCS, roughness and normal stress used to derive it. In order to improve the parameter selection process, it was decided to fix $c$ to -1.08 for peak and -1.14 for ultimate values and the regression process was repeated to determine $b$. The fitting parameter $b$ is shown in terms of relative roughness, $R$ in Figure 11. It can be seen that for $R$ values of up to approximately 3, the data seems to have a parabolic shape whereas for values between 6 and 13 a linear pattern is observed. As described earlier, Sandstone - steel and Andesite - steel interfaces seem to exhibit similar behaviour, possibly due to the similar Mohs hardness value (and consequently $M$). For the same reason, Flagstone - steel and Limestone - steel interfaces also exhibit similar behaviour. Therefore, it was decided to investigate the variation of $b$ with $R$, for these two groups of rocks, individually (Figure 12).

The variation of arithmetic fitting constant $b$ is represented by Equation 8 and 9 for peak and ultimate values, respectively for the Sandstone - steel and Andesite - steel interfaces:

$$b_{\text{peak}} = 0.857 - (0.00082R)$$  \hspace{1cm} 8

$$b_{\text{ultimate}} = 0.968 + (0.00537R)$$  \hspace{1cm} 9

Between $R = 0.021$ and $R = 5.862$, $b_{\text{peak}}$ and $b_{\text{ultimate}}$ values vary by only 0.5 % and 3.2 % respectively. This trend denotes a relatively minimal effect of $R$ on arithmetic fitting constant $b$. Especially for peak values, the value of $b$ seems to be unaffected by $R$ and $R$ could potentially be ignored in this case. For Flagstone and Limestone interfaces the relative roughness ratio ranges between 0.073 and 12.593. The variation of $b$ within this range is described by Equation 10 and Equation 11.

$$b_{\text{peak}} = 0.494 + (0.03202R)$$  \hspace{1cm} 10

$$b_{\text{ultimate}} = 0.468 + (0.04279R)$$  \hspace{1cm} 11

The average $b_{\text{peak}}$ and $b_{\text{ultimate}}$ values vary by 80 % and 113 % respectively, exhibiting a significant effect of relative roughness ratio $R$, on the value of $b$ and consequently the shear strength of the interface. This difference is explained by the relative hardness ratio of the interfaces, as discussed previously.

If the rock type of interest is the same as one of the aforementioned rock types (e.g. Old Red Sandstone, Flagstone etc), then the equations above can be used. If a different rock type is of interest the relative roughness can be determined and the selection of the appropriate $b$ value can be based on the relative hardness ratio $M$ of the interface. Equation 8 and 9 can be used for $0.57 \leq M \leq 0.67$. Equation 10 and 11 shall be used for $0.89 \leq M \leq 1.33$. However, it is believed that Equation 10 and 11 could also be used (conservatively since these equations will typically lead to lower values of $b$ compared to Equation 8 and 9) for $M$ values between 0.67 and 0.89. The relative hardness, $M$ can take values between 0.4 and 4.0 (considering steel Mohs hardness = 4), however the aforementioned equations shall not be used for relative hardness $M$ values outside of this range without additional testing.

Figure 13 shows that the approach performs relatively well when used to predict the interface friction angles of the four rock types across all roughness values when the input data is re-analysed. This should be the case as the input data to develop the refined analytical approach is the same as that shown here as measured. Figure 13a does show though the difficulty of applying the approach down at low stress levels and this would suggest that the approach should be reserved for higher stress levels only (Figure 13b), although the approach at lower stress levels appears generally conservative.
The results of this study highlight that rock-steel interface behaviour needs to capture several factors such as UCS, normal stress, relative roughness ratio, R and relative hardness ratio, M. It should be noted here that a harder rock doesn’t necessarily have higher UCS. For example, Sandstone consists of hard silica grains, but the matrix is relatively weak leading to a lower UCS value compared to a “softer” rock that may have a high UCS (e.g. Flagstone). Thus, basing Interface strength on UCS alone is not appropriate. It is also apparent that there is scope for using different materials at the interfaces between a foundation and rock to try and take advantage of the observe ploughing effects. For example, a facing of high-density plastic or more sustainable wood could attached to a steel foundation element to encourage such behaviour. Where steel is used there may be scope for selecting the hardness of a particular type relative to that of the rock as apart from hardness, only the roughness of the steel can be modified. In the harder rock it would appear that relative hardness is a more important consideration than relative roughness. Whereas when the steel and rock have similar hardness there is a benefit in increasing the surface roughness of the steel.

