Characterising chalk-concrete interfaces for offshore renewable energy foundations

Ziogos, A.; Brown, M. J.; Ivanovic, A.; Morgan, N.

Published in:
Engineering in Chalk

DOI:
10.1680/eiccf.64072.521

Publication date:
2018

Document Version
Peer reviewed version

Characterising chalk-concrete interfaces for offshore renewable energy foundations

A. Ziogos*[1], M.J. Brown[2], A. Ivanovic[3] and N. Morgan[4]

[1] *GDS Instruments, Hook, UK*
[2] *University of Dundee, Dundee, UK*
[3] *University of Aberdeen, Aberdeen, UK*
[4] *Lloyd's Register EMEA, Aberdeen, UK*
* *Corresponding Author*

ABSTRACT Deployment of renewable energy foundations, be it piles or gravity based structures, may come into contact with chalk in southern UK waters and in other parts of European offshore and nearshore deployment. To aid more appropriate design it is useful to understand the interface shear strength between the foundation and the underlying rock where this is exposed at surface or where the foundation penetrates. In this paper, the interface shear strength between chalk and unbonded concrete is investigated for constant normal stress conditions over a range of normal stresses using tilt table and specialised interface shear testing apparatus. The results show that the interface strength of chalk is significantly influenced by the normal stress used during testing where at lower stresses the interface strength exceeds the basic friction angle determined for a chalk-chalk interface and degradation of the interface strength below the basic friction angle occurs when normal stresses exceed 73% of the tensile strength of the chalk material. This degradation is more severe at small displacements than previously observed for chalk-steel interfaces. At low normal stresses and displacements, the shear strength of the chalk-concrete interface can be represented by an alpha type approach related to the chalk unconfined compressive strength as previously developed for higher strength rocks.

1 INTRODUCTION

Current and future offshore renewable energy maybe founded directly onto chalk in the case of tidal stream generators (gravity base foundations, GBS) or penetrate chalk during pile installation. Gravity base structures may be formed from steel (Ziogos et al. 2017) or concrete and offshore piles are most likely to consist of steel tubular piles. To allow design of such foundations it is necessary to understand the specific foundation-rock interface behaviour. Surprisingly there is very little literature or design based guidance on this situation especially where concrete is not cast against the rock (or unbonded). NAVFAC (1986) for instance recommends a coefficient of friction, μ, of 0.7 (interface friction angle, δ= 35°) 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.

Where rock-foundation interfaces have been studied in more detail, for example pile rock sockets (Horvath 1978; Williams & Pells 1981), very high confining stresses may occur, the concrete is cast against the rock and constant normal stiffness (Clayton & Saffari-Shooshtari 1990) rather than constant normal stress conditions may occur.

In this paper, the shear strength of both dry and saturated unbonded chalk-concrete interfaces are investigated under constant normal stress conditions and at various normal stress levels in order to develop insight for design purposes. This work follows on from that by Ziogos et al. (2017) that considered chalk-steel interface shear behaviour.

2 LABORATORY TESTING

2.1 Description of the 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 350 × 300 × 280 mm are directly obtained after quarrying. Unfortunately, due to the working status of the quarry, the research team was not allowed to access for sampling or to assess the exact structural setting of the chalk in situ. The chalk was White chalk assumed to be from the Flamborough Chalk Formation (Upper Chalk unit, northern province English Chalk) and thought to be consistent with that referred to by Lord et al. (2002) as the Flamborough Sponge Bed (Whitham 1991, 1993). The chalk was ideal for characterisation and interface testing as it was free from flints.

The characterisation of the chalk is summarised in Table 1. The chalk can be classified as very high density according to CIRIA 574 (Lord et al. 2002). Determination of the various properties is described in more detail in Ziogos et al. (2017).

Table 1 Summary of key index properties for the chalk used in this study (modified after Ziogos et al. 2017).

