PIPE-SOIL INTERACTION FOR SURFACE-LAID PIPELINES IN CARBONATE SEDIMENTS

Fraser Bransby, University of Western Australia and Fugro, Perth, Western Australia, Australia, fraser.bransby@uwa.edu.au.
Han Eng Low, Fugro, Perth, Western Australia, Australia, he.low@fugro.com.
Fangyuan (Julia) Zhu, Fugro, Perth, Western Australia, Australia.
Romain Clavaud, Fugro, Abu Dhabi, UAE.
David White, University of Southampton, UK.

ABSTRACT

Correctly predicting pipe-seabed interaction (PSI) response is critical for surface-laid pipeline design. Recent updated codes and guidance documents are based on recent research that has mostly been conducted for (undrained) soft clays because the focus has been on HTHP pipelines, mostly in deep water. Consequently, the guidance on pipe-soil interaction behaviour in carbonate soils (as encountered for example, in the Arabian Gulf and the North-West Shelf of Australia) has not been updated, leaving the industry with open ended practices which may lead to questionable design. Pipe-soil interaction in carbonate soils will differ to 'conventional' soils (e.g. clays and clean silica sands) because of the higher sensitivities (increasing lay embedment), the higher angles of internal friction (leading to larger pipe-soil interface resistances and axial friction factors), the wider particle size distributions (which lead to soil drainage conditions depending on pipeline loading event) and the high degree of spatial variability. Each of these issues need to be addressed explicitly in any PSI calculation approach (and in the associated site investigation programme) in order to provide reliable pipeline design inputs. Consequently, this paper discusses carbonate soil PSI response and compares the results of PSI tests in carbonate soils to calculations using public domain code-based methods to give general recommendations about pipe-soil interaction on carbonate seabeds.

Keywords: Pipeline geotechnics, pipe-soil interaction, carbonate soils, site investigation.

INTRODUCTION

Offshore pipelines and flowlines are frequently laid on the seabed and left untrenched as this is commonly the lowest cost solution. As a consequence, their design must account for how the pipeline responds as it is loaded by waves and currents, as it experiences cycles of heating and cooling, and it free-spans over uneven seabeds. All of these design issues are affected by the interaction of the pipeline with the seabed which will govern the stability, displacement/curvatures and/or strains in the pipeline. Furthermore, both low and high seabed resistance may govern design as outlined by White et al. (2014), and so statistical ranges of the highest likely (or high estimate, HE), lowest likely (or low estimate, LE) and most likely (best estimate, BE) seabed resistance are required for each design case. Consequently, geotechnical support to a project consists of providing (LE, BE, HE) geotechnical design inputs of seabed resistance along the length of the pipeline relevant for each limit state the pipeline is subject to. These inputs are normally provided in terms of 'friction factors', which quantify the limiting soil resistance when the pipeline moves laterally or axially compared to its self-weight, and in terms of springs describing how the vertical component of soil resistance changes as the pipeline moves up or down.

There has been a large volume of research recently conducted motivated particularly by the large increase in numbers of high temperature, high pressure (HTHP) pipelines for which lateral buckle and end-expansion management has been critical. Given that many of these have been in deep water, a majority of the research done has address the (generally undrained) behavior of pipelines on clay soils. This research has recently made its way into updated codes and guidance documents (e.g. SAFEBUCK 2015, DNVGL-RP-114 2017, API RP2GEO 2014, ISO 2016). The (generally older) empirical equations recommended in the design guidelines for drained sand response (e.g. Verley and Sotberg 1992) were developed based on model tests conducted on siliceous soil.

Carbonate soils are encountered worldwide (e.g. Murff 1987; Watson et al. 2019) and correspond with areas of (increasing) pipeline concentration in the Arabian Gulf and the North-West Shelf of

Australia. Despite this, guidance on pipe-soil interaction (PSI) response in carbonate soils has not been updated recently, with the inapplicability of the approaches for carbonate soils stated explicitly in the superseded DNV-RP-F109 (2010) ("Special considerations should be made if the sand contains a high fraction of calcium carbonate") and although this specific text is not included in DNVGL-RP-F114 (2017), the same carbonate soil PSI section from DNV-RP-F109 (2010) is included. This omission is concerning because carbonate soils have different (though measureable) properties to non-carbonate materials and these lead to differences in PSI response which are not always captured by the design codes/guidelines. Without direct consideration of these differences, design advice may not reflect the reality of the seabed reaction forces the pipeline will experience during its design life and lead either to unnecessary capital expenditure (e.g. see case study by Abdel-Hakim et al. 2018) or expose the pipeline to operational risk (and potentially increased remediation costs). The current lack of guidance from the codes and design guidelines leaves the industry with open ended practices to derive PSI parameters for carbonate soils, and operators are often left with limited reliable means to ensure their assets are designed appropriately.

Based on the above, this paper will first highlight the differences between carbonate and non-carbonate soil properties. It will then provide evidence of the deficiencies of existing design guidance to encapsulate how this carbonate behavior affects pipe-seabed interaction before providing recommendations.

CHARACTERISTICS OF CARBONATE SOILS

Clarke and Walker (1977) defined carbonate sediments as being those comprising of greater than 90% of calcium carbonate ($CaCO_3$). However, soils with > 50% $CaCO_3$ are termed 'siliceous or clayey carbonate' (Clarke and Walker 1977) and these soils (and potential soils with even less $CaCO_3$ content) may still exhibit many or all of the typical carbonate soil properties.

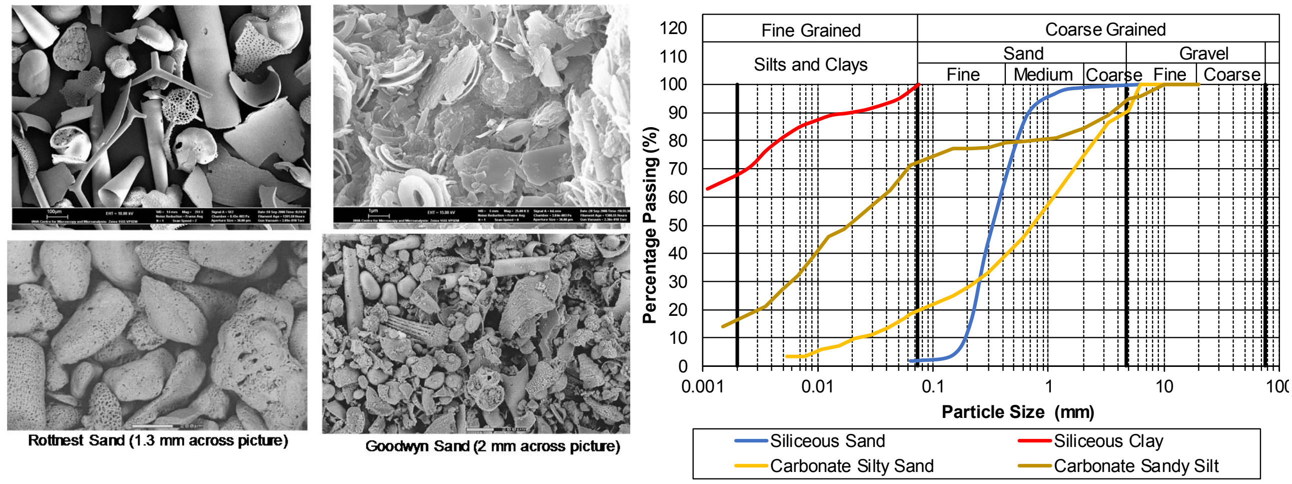
The origins and geological formation processes of carbonate soils were described by Watson et al. (2019). The formation processes of carbonate soils result in high spatial variability so that significantly different properties may be expected along a pipeline. Consequently, soil parameter ranges are often wide compared to uniform soil deposits, and pipeline input ranges must account for this variability realistically. Furthermore, outcropping (and shallow subcropping) cemented layers are common in shallow and intermediate water depth.

The differences in mechanical behavior of uncemented carbonates can be linked to the grain properties (which are a result of the geological processes during and after deposition). The common main differences in grain properties for uncemented carbonate sediments are:

i. Carbonate soil grains are generally more angular than siliceous soils as a result of their biological origin (see Fig. 1a);
ii. Carbonate soils are often found with a wide range of particle sizes (i.e. well graded; see Fig 1b);
iii. The grains may be very crushable.