4 Summary and Conclusions

There is a dearth of information with respect to the behaviour of rock-steel interfaces where these are unbonded and at relatively low stresses. Interface characterisation information is particular useful for lightweight gravity structures placed upon a rock seabed or the behaviour of pipelines laid on the seabed. This study has attempted to develop a basic data set to improve this lack of existing information for a limited range of rock types found across the UK. As well as presenting useful design input parameters the study has also investigated the effect of various controlling rock/interface characteristics on the interface strength. This has included the roughness or relative roughness, the rock strength (UCS) and the relative hardness of the interface surfaces.

The results show that as in soil interfaces the normal stress has significant control on the strength of the interface, but this influence is non-linear with larger friction angles obtained at low stresses due to dilation and the interface asperities riding over each other as indicated by small upward movements on the interface. At higher stress levels friction angles reduce and the shearing behaviour becomes less erratic. Due to the nature of the interfaces, peak shear resistance occurs at relatively low displacements so it is suggested that it is more appropriate to use ultimate friction angles in design.

It is important for such solid interfaces that the hardness and relative hardness is given due consideration, and that this may control behaviour rather than just purely relative surface roughness. Where the hardness of the two counter faces (rock and steel) differs significantly (e.g. Sandstone and Andesite), the shearing consists of ploughing (irrespective of steel Rv) and the interfaces exhibit similar behaviour. In contrast, Flagstone and Limestone interfaces have relative hardness ratio M close to 1 (i.e. the rock surface has similar hardness to the steel interface). As a result, higher localised stress is required for ploughing to occur, hence the interfaces are affected more by the roughness of the steel. Increasing steel roughness, tends to increase the interface shear strength, however this is more apparent for M closer to 1 (i.e. Flagstone and Limestone). When M is significantly different to 1 (i.e. Sandstone and Andesite), the effect of steel roughness is minimised increases and ploughing into the steel (or into the rock) occurs.

A previously developed analytical approach to predicting the shear resistance on the interfaces (referred to as the alpha factor approach) was further improved to capture the behaviour of rock – steel interfaces and estimate the shear strength of interfaces within the UCS and normal stress range used in this study. This approach incorporates rock strength (UCS), normal stress on the interface, roughness and hardness to improve the prediction of the shear resistance of unbonded rock-steel interfaces. It is noted though that although this was developed based upon grout-steel interfaces and
improved based upon the rock types investigated here, there is still a need for wider validation of this approach for different rock types and foundation interface materials outside of those tested here.

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Notation list added as required
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- **Ultimate**
  - Flagstone-Steel, \( R = 0.073 \)
  - Flagstone-Steel, \( R = 1.310 \)
  - Flagstone-Steel, \( R = 6.181 \)

- **Basic (Rock-Rock)**

- **Tilt table, \( R = 6.181 \)**

- **Tilt table, \( R = 0.073 \)**

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\[
\phi_{\text{basic (Rock-Rock)}}
\]

\[
\text{Tilt table, } R=5.862
\]

\[
\text{Tilt table, } R=0.069
\]