Property	Value
Dry density (Mg/m^3)	2.06
Porosity (%)	23
Voids ratio	0.3
Saturated moisture content (%)	11.4
Specific Gravity	2.7
UCS, dry (MPa)	30.0
UCS, saturated (MPa)	9.3
Tensile strength, dry (MPa)	1.1
Tensile strength, saturated (MPa)	0.96
Young's Modulus, dry (GPa)	8.6
Young's modulus, saturated (GPa)	2.85
Saw cut roughness, R_a (μm)	3.1

2.2 Scope of testing and interface preparation

Initially the approach to chalk-concrete interface testing was to use stresses relevant to those that might be assumed for GBS tidal stream generator foundations (in this case, up to 316 kPa, which also corresponded to the maximum normally achievable in a 60 × 60 mm shear box). Although it was realised when testing chalk-steel interfaces that interesting results could be obtained when the normal stress was increased above $0.33T_0$ (where T_0 is the tensile strength of the chalk) or 316 kPa in this case (Ziogos et al. 2017). Ziogos et al. (2017) also showed that increasing the normal stress during testing led to potential degradation of the chalk-steel interfaces and significant degradation could be obtained by increasing the displacement levels during testing from typical levels of 10 mm to 7 m, Ziogos et al. (2017).

The tests were undertaken for chalk-concrete interfaces on both dry and saturated samples, with normal stresses ranging from 16 to 316 kPa (0.015-0.273 $T_{0,dry}$) for dry samples, and from 16 to 1000 kPa (0.017-1.042 $T_{0,sat}$) in saturated samples with displacement limited to 10 mm in this case.

Chalk samples were prepared by coring the sampled chalk blocks to form 54 mm nominal diameter core samples which were dry cross cut with a diamond saw resulting in samples that had a typical centerline average roughness of R_a = 3.1 μm. Simple tilt table testing (USBR 6258, 2009) on the saw cut chalk-chalk interface resulted in a basic friction angle ϕ_b = 30.5°.

The concrete interfaces were formed by casting cylinders (300 mm high and 150 mm diameter). The cylinders were then sub-cored and saw cut to obtain disc shaped samples of 54 mm diameter. The target concrete mix was C60 to comply with the recommendations for offshore concrete structures (Sandvik et al. 2004). The mix proportions were : 370 kg/m^3 cement, 185 kg/m^3 water, 925 kg/m^3 sand and 890 kg/m^3 10 mm aggregate (typical slump 130 mm). The resulting cube strength at the time of testing was 61.5 MPa. The resulting concrete interface had a roughness of R_a = 6.8 μm, effectively twice as rough as the chalk and a concrete-concrete interface friction angle of 30° which is close to the chalk basic friction angle. Tilt table testing of chalk-concrete interfaces yielded a friction angle of 34°.

2.3 Interface shear tester

The main programme of interface shear testing (apart from tilt table testing) was undertaken using a purpose built GDS computer controlled interface shear tester (IST) (Figure 1). The IST consists of an axial actuator at the top of the rig, which can apply up to 5 kN of vertical force and a rotational actuation system at the base, capable of applying torque up to 200 Nm as configured here.

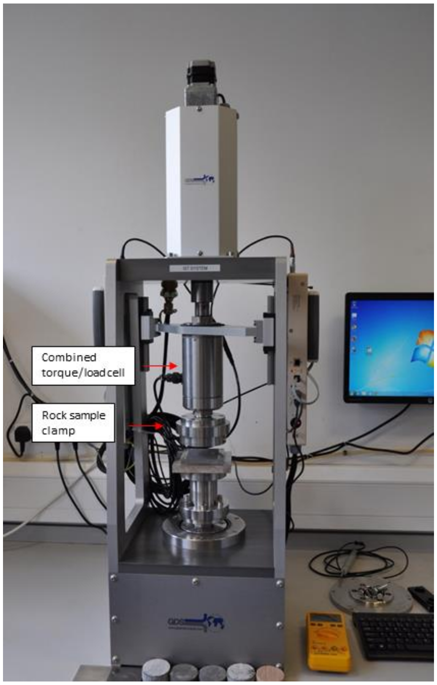

Figure 1. The IST testing device in dry steel- rock interface testing mode. Rock samples are shown in the foreground.

Below the axial actuator there is a combined torque /load cell with capacities of 200 Nm and 5 kN respectively. Axial and rotational deformation are measured by the respective stepper motor systems. 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. The apparatus used here is an evolution of that previously described by Kuo et al. (2015) for the low-stress testing of pipeline coatings and interfaces.