In general, carbonate soils have:

- ***High angles of friction, ϕ'*** (and high undrained shear strength ratios, s_u/σ'_{vi}) as a result of grain angularity. This can also lead to increased pipe-soil interface friction coefficients (μ) for rough pipeline coatings. Examples of the difference in peak angle of friction between a carbonate and siliceous soils are shown on Fig. 2a with similar increases observed in residual (or critical state) angles of friction (as shown Fig. 2b). These higher angles of internal friction and higher pipe-soil interface shear resistances often leads to higher axial and lateral seabed resistances. Consequently, site- specific testing should be conducted to quantify this rather than using (non-carbonate) database information to estimate design interface friction properties.



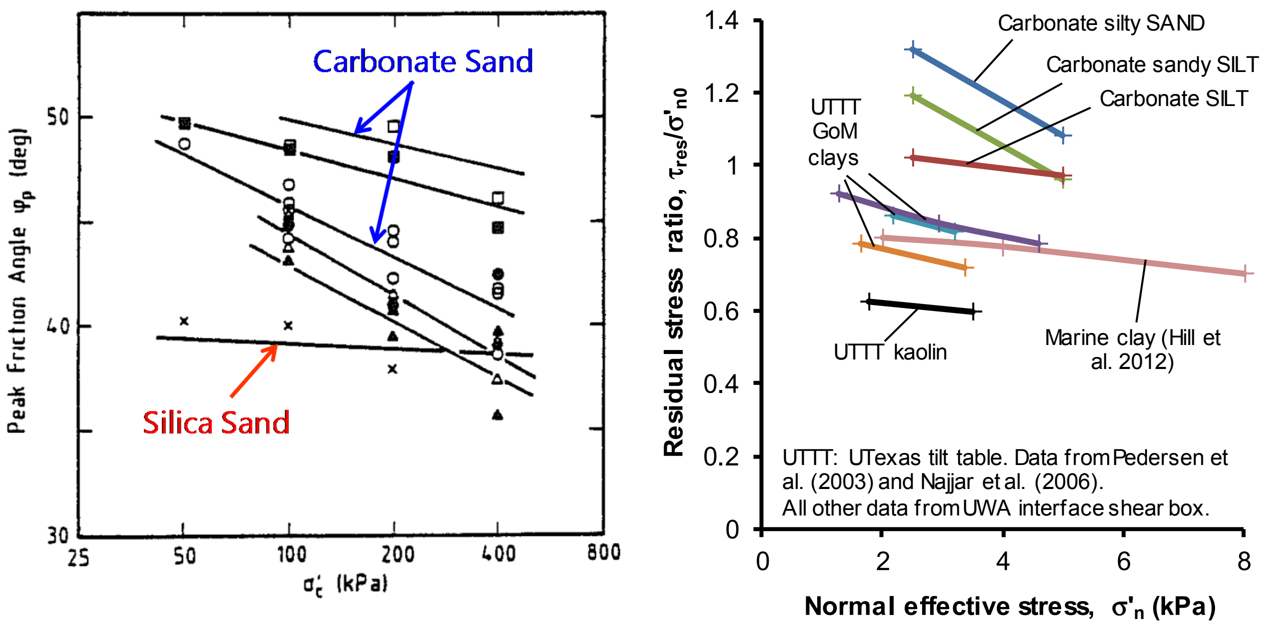
(a) Carbonate grains (angular and crushable)

(b) Particle size distributions (wide range of sizes

Fig. 1. Example characteristics of carbonate soils

- Wide ranges of potential grain packing densities and so the potential for ***large volume changes during compression*** or as a result of cyclic loading.
- High susceptibility to ***large cyclic strength reduction*** or large strength reductions during remoulding. The more significant cyclic strength reduction for carbonate soils is shown in Fig. 3a based on series of undrained simple shear tests. The reducing remoulded strength (i.e. the increased sensitivity, S_t) is illustrated on Fig. 3b and leads to significantly more as-laid pipe embedment for a carbonate soil than for an equivalent monotonic-strength clay.

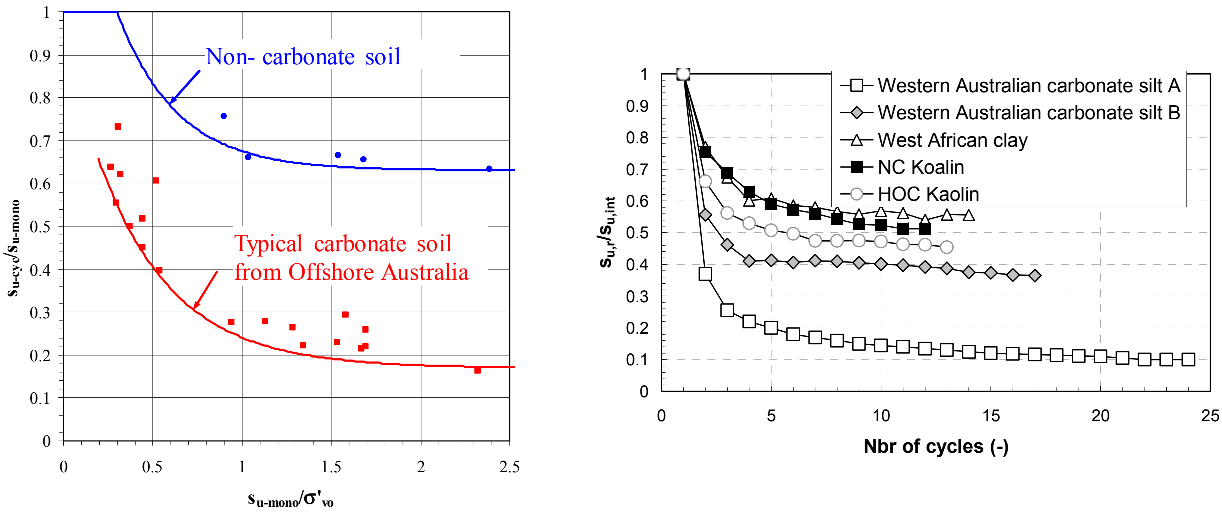
The wide range of particle sizes of carbonate soils shown in Fig. 1b can lead to wide ranges of coefficient of consolidation (c_v) of the soil and therefore affect drainage response around the pipeline. In particular, many carbonate sands have large silt contents lowering the c_v of the soil and leading to drainage conditions which can be undrained (or partially drained) for faster pipeline movements (e.g. caused by wave-loading) and drained for slower movements (e.g. caused by slow axial pipeline expansion). Design methods must encompass this transitional behavior rather than



(a) Peak angles of friction (Hull et al. 1988)

(b) Interface friction coefficients (White et al. 2012)

Fig. 2. Comparison between the drained frictional properties for siliceous and carbonate soils