**Ultimate**
- Andesite-Steel, \( R = 0.069 \)
- Andesite-Steel, \( R = 1.241 \)
- Andesite-Steel, \( R = 5.862 \)

\[
\text{Normal stress, } \sigma_n \text{ (kPa)}
\]
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- Steel $R_a = 0.4\mu m$, $b = 1.08$, $c = -1.14$ (■, ◆, ▲, ■)
- Steel $R_a = 7.2\mu m$, $b = 0.96$, $c = -1.09$ (□, ◎, △, ⊙)
- Steel $R_a = 34\mu m$, $b = 0.62$, $c = -1.01$ (■, ◆, ▲, ◎)

- Sandstone
- Andesite
- Flagstone
- Limestone

Normalised unconfined compressive strength, $UCS/\sigma_n$
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Table 1 Steel interface roughness values compared to those of the rock samples

| Steel $R_s$ (μm) | Sandstone | Flagstone | Andesite | Limestone |
|------------------|-----------|-----------|----------|-----------|
| 0.4              | 0.021     | 0.073     | 0.069    | 0.148     |
| 7.2              | 0.379     | 1.310     | 1.241    | 2.667     |
| 34.0             | 1.789     | 6.181     | 5.862    | 12.592    |
| Rock type     | Tensile strength, $T_0$ (MPa) | UCS after Eq. 6 (MPa) | Basic friction angle, $\phi_b$ (°) | Roughness, $R_a$ (μm) |
|---------------|-------------------------------|-----------------------|-----------------------------------|----------------------|
| Sandstone     | 2.6                           | 34.30                 | 38.5                              | 19                   |
| Flagstone     | 10.0                          | 145.15                | 34.3                              | 5.5                  |
| Andesite      | 13.0                          | 192.75                | 33.2                              | 5.8                  |
| Limestone     | 10.8                          | 157.95                | 25.2                              | 2.7                  |
Table 3 Summary of material surface hardness values

| Material   | Mohs relative hardness | Vickers hardness (kg/mm²) | Relative Hardness, M (Equation 7) |
|------------|------------------------|---------------------------|----------------------------------|
| Sandstone  | 7                      | 1161                      | 0.57                             |
| Flagstone  | 3                      | 157                       | 1.33                             |
| Andesite   | 6                      | 817                       | 0.61                             |
| Limestone  | 4.5                    | 432                       | 0.89                             |
| Mild Steel | 4                      | 315                       | -                                |
Table 4 Summary of results from rock – steel interface testing

| Rock type | Normal stress (kPa) | Normal stress (kPa) | Normal stress (kPa) | Normal stress (kPa) |
|-----------|---------------------|---------------------|---------------------|---------------------|
|           | 0.4 | 7.2 | 34.0 |
| Sandstone |     |     |     |
|           | 16  | 37.7| 29.4| 40.4|
|           | 79  | 32.3| 29.1| 35.8|
|           | 159 | 29.7| 27.9| 33.8|
|           | 316 | 29.2| 26.1| 30.9|
| Flagstone |     |     |     |
|           | 79  | 23.6| 14.6| 21.6|
|           | 159 | 20.2| 11.2| 12.5|
|           | 316 | 18.0| 12.5| 14.1|
| Andesite  |     |     |     |
|           | 16  | 27.3| 20.2| 35.5|
|           | 79  | 29.7| 22.2| 29.7|
|           | 159 | 26.7| 21.6| 26.7|
|           | 316 | 25.4| 20.8| 26.6|
| Limestone |     |     |     |
|           | 16  | 16.9| 12.8| 33.1|
|           | 79  | 13.5| 9.6 | 28.8|
|           | 159 | 13.1| 8.9 | 17.5|
|           | 316 | 9.9 | 6.8 | 14.6|
Table 5 Summary of the arithmetic fitting constants b and c in Equation 1

| Steel roughness, $R_a$ (μm) | Peak b  | Peak c | Ultimate b | Ultimate c |
|----------------------------|---------|--------|------------|------------|
| 0.4                        | 1.08    | -1.14  | 1.14       | -1.18      |
| 7.2                        | 0.96    | -1.09  | 1.25       | -1.19      |
| 34.0                       | 0.62    | -1.01  | 0.62       | -1.05      |