Submerged testing of saturated samples was achieved by creating a custom-made poly methyl methacrylate (PMMA) bath (filled with de-aired and de-ionised water) that was attached to the lower rotation platen. The saturated samples were kept under constant normal stress for 15 minutes prior to shearing with shearing undertaken at a low rate of 0.005 mm/s (equivalent horizontal displacement). Further details of the testing apparatus and conversion of torque to shear stress and radial deformation to linear displacement are given in Ziogos et al. (2017).

3 RESULTS AND DISCUSSION

3.1 Results of IST testing

The results of the IST testing for both dry and saturated chalk- concrete interfaces are shown in Figure 2 and Figure 3. The results for the dry tests (Figure 2) show higher shear stress resistance during interface testing than the saturated tests (Figure 3) which may be anticipated due to the known effects of dry versus saturated UCS rock strength determination as seen in Table 1 and referred to in Mathews & Clayton (1993). In the dry samples, the normalised shear stress is relatively low at low normal stress (16 kPa) and then increases with increasing normal stress up to 159 kPa ($0.16T_0$) before decreasing down to lower levels with increasing normal stress. This initial low shear resistance may be associated with the chalk sliding on the concrete. Then as the normal stress increases, surface damage is caused in the chalk which allows the concrete to “bite” into it (Figure 4). This matches the behaviour observed by Ziogos et al. (2017) for chalk-steel interfaces. Similar behaviour is observed for the saturated tests but as the tests were taken to higher normal stresses (Figure 5) there appears to be some additional significant post-peak degradation associated with the 700 kPa ($0.73T_0$) normal stress and a significant reduction in normalised shear stress when the normal stress reaches 1000 kPa ($1.04T_0$). The variation of shear stress-displacement associated with this high normal stress test is also very “noisy” and displays significant low displacement drops in shear stress (Figure 3).

For the dry chalk, average peak friction angles up to 45.6° are obtained (Figure 4) but these values are erratic and not sustained (Figure 2) thus design based upon ultimate values would seem more appropriate where these are actually very similar to the peak values. The ultimate values average at 44.9°, and someway above ($1.47\phi_b$) the chalk-chalk interface value from tilt table testing ($\phi_b = 30.5°$) over the range of normal stresses tested. Ultimate values are 20% higher than the tilt table friction angle for chalk-concrete. The peak interface angles obtained for saturated chalk (39.2°, $\delta_{sat}/\delta_{dry} = 0.860$) are lower as would be anticipated based upon the lower T_0 of saturated chalk ($T_{0,sat}/T_{0,dry} = 0.873$, Table 1).

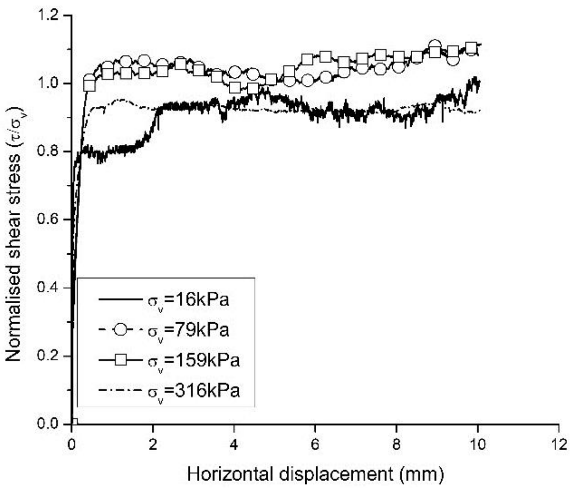

Figure 2. Results of IST testing chalk-concrete interface for dry chalk.

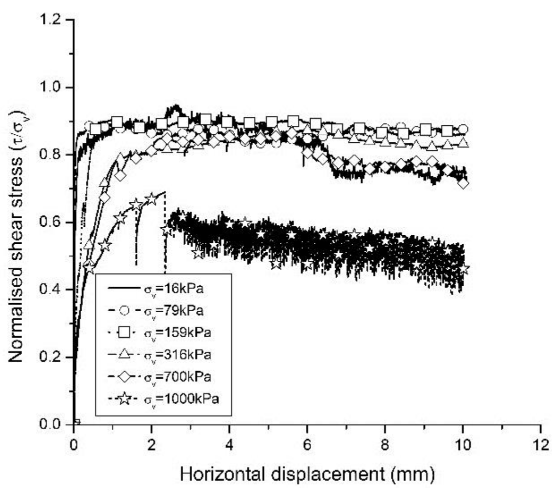

Figure 3. Results of IST testing chalk-concrete interface for saturated chalk.