(a) Undrained cyclic shear strength **(b) Sensitivity (White and Gaudin 2008)**

Fig. 3. Example cyclic characteristics of carbonate soils

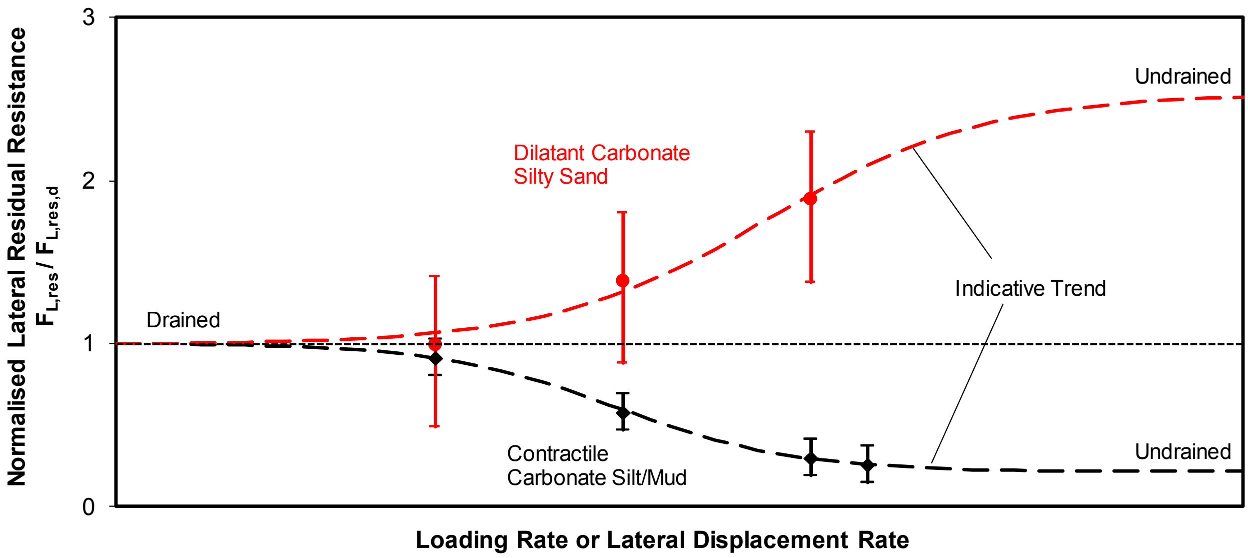


Fig. 4. Importance of drainage conditions on PSI parameters

assuming (for example) that any 'sand' is drained (or any 'silt' (or clay) is undrained). The importance of the drainage condition (and density) is shown schematically in Fig. 4.

The above differences in carbonate soil response are addressed in terms of how they affect pipe-soil interaction in the following sections.

GENERAL DESIGN METHODOLOGY

General Approach

For geotechnical inputs to be reliable for use in pipeline design, they must be able to account for the specific combination of site-specific seabed properties, the properties of the particular pipeline (including on how it is planned to be installed) and reflect the pipe-soil interaction processes occurring during the particular pipeline loading event being analysed. Furthermore, LE to HE design ranges should consider the uncertainties about each of these particular aspects of input. The process is shown schematically in Fig. 5 and has been described in general in White et al. (2015), DNV-RP-F114 (2017) and by Abdel-Hakim et al. (2018).

Much of the effort denoted in Fig. 5 involves activities designed to determine the site-specific

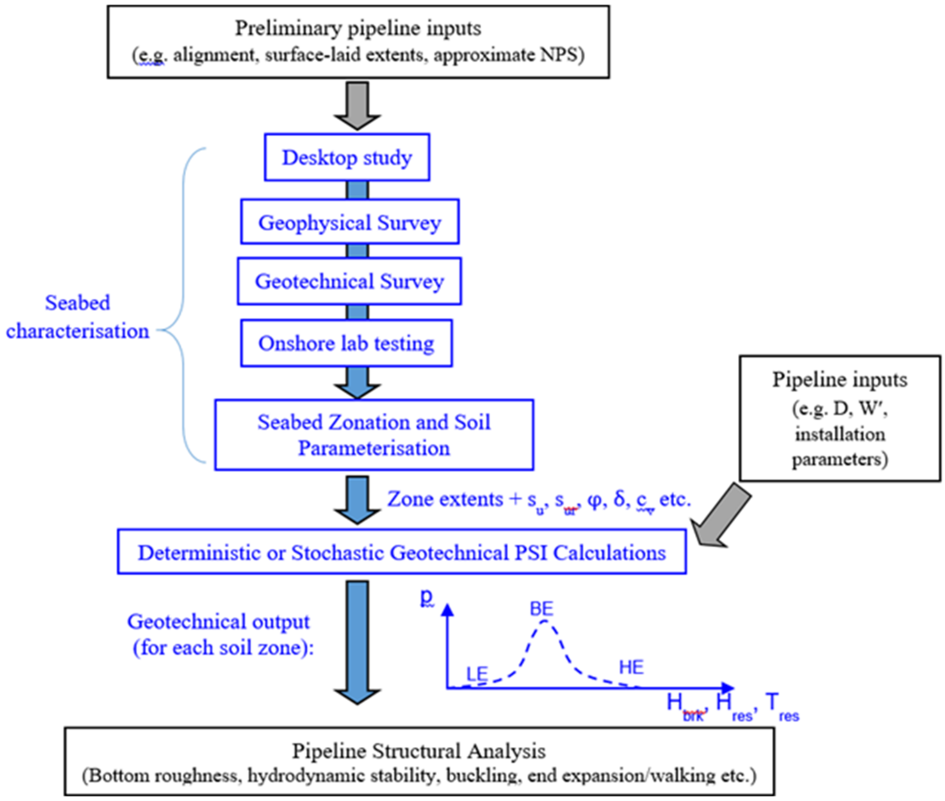


Fig. 5. Overall geotechnical PSI methodology (after Abdel-Hakim et al. 2018)

properties of the near-surface seabed. This process is designed to split areas of seabed along the pipeline alignment into zones of similar soil properties and then find the range of relevant seabed properties for each of those zones. The properties (and the zones) are deduced from integrating information from a combination of geophysical survey(s), geotechnical survey(s) (involving relevant in situ tests and high quality shallow sampling) and a targeted onshore element testing programme (e.g. Abdel-Hakim et al. 2018). This is particularly important for carbonate soil conditions where the seabed properties are frequently very variable and not within the band of ‘expected’ properties.

The importance of seabed zonation is shown diagrammatically on Fig. 6. In this figure, the net cone penetration resistance (q_{net}) profiles acquired along an example pipeline route are shown on Fig. 6a. Based on these q_{net} profiles, the seabed along the pipeline route is clearly highly variable (ranging from sand to silt) and hence the LE to HE design ranges selected based on these profiles as a whole (denoted by red and blue lines on Fig. 6a) must be very broad to encompass this variability. When this wide design range is used to calculate friction factors, the range of output friction factors will be correspondingly wide. However, if examination of the geophysical and geotechnical data along the pipeline is able to split the seabed into a sandier ‘Zone 1’ (Fig. 6b) and a siltier ‘Zone 2’ (Fig 6c), the design range of each zone will then be narrower than that of the whole pipeline route. Consequently, the friction factor design ranges for each seabed zone will be narrower than the previous ‘whole pipeline’ range. This narrower friction factor ranges are likely to lead to more cost-effective design because less seabed infrastructure is likely to be required to manage the range of possible pipeline operational response.

Calculation Framework

Once the seabed properties are known and pipeline design inputs have been obtained, geotechnical calculations will be performed to evaluate the statistical ranges of seabed resistance to pipeline movement and thereby select PSI design ranges (see Fig. 5). For carbonate soil conditions, it is particularly important that:

i. Calculation methods used should explicitly account for the relevant mechanical properties of the carbonate seabed (including appropriate consideration of the drainage conditions experienced by the pipeline in different design conditions), and

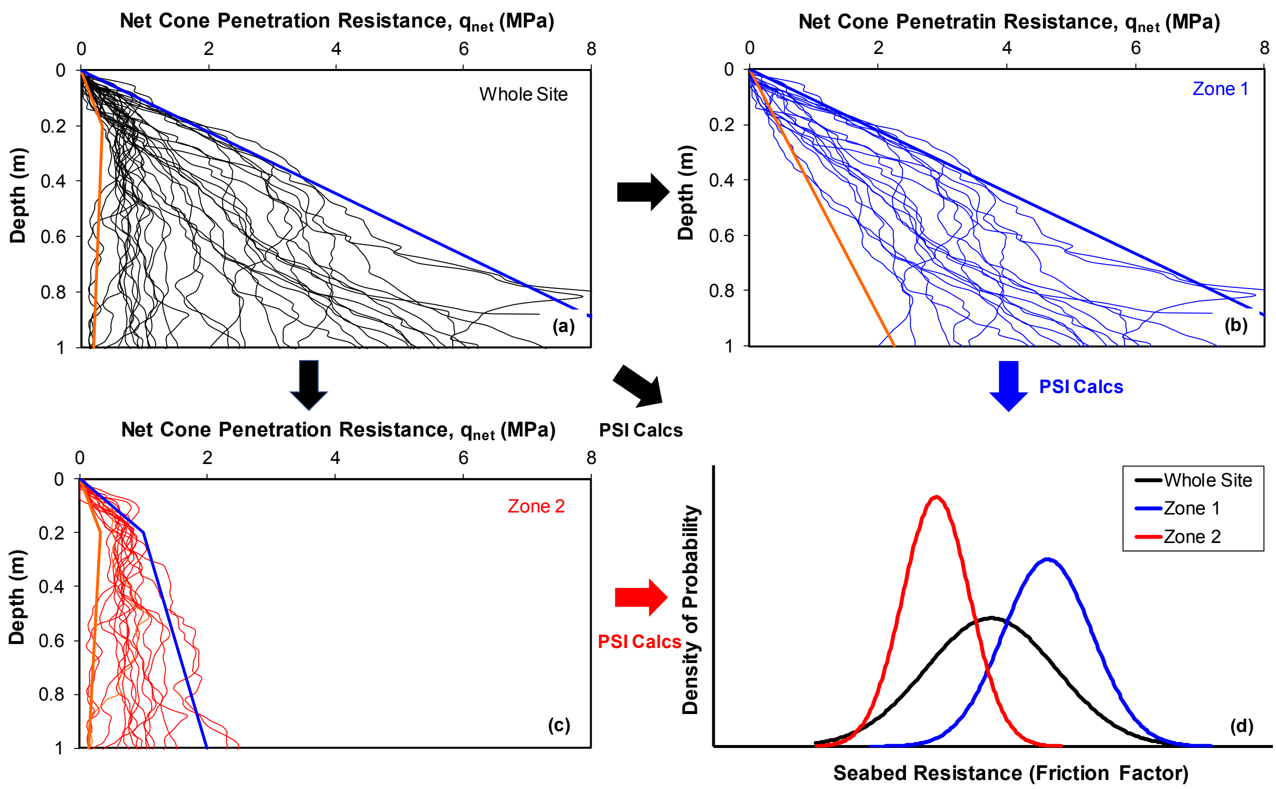


Fig. 6. Schematic showing importance of seabed zonation in PSI work

ii. Statistical methods are used to quantify the output design ranges for the specific probability levels required by the project. This will typically narrow the adopted design ranges by reducing the influence of unrealistic (extreme) or improbable combinations.

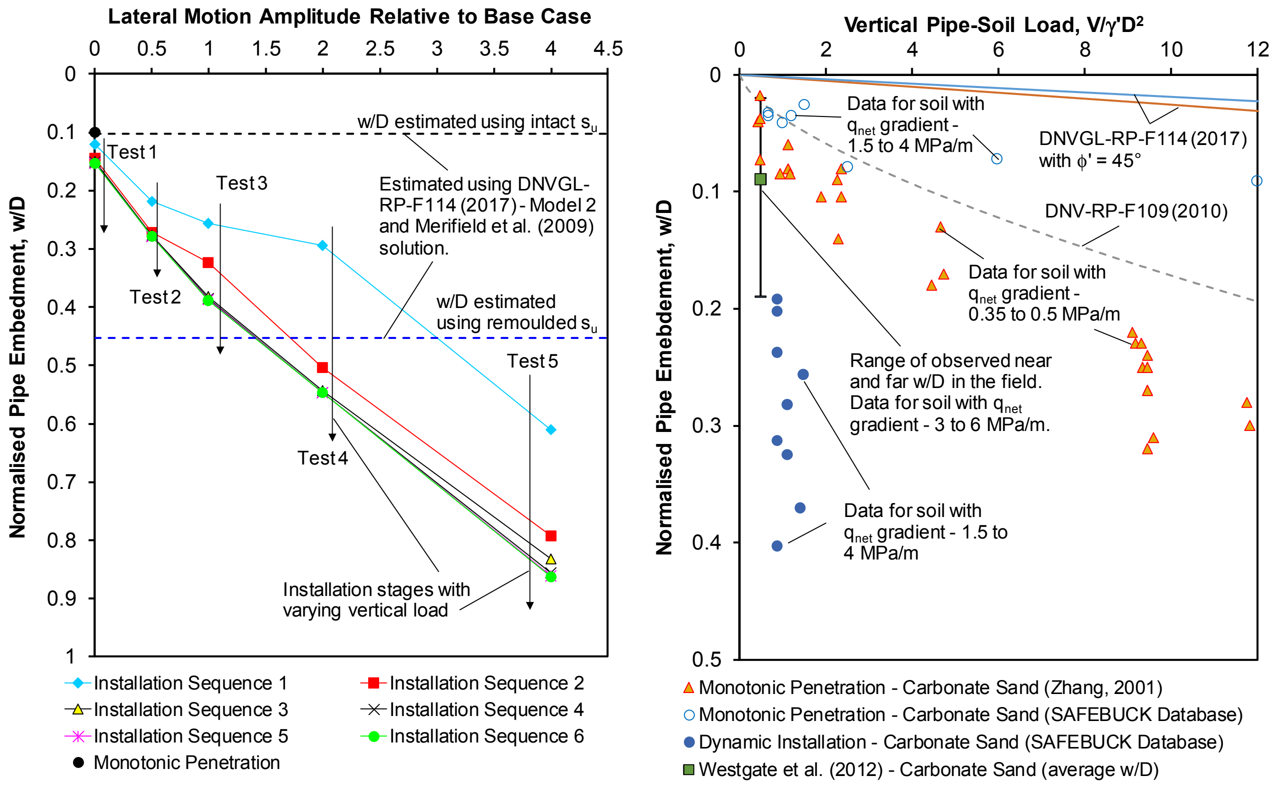
Statistical PSI calculation approaches have been described elsewhere (e.g. White et al. 2014; Bransby et al. 2015) and so the remainder of this paper will concentrate on point i).

PSI CALCULATIONS FOR CARBONATE SEDIMENTS

PSI calculations generally involve first making estimates of as-laid pipeline embedment (considering pipelay effects), and then considering the effect of installation and any following precommissioning sequence on the properties of the soil around the pipeline, before finally performing calculations to reveal seabed resistance to subsequent lateral, axial and vertical pipeline movements during operation. For pipelines laid on mobile seabed, the potential for sediment mobility to change pipeline embedment after pipelay may also need to be considered (e.g. Bransby et al. 2014) in the calculation of seabed resistance, but this is not discussed in this paper. For each PSI response, the calculation should consider the likely soil drainage conditions and may require the calculation of both the drained and undrained soil resistances and interpolation between these resistances to select the design resistances that are appropriate for the pipeline operational conditions (see Fig. 4). The recommended calculation methods for carbonate soils are discussed in turn below.

As-laid Embedment Calculations

When a pipeline penetrates monotonically into the seabed (e.g. under its self-weight), the vertical seabed resistance will reflect the work done to plastically fail the soil beneath the pipeline. Therefore, a relationship between pipeline embedment and seabed resistance can be developed using plasticity theory or numerical analysis (e.g. Aubeny et al. 2005; Merifield et al. 2009) to calculate the pipe embedment for a given pipeline weight (or vertical load). However, during pipelay, there are two processes that will increase the amount of pipeline embedment as compared to what would be expected if the pipeline was simply placed gently onto the seabed. The two processes are:



(a) Undrained embedment in carbonate mud **(b) Drained embedment**

Fig. 7. As-laid embedments: comparison between model test results and predictions by design guideline calculation models

i. The increased load (higher than the pipeline self-weight) applied to the seabed in the touchdown zone due to lay catenary, and
ii. The dynamic movements of the pipeline in the touchdown zone.

The increased load application in the touchdown zone can be estimated by considering the bottom lay tension used to lay the pipeline and the pipeline bending stiffness (EI) in the calculation of the load multiplier (k_{lay}), as suggested by Randolph and White (2008) and has now been included in DNVGL-RP-F114 (2017). However, calculation methods to account for dynamic pipeline movements in the estimation of pipeline 'as-laid' embedment are more uncertain (particularly for drained soil conditions and carbonate soils) and are discussed below.

Undrained embedment: Figure 7a presents the embedment data measured in a set of centrifuge tests in carbonate mud. In these tests, dynamic pipelay effects were simulated using cyclic vertical and lateral pipe motions and the changing vertical seabed reaction force representing the conditions as the pipe section progresses through the touchdown zone during pipelay. As shown on Fig 7a, the pipeline embedment measured in the monotonic penetration test can be predicted accurately using bearing capacity equations recommended in DNVGL-RP-F114 (2017) (Model 2) and by Merifield et al. (2009) using the intact undrained shear strength (s_u). However, these equations underestimate the pipeline embedment caused by the dynamic installation process.