The similarity in the drop in strength at the interface and in T_0 from dry to saturated suggests that T_0 is playing a direct role in interface shear strength. The ultimate friction angles are again higher than the basic friction angles for chalk 1.28 (ϕ_b). Figure 5 suggests that, at low normal stresses and at stresses not exceeding $0.73T_0$, the simply measured chalk-concrete friction angle may be used as a lower bound to design.

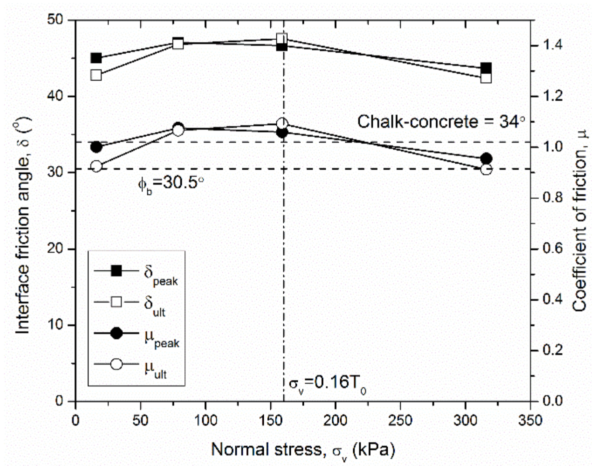

Figure 4. Summary of results for chalk-concrete interface for dry chalk.

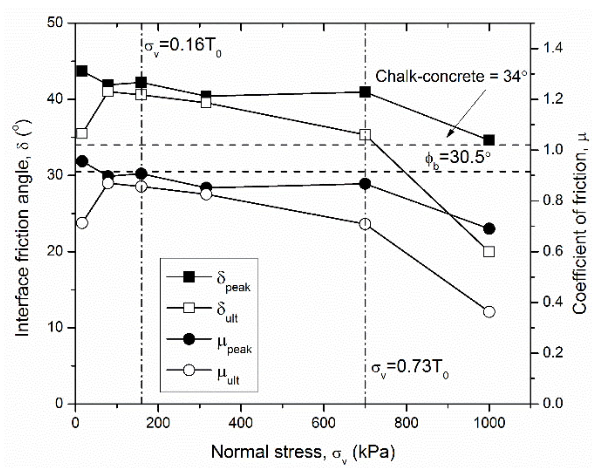

Figure 5. Summary of results for chalk-concrete interface for saturated chalk.

Figure 5 shows that, if the normal stress exceeds 73% of the tensile strength of the chalk, there is a significant drop in shear resistance. As noted in Table 2, the samples tested at $\sigma_v = 700$ kPa showed marked surface damage (SD) in the form of chalk powder for dry samples and chalk putty for saturated samples with perimeter chips in the round samples. For samples tested at $\sigma_v = 1000$ kPa where the tensile strength of the chalk was exceeded, the samples chipped and cracked through the full sample thickness (non-intact = NI). Although these samples were not intact after removal from the clamping system it is believed that the surface shear behaviour is still valid as clamping maintained the integrity of the sample and shearing surface during the test. Based upon this behaviour in constant normal stress testing, the adoption of linear failure envelopes (Clayton & Saffari-Shooshtari 1990) is not appropriate unless testing and application is limited to low stress levels.

Table 2 Summary of IST testing results.

Normal stress (kPa)	Initial[1] sample state	Post test[2] sample condition	Peak shear stress (kPa)	Ultimate shear stress (kPa)
16	D	I	16.0	15.0
79	D	I	85.0	84.5
159	D	I	168.5	174.0
316	D	I	301.5	288.5
16	S	I	15.5	11.5
79	S	I	71.0	68.5
159	S	I	144.0	136.0
316	S	I	269.0	261.0
700	S	SD	607.0	496.5
1000	S	NI	690.0	363.0