Through the back-analysis of three installed pipelines, Westgate et al. (2010a, 2012) suggested that the dynamic as-laid embedment for both carbonate and non-carbonate clays/silts may be reasonably approximated by using the remoulded s_u in the embedment calculation. This approach has been recognized in DNVGL-RP-F114 (2017) as a reasonable approach if there is no project-specific data to suggest otherwise. However, as shown by the centrifuge test data presented on Fig. 7a, the prediction of DNVGL-RP-F114 (2017) Model 2 using remoulded s_u on Fig. 7a may potentially overestimate or underestimate the pipeline embedment, depending on how vigorous the lateral pipe motion in the touchdown zone during pipelay. In addition, carbonate mud has the potential for a greater loss of strength than indicated by a conventional measure of remoulded strength, e.g. from a cyclic T-bar test (see Fig. 3b).

In summary, for undrained conditions, the approach of using fully remoulded s_u with pipeline bearing capacity equations may generally provide a reasonable best estimate as-laid embedment (e.g. Westgate et al. 2010a, 2012). However, based on the authors' experience in back analysis of field 'as-laid' embedment observations and project-specific model test data, the dynamic lay effects in undrained soils is a function of sea state during pipelay (also reported by Westgate et al. 2010b), lay rate, pipelay vessel characteristics and the susceptibility of the soil to remoulding and softening due to water entrainment (e.g. Sahdi et al. 2020). In general, carbonate sediments are more susceptible to remoulding and softening due to water entrainment (as shown on Fig. 3b) and hence s_u lower than remoulded s_u may occasionally be required to accurately predict embedment.

Drained embedment: Figure 7b compares the vertical penetration response calculated using the calculation models for drained soils recommended in DNVGL-RP-F114 (2017) and DNV-RP-F109 (2010) and the pipeline embedment data measured in centrifuge tests in carbonate sands (Zhang 2001 and SAFEBUCK database) and observed in field for a pipeline laid on a carbonate sandy seabed (Westgate et al., 2012). Note that the differences between the monotonic pipe embedment measured in centrifuge tests reported by Zhang (2001) and those in SAFEBUCK database and the differences between the dynamic pipe embedment for SAFEBUCK database and those observed by Westgate et al. (2012) in the field could be attributed to the differences in soil strength and stiffness. Consequently, net cone penetration resistance (q_{net}) gradients are annotated on Fig. 7b.

As shown on Fig. 7b, the calculation model recommended in DNVGL-RP-F114 (2017) underestimates the pipeline penetration for a given vertical load even for monotonic pipeline penetration. In addition, while the calculation model recommended in DNV-RP-F109 (2010) was developed based on data measured in model tests in which dynamic lay was simulated, the model also underestimate the embedment for dynamically installed pipelines either in the centrifuge or in the field. These large disparities in calculated and measured/observed embedment warrant serious attention because they will result in very different friction factors, hydrodynamic shielding and heat transfer from the pipeline.

DNVGL-RP-F114 (2017) does not recommend a calculation approach to account for the drained dynamic lay effect, simply stating that: "The embedment predictions in drained conditions should be evaluated carefully". Westgate et al. (2012) demonstrated that the cycle-by-cycle prediction may work but further study is required to address how to relate the cyclic pipeline movements in the touchdown zone, the seastate and the lay vessel characteristics to the changing soil strengths in the touchdown zone. These uncertainties must be accounted for in the calculation of 'as-laid' embedment.

In summary, Fig. 7 highlights the challenges of predicting pipeline embedment even if the pipeline loading and movement history is known during lay. It is also particularly concerning because further geotechnical advice (particularly for lateral friction factors) are very dependent on the input pipeline embedment values. Possible options to increase the accuracy of as-laid embedment predictions may include consideration of:

i. The systematic back analysis of the 'as-laid' embedment of the nearby pipelines or pipelines laid in similar seabed conditions (such as those reported by Westgate et al., 2010a, 2012); and/or
ii. Conducting project-specific pipe-soil interaction tests in situ, within box cores or within reconstituted (but project-specific) soil samples.

Lateral Breakout Resistance Calculations

There are four main design approaches for calculating lateral breakout resistance in the literature:

i. empirical relationships which consider V and w/D (and potentially geotechnical parameters such as s_u or ϕ') as inputs (e.g. Verley and Sotberg 1992; Verley and Lund 1995; Eqn. 4.22 of DNVGL-RP-F114 2017);
ii. limit equilibrium-based approaches that calculate lateral resistance using methods based on passively loaded retaining walls (e.g. DNVGL-RP-F114 2017) with base shear and passive components,

iii. methods that use failure envelopes to describe the interaction of horizontal and vertical soil resistance (Zhang 2001; Merifield et al. 2009), and
iv. direct calculations using finite element analysis or finite element limit analyses to calculate seabed resistance for specific (generally wished-in-place) conditions [or to generate failure envelopes for input into method iii].

Undrained lateral breakout resistance: Empirical methods (encapsulating dimensionless groups such as w/D, V/s_uD and $\gamma' D/s_u$) are recommended in DNVGL-RP-F114 (2017). The form of the equations and fitting parameters in DNVGL-RP-F114 (2017) were based on empirically fitting data sets from centrifuge and laboratory pipe tests as part of the SAFEBUCK JIP. An example relationship of lateral resistance against pipe weight is shown on Fig. 8a for a specific set of pipeline and soil properties and lay embedment. Also shown on Fig. 8a is a failure envelope calculated using (finite element) limit analysis (FELA) for the same set of conditions. There are clearly significant disparities between the two approaches. Project-specific validation of these methods compared to the results of centrifuge model tests in carbonate soils where pipeline installation was modelled using dynamic lateral pipeline movements suggest that the failure envelope approach best encapsulates the lateral capacity (as also observed by Cocjin et al. 2018) even though the approach does not reflect the post-installation near-pipeline geometry.

Drained lateral breakout resistance: Figure 8b compares the results from lateral breakout resistance calculations for drained soil conditions using the 'Method 2' approach in DNVGL-RP-F114 (2017) (Verley and Sotberg 1992), the 'Method 1' approach in DNVGL-RP-F114 (2017) and a Fugro retaining wall-based method with a calibrated K_p with the results of centrifuge PSI tests using a smooth, overpenetrated pipe (as relevant for dynamic laid pipelines) in carbonate sand (Zhang 2001).

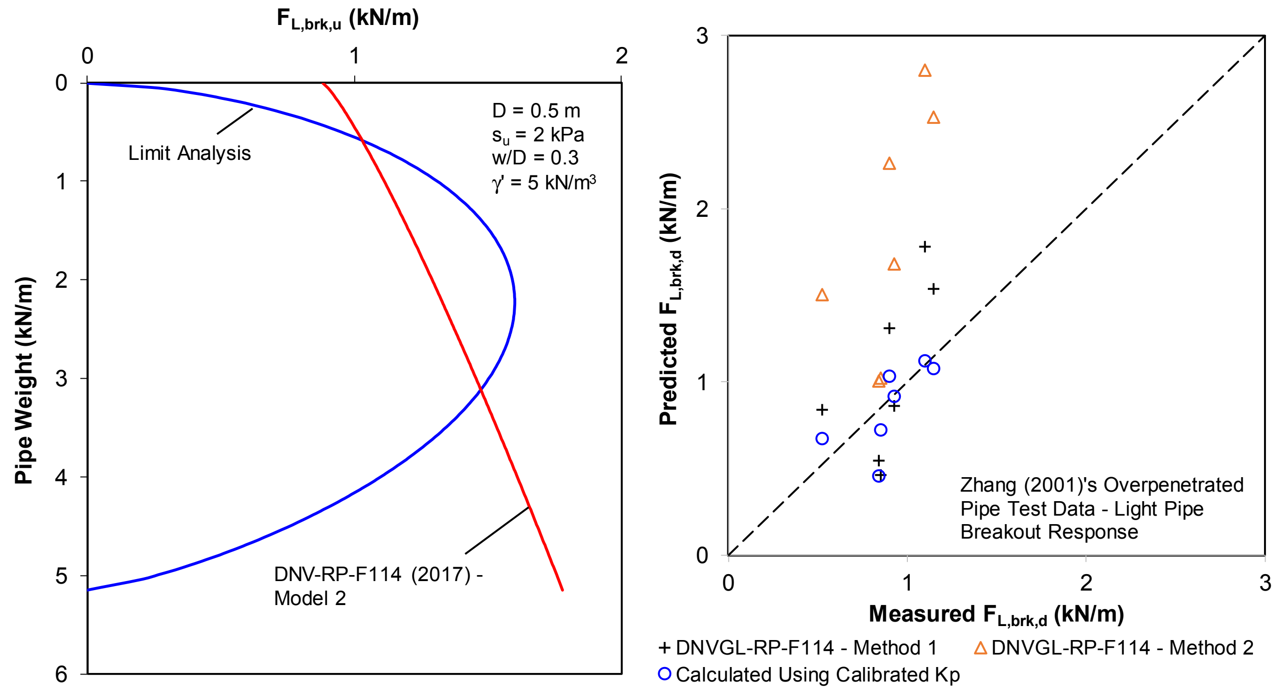
When compared to the centrifuge test results, the DNVGL-RP-F114 (2017) Method 1 and Method 2 (particularly) tend to overestimate the breakout friction factors. In addition, the analysis procedure for Method 1 provided in DNVGL-RP-F114 (2017) is unclear. The tests show less of a depth dependency on resistance than in the calculations, which also have the drawback of not including any soil strength or pipeline interface properties to modify the calculations for site-specific conditions (e.g. Method 2 assumed constant interface friction coefficient of 0.6, independent of soil and pipeline surface roughness). Consequently, it appears that the code-based approaches should be treated with caution for carbonate soils.

The predictions using a calibrated K_p and measured pipe-soil interface friction coefficient are more accurate. It is possible to calibrate K_p using project-specific model tests and use project-specific measured drained interface friction coefficient values in the calculation to allow for the pipeline surface roughness and its interaction with site-specific soil.

Ideally, both drained and undrained breakout friction factors should be calculated using the failure envelope method, whereby the site-specific envelopes could be quantified using a numerical approach which had been validated with model pipe tests. Note that this approach is more challenging for diving pipes in drained conditions due to the nature of the required expanding failure envelope and also needs to be extended to partially drained conditions (which is not covered in current design guidelines).

Lateral Residual Resistance Calculations

Undrained residual resistance: The calculation approach for undrained residual resistance suggested in DNVGL-RP-F114 (2017) is based on an equation developed during the SAFEBUCK JIP, whereby the residual lateral resistance is solely a function of the initial pipeline embedment. This is clearly a simplification to reality, but provides a good approximation (for the predominantly clay soils in the SAFEBUCK database and for 'light' pipe behaviour) as the size of the berm 'pushed' by the pipeline when residual resistance conditions are reached is closely related to the initial embedment of the pipeline and the strength of the berm (e.g. Chatterjee et al. 2012). The strength



(a) Undrained lateral breakout **(b) Drained lateral breakout**

Fig. 8. Undrained lateral breakout resistance calculations

of the berm depends on its sensitivity (which falls within a narrow range for a typical clay). DNVGL-RP-F114 (2017) notes that the empirical equation was developed from a database of "mainly very soft West African clays" and significant uncertainty remains (with an uncertainty factor of 1.5 recommended) and that "there is a need to test the model further against a larger database, possibly also modifying the model to account for other parameters". These caveats are critical for carbonate soils as shown below.

Typical undrained pipe model test results for overpenetrated 'light' pipes in two types of carbonate soils are shown alongside the SAFEBUCK / DNVGL-RP-F114 (2017) equation on Fig. 9. For contractile, fine-grained carbonate silts (the pink shaded area), lower undrained residual resistances were measured than that predicted by the SAFEBUCK / DNVGL-RP-F114 (2017) equation. This is believed to be due to the strength of the soil berm being pushed by the pipe at residual conditions is much lower than that for the SAFEBUCK clays because of the higher sensitivities of carbonate silts. In contrast, for coarser-grained carbonate silty sands (blue shaded area), the measured lateral residual resistances are significantly higher than that predicted using the SAFEBUCK / DNVGL-RP-F114 (2017) equation. This is believed to be because these carbonate silty sands dilate during shearing and so the negative excess pore pressures generated during undrained shear increase the strength of the soil berm pushed by the pipe in residual conditions. It appears clear that knowledge of the nature of the site-specific carbonate soil is critical to making a good prediction of residual seabed resistance, with generic code approaches unable to capture significant differences in seabed response.

Furthermore, the above relationship is for light/rising pipe response (as typical for as-laid pipelines in carbonate soils). More complex analysis is required to account for the accretion of the berm in front of the pipeline for diving pipe conditions.

Drained residual resistance: To calculate the drained residual resistance, DNVGL-RP-F114 (2017) recommends a 'Model 1' approach that uses the equations recommended for the calculation of the drained breakout resistance but with an (unspecified) 'shallower penetration depth' or zero embedment and a 'Model 2' equation recommended by Verley and Sotberg (1992). The 'Model 2' equation was developed based on a best estimate fit to a database of tests conducted in siliceous sand and contains no soil strength (or interface strength) parameters with which to 'tune' the calculations to site-specific soil or project-specific pipeline interface conditions.

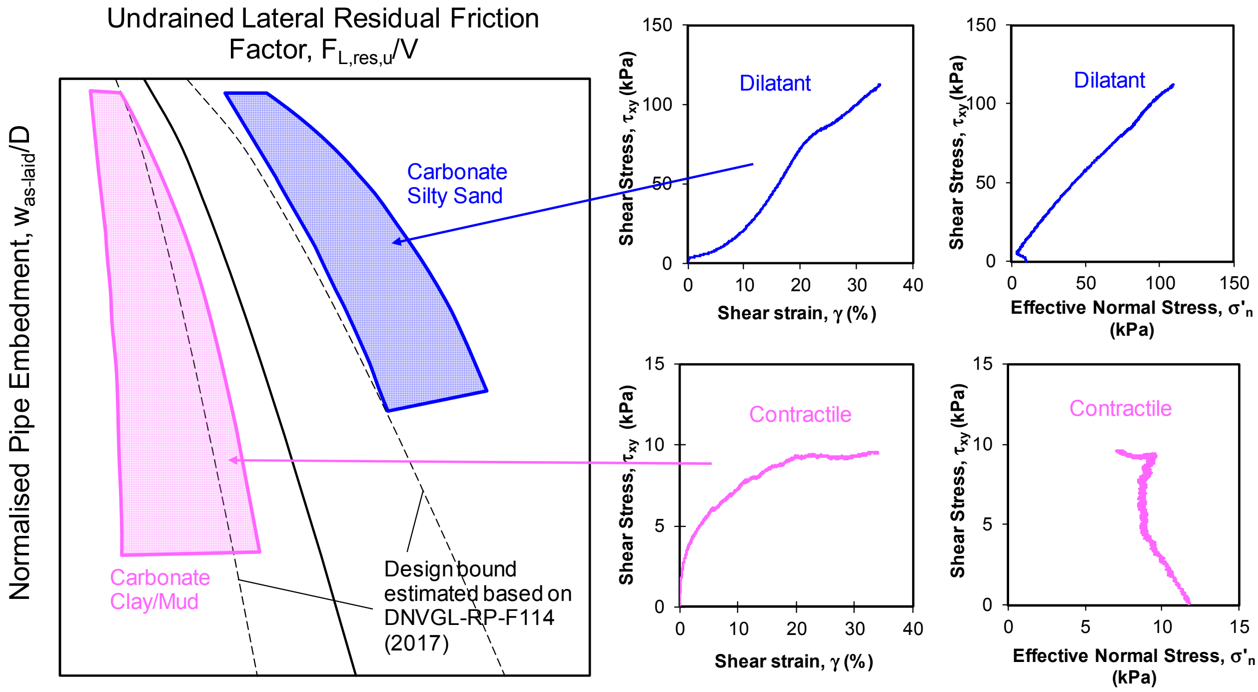


Fig. 9. Undrained lateral breakout resistance calculations

From examination of a proprietary database of centrifuge PSI tests in carbonate soils, it appears that the residual lateral friction factor is approximately equal to the friction coefficient of the interface between the soil and the pipeline, independent of the initial pipeline embedment. Consequently, the approaches recommended in DNVGL-RP-F114 (2017) are likely to underestimate the drained lateral residual resistance for rough pipelines in carbonate soils. Furthermore, it is strongly recommended that interface tests are conducted using a representative interface from the proposed pipeline and site-specific soil because there could be a factor of two difference in drained lateral residual resistance from a smooth (unsintered PP) pipeline to a fully rough (e.g. impinged concrete weight coated) pipeline.