[1] D = dry, S = saturated
[2] I = intact, SD = surface damage, NI = non-intact

Comparison of the results with those shown by Ziogos et al. (2017) for tests on chalk-steel interfaces where the roughness of the steel was also varied between 0.4 to 34 µm show a marked difference. For the chalk -steel interfaces, the shear resistance always exceeds the basic friction angle for chalk. This even occurs at high normal stress levels thus recommending the basic friction angle as a lower bound design assumption (even at normal stresses exceeding the tensile strength seemed appropriate for low displacement levels). Here the friction angle is lower for the chalk-concrete at high normal stresses. This may be due to the relative hardness of the steel and concrete interfaces. For example, the published tensile strength of C60 concrete is 4.4 MPa (EN1992, 2004) and potentially not only the chalk but the concrete interface is degrading at higher normal stresses.

3.2 *Implications for industrial practice*

Ziogos et al. (2017) previously proposed that due to the simplicity of tilt table testing that it could be used to determine lower bound design parameters. It is noted though that specialist testing equipment (similar to the IST) would have a role to play where more refined parameter definition is required. For the chalk-concrete interface, this advice is only valid for lower normal stresses below $0.73T_0$. Once this is exceeded, there appears to be considerable degradation of the interface and further detailed investigation would be required for a specific application. It is also worth noting that this guidance is based upon limited interface displacement as Ziogos et al. (2017) showed significant reductions in interface shear strengths with increasing interface displacement for example in applications such as pile driving.

To aid use in design, Ziogos et al. (2015a, 2015b and 2017) proposed an alpha type approach (α = shear stress normalised by UCS) for unboned rock-steel (including chalk) and cement-steel interface strength prediction of a form similar to that used for pile rock socket adhesion factors (Tomlinson 2001). Alpha values were several orders of magnitude lower than those found in bonded rock sockets UCS was also normalised by the vertical stress as this was seen to have significant effect.

Figure 6 shows two lines that represent the alpha factor values from previous interface testing of various rocks against steel interfaces (Old Red Sandstone is shown for comparison) of different roughness. The lines are described by Equation 1 where b and c are fitting parameters:

$$\alpha = b\left(\frac{UCS}{\sigma_v}\right)^c \quad (1)$$

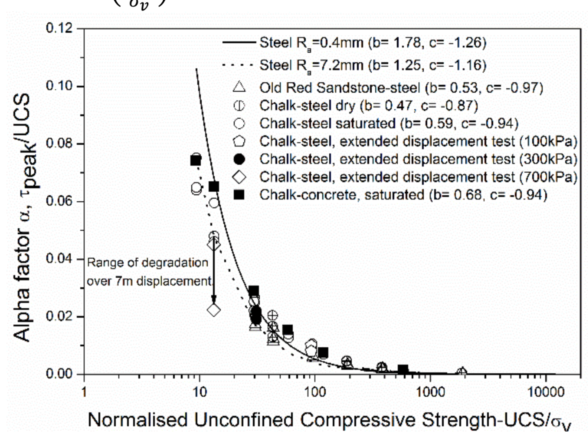

Figure 6. Alpha factors for chalk-concrete compared with chalk-steel and sandstone-steel and contours from Ziogos et al. (2015a) (modified from Ziogos et al. 2017).

It seems that the relationship previously derived by Ziogos et al. (2017) for rocks of much higher UCS can be applied to the chalk-steel and chalk-concrete interfaces and offers an alternative approach to interface predictions where displacements are limited. As noted by Ziogos et al. (2017) and shown in Figure 6, caution needs to be exercised when larger displacement events occur especially where these are at normal stresses where degradation is likely to occur (degradation shown for 7 m events, Ziogos et al. 2017). The behaviour studied here and previously is only for monotonic loading and the behaviour when subject to cyclic loading would need to be studied before generic design guidance could be given in an offshore environment.

4 SUMMARY AND CONCLUSIONS

In this paper, the interface shear strength between chalk and unbonded concrete was investigated for constant normal stress conditions over a range of normal stresses using tilt table and specialised interface shear testing apparatus. The results show that the interface strength for chalk is significantly influenced by the applied normal stress. At lower stresses the interface strength exceeds the basic friction angle (ϕ_b) determined for a chalk-chalk interface (and the chalk-concrete interface angle from tilt table testing which may be taken as a lower bound design value). Degradation of the interface strength below ϕ_b occurs when normal stresses exceed 73% of the tensile strength of the chalk material. This degradation is more severe at small displacements than previously observed for chalk-steel interfaces. At low normal stresses and displacements, the behaviour of the chalk-concrete interface can be represented by an alpha type approach related to the UCS of chalk as previously developed for higher strength rocks. Care should be taken though at greater displacements than those studied here and further work is required to investigate the effect of cyclic loading for offshore applications.