In summary, there are potentially significant differences in the residual lateral resistances expected for a pipeline in carbonate soils than that predicted using design guideline calculation methods, both for drained and undrained soil conditions. To reflect the likely behaviour, the calculation approaches must encapsulate whether the soil is contractile or dilatant in undrained soil conditions and the pipe-soil interface properties for drained conditions and consider drainage transition (e.g. Fig. 4) for partially drained conditions. These disparities will be significant for consideration of the dynamic stability of pipelines under hydrodynamic loading or when assessing the tolerability of lateral buckles.

Axial Residual Resistance Calculations

The axial residual resistance calculation approaches that are recommended in DNVGL-RP-F114 (2017) (and other recent codes) were generally developed as part of the SAFEBUCK JIP and associated research (e.g. Ballard et al. 2013; White et al. 2012) and use the pipe-soil interface shear strength parameters as input in the calculation. Consequently, the recommended approaches are generally applicable for carbonate soils. However, four important considerations should be considered when using these approaches to calculate the axial residual resistance for carbonate soils:

- It is important that the pipe-soil interface shear strength properties for the project-specific pipeline roughness and near-seabed soil are measured as part of the geotechnical investigation campaign. This is because the interface shear strength properties for carbonate soils can be very different and significantly higher than those for siliceous soil, particularly for pipelines with rough coating (as shown in Fig. 2). Higher pipe-soil interface shear strength will lead to higher axial friction factors and very different pipeline operational response.

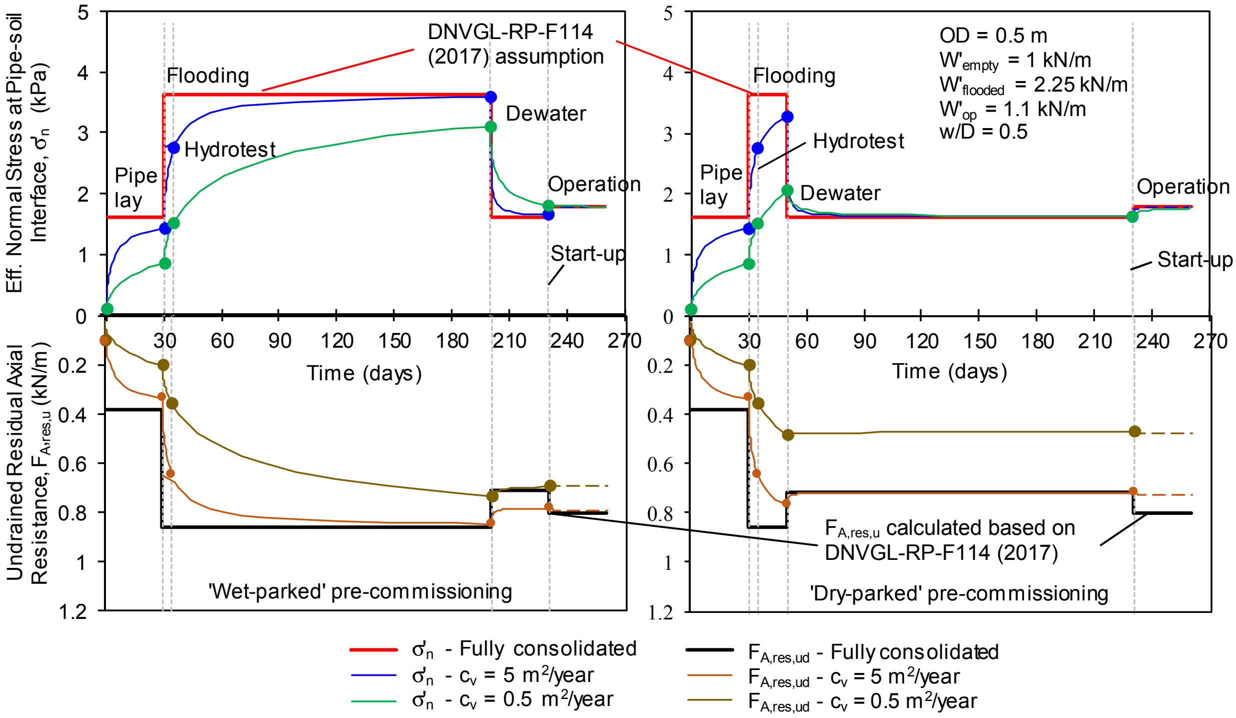
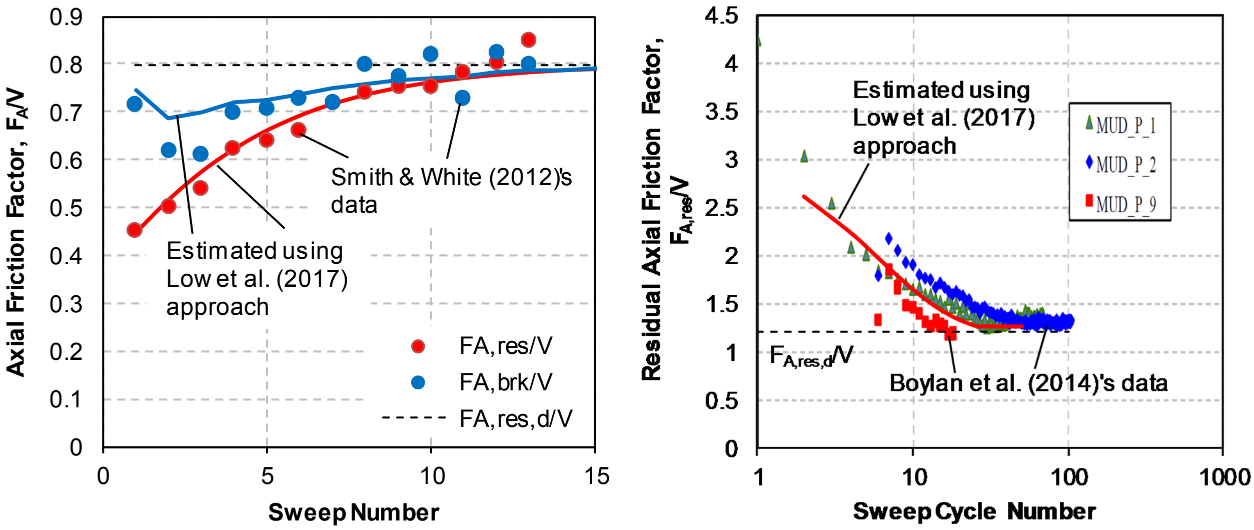


Fig. 10. Evolution of effective stress at the pipe-soil contact interface and the $F_{A,res,u}$ throughout the pre-commissioning (Low et al. 2017)

- Due to the potential large range of coefficient of consolidation or permeability (c_v and k), axial seabed interface response in carbonate soil is often partially drained. Therefore, the adopted calculation approaches should be able to capture the drainage transition during the initial and subsequent pipeline axial movements (e.g. White et al. 2012; Low et al. 2017).
- The axial residual resistance at start-up is dependent on the effective stress history experienced by the soil at the pipe-soil interface during the pipelay process and the precommissioning stages (Fig. 10). As shown on Fig. 10, due to the differences in precommissioning procedure and soil c_v, the start-up axial residual resistance can be significantly different and different from that calculated using the DNVGL-RP-F114 (2017) approach. Due to the potential large range for c_v for carbonate soils, the calculation method needs to be able to capture this variability to reliably calculate the axial residual resistance for carbonate soils.
- The changes in axial residual resistance (either consolidation hardening (Fig. 11a) or softening (Fig. 11b)) during cyclic axial displacement is also dependent on the effective stress history experienced by the soil at the pipe-soil interface during the pipelay process and the precommissioning stages. If the soil at the pipe-soil interface is normally consolidated or lightly overconsolidated, the axial residual resistance will gradually increase to drained axial residual resistance ($F_{A,res,d}$/V) as shown on Fig. 11a. However, if the soil at the pipe-soil interface is overconsolidated (either due to the geological stress history or stress history induced by the pipeline precommissioning procedures), the initial undrained resistance can be greater than the drained value. With cycles and time, this resistance decreases ('consolidation softens' down to the drained value, as shown by the model tests reported by Boylan et al. (2014; Fig. 11b)). Therefore, due to the potentially larger range for c_v and higher pipe-soil interface strength of carbonate soils as compared to siliceous soils, the calculation method needs to be able to use these soil properties explicitly to reliably calculate the changes in axial residual resistance due to the cyclic axial pipe displacement during operation.

With the above considerations in mind, for **undrained axial residual resistance** calculations, it is critical to trace the stress history experienced the soil at the pipe-soil interface as a result of geological conditions (which may be 'erased' by pipe-lay), the pipe-lay process and any precommissioning sequence. DNVGL-RP-F114 (2017) does not encapsulate this as shown in Fig. 10. The approach presented in Low et al. (2017) which use project specific pipeline and pipe-soil interface strength properties and with a sound theoretical basis is recommended.



(a) Axial PSI model tests in normally consolidated siliceous clay (Smith and White 2014)

(b) Axial PSI model tests in overconsolidated carbonate silt with mud (Boylan et al. 2014)

Fig. 11 Evolution of residual axial friction factor due to cyclic axial displacement

As for accurate calculations of **drained axial residual resistance**, the calculation method provided in DNVGL-RP-F114 (2017) is recommended but needs to be parameterized with measured drained interface friction coefficient data for the particular pipeline roughness and soil combination expected in the field (noting that drained interface friction for carbonate soil can be significantly higher than the siliceous sand, e.g. Fig. 2)

SUMMARY AND CONCLUSIONS

The paper has discussed pipe-soil interaction parameters for carbonate soil conditions, explaining the differences in carbonate soil element behaviour that can lead to differences in pipeline response. The results from some public domain pipe-soil interaction experiments on carbonate soil are then compared to design guideline calculations for lay embedment, lateral resistance and axial resistance and reveal disparities.

The comparisons reveal that lay embedments are likely to be under-predicted significantly for carbonate soils (due to their susceptibility to cyclic degradation, high sensitivity and large compressibility) using code-based approaches particularly for drained soil conditions. This is significant as poor predictions in as-laid embedment in particular will lead to unrealistic predictions of lateral breakout resistance (and often residual resistance).

Other significant potential disparities for carbonate soils, were the residual lateral soil resistances for undrained, drained and partially drained soil conditions. For undrained soil conditions, the design guideline (and SAFEBUCK) approaches are based on an empirical equation without soil properties and so deviation in properties from the 'mainly very soft West African clay' conditions in the database from which the equation was produced are likely to lead to deviations in friction factor. Such deviations were demonstrated for contractile carbonate silts and dilatant carbonate silty sands, highlighting the need for consideration of site-specific soil properties (and interface conditions) in order to generate realistic design friction factors.

Finally, drained residual lateral resistance and axial drained resistance is strongly dependent on how the pipeline interface shears on the surface of the seabed. Because of the nature of the carbonate soil grains, there is a potential for larger friction factors than in codes for pipelines with rough interfaces, but these friction factors could be halved for a smooth pipeline. It is recommended that design approaches incorporate the results of site- and pipeline-specific pipe-soil interface tests.

The above information has highlighted the importance of considering the site-specific properties of the seabed on which the pipeline is to be installed (and the properties of the pipeline) and performing calculations which can encapsulate parameters describing these properties. This requirement is particularly important on carbonate soils, where the soil strength, stiffness and drainage properties differ from conventional clays and sands. However, at present, many code-recommended calculation methods are at least partly empirical and are linked to databases of tests on non-carbonate soils. Their use (without modification) appears unlikely to produce reliable sets of friction factors for design in carbonate soil conditions.

REFERENCES

Abdel-Hakim, M., Abdel Azeem, M., Bransby, M.F., Low, H. E., Clavaud, R., Bergkamp, B. and Kizhikkilod, J., 2018. Cost Savings for Subsea Pipelines Using Enhanced Pipe-Soil Interaction Assessment. In Abu Dhabi International Petroleum Exhibition & Conference. Society of Petroleum Engineers.

API, 2014. Geotechnical and Foundation Design Considerations. Recommended Practice RP2 GEO. American Petroleum Institute.

Aubeny, C.P., Shi, H. and Murff, J.D. 2005. Collapse loads for a cylinder embedded in trench in cohesive soil, International Journal of Geomechanics, ASCE, Vol. 5, No. 4, pp. 320-325.

Ballard, J.C. and Jewell, R., 2013. Observations of pipe-soil response from in-situ measurements. In Offshore Technology Conference. Offshore Technology Conference.

Boylan N.P., White D.J. and Brunning P., 2014. Seabed friction on carbonate soils: Physical modelling of axial pipe-soil friction. Proc. Offshore Technology Conf., Houston. Paper OTC-25398-MS.

Bransby, M.F., Borges Rodriguez, A., Zhou, H., Tom, J. and Low, H.E. 2014. Sediment Mobility Effects on Seabed Resistance for Unburied Pipelines. Proc. Offshore Technology Conference, OTC 25287.

Bransby, M.F., White, D.J., Low, H. E. and Westgate, Z., 2015. Accurate Descriptions of Pipe-soil Interaction to Facilitate the Design of High Temperature Pipelines. Proc. OPT Asia, Kuala Lumpur, October 2015.

Chatterjee, S., White D.J. and Randolph M.F., 2012. Numerical simulation of pipe-soil interaction during large lateral movements on clay. Géotechnique 62(8), 693-705.

Clarke, A.R. and Walker, B.F. 1977. A proposed scheme for the classification and nomemclature for use in the engineering description on Middle Eastern sedimentary rocks, Géotechnique, 27(1), 93-99.

Cocjin, M.L., Gourvenec, S.M. and White, D.J., 2018. Softening and consolidation around seabed pipelines: centrifuge modelling. Géotechnique 68(2), 118-132.

DNV-RP-F109, 2010. On-bottom Stability Design of Submarine Pipelines. DNV Recommended Practice, October 2010.

DNVGL-RP-114, 2017. Pipe-soil interaction for submarine pipelines. Recommended practice, DNVGL.

White, D.J. and Gaudin, C, 2008, Simulation of seabed pipe-soil interaction using geotechnical centrifuge modelling. Proceedings of the Deep Offshore Technology Conference (Asia-Pacific). Perth, Australia.

Hull, T.S., Poulos, H.G. and Alhossein, H. 1988. Static test results of carbonate sediments. Proc. Int. Conf. on Calcareous Sediments, Perth, Western Australia.

ISO, 2016 Petroleum and natural gas industries - Specific requirements for offshore structures -- Part 4: Geotechnical and foundation design considerations. ISO 19901-4. International Standards Organisation.

Low, H.E., Ramm, M., Bransby, M.F., Westgate, Z.W. and White, D.J., 2017. Effect of Through-life Changes in Soil Strength and Axial Pipe-Seabed Resistance for HPHT Pipeline Design. Proc. Int. Conf. on Offshore Site Investigation and Geotechnics. SUT, London, September 2017.

Merifield, R.S., White, D.J. and Randolph, M.F., 2009. Effect of surface heave on response of partially embedded pipelines on clay. Journal of Geotechnical and Geoenvironmental Engineering, 135(6), pp.819-829.

Murff, J.D., 1987. Pile capacity in calcareous sands: State of the art, J. Geotech. Engrg, 113(5), 490-507.

Randolph, M.F. and White, D., 2008. Pipeline embedment in deep water: processes and quantitative assessment. In Offshore Technology Conference. Offshore Technology Conference.

Smith, V.B. and White D.J., 2014. Volumetric hardening in pipe-soil interaction. Proc. Offshore Technology Conference, Asia. Kuala Lumpur. Paper OTC-24856-MS.

Verley, R.L.P. and Sotberg