ACKNOWLEDGEMENT

The Energy Technology Partnership (ETP) and Lloyd's Register EMEA are gratefully acknowledged for the funding of this project. The authors would also like to acknowledge the support of the European Regional Development Fund (ERDF) SMART Centre at the University of Dundee that allowed purchase of the equipment used during this study. The views expressed are those of the authors alone, and do not necessarily represent the views of their respective companies or employing organisations.

REFERENCES

Clayton, C.R.I. & Saffari-Shooshtari, N. (1990) Constant normal stiffness direct shear testing of chalk/concrete interfaces. *Proc. Of the Int. Chalk Symp*. Thomas Telford, London, UK, 233-238.
EN 1992-1-1:2004 *Eurocode 2: Design of concrete structures*.
Horvath, R.G. (1978) *Field load test data on concrete to rock bond strength for drilled pier foundation*. University of Toronto, Toronto, Canada, Publication 78-07.
Kuo, M.Y.H. Vincent, C.M. Bolton, M.D. & Rattley, M. (2015) A new torsional shear device for pipeline interface shear testing. *Proc. 3rd I.S.F.O.G*. Taylor & Francis, London, UK, 405-410.
Lord, J.A. Clayton, C.R.I. & Mortimore, R.N. (2002) *Engineering in chalk*. CIRIA, London, UK, CIRIA Publication C574.
Matthews, M.C. & Clayton, C.R.I. (1993) Influence of intact porosity on the engineering properties of a weak rock. Geotechnical engineering of hard soils- soft rocks. A.A Balkema, Rotterdam, the Netherlands. 693-702.
NAVFAC (Naval Facilities Engineering Command) (1986) *Soil mechanics design manual 7.01*. Naval Facilities Engineering Command Publications Transmittal. Alexandria, VA, USA.
Sandvik, K. Eie, R. & Advocaat, J.D. (2004) Offshore structures a new challenge: How can the experience from the marine concrete industry be utilized. *XIV National Conference on Structural Eng*.
Tomlinson, M.J. (2001) *Foundation design and construction*. 7th Ed. Pearson Education Limited, UK.
USBR (United Sates Bureau of Reclamation) (2009) *USBR 6258: Procedure for determining the angle of basic friction (static) using a tilting table test*. U.S. Dept. of the Interior Bureau of Reclamation, Technical Service Centre, Denver, CO, USA.
Whitham, F. (1991) The stratigraphy of the Upper Cretaceous Ferriby, Welton and Burnham formations N of the Humber, north-east England. *Proc. of the Yorkshire Geological Soc*. **48(3)**: 247-254.
Whitham, F. (1993) The stratigraphy of the Upper Cretaceous Flamborough Chalk Formation north of the Humber, north-east England. *Proc. of the Yorkshire Geological Society* **49(3)**: 235-258.
Williams, F.P. & Pells, J.N. (1981) Side resistance rock sockets in-sandstone, mudstone, and shale. *Canadian Geotechnical Journal* **18(4)**: 502–513.
Ziogos, A. Brown, M.J. Ivanovic, A. & Morgan, N. (2015a) Interface shear characteristics of Scottish rock samples from sites with tidal energy potential. *XVI European Conf. on Soil Mechanics and Geotechnical Eng.*. ICE Publishing, London. pp. 1357-1362.
Ziogos, A. Brown, M.J. Ivanovic, A. & Morgan, N. (2015b) Investigation of rock-steel interface testing for gravity foundations for marine energy generators. *3rd Int. Symp. on Frontiers in Offshore Geotechnics*. Taylor & Francis Group, London. pp. 1245-1250.
Ziogos, A. Brown, M.J. Ivanovic A. & Morgan, N. (2017) Chalk-steel interface testing for marine energy foundations. ICE Proceedings: Geotechnical Engineering 170 (GE3), 285-298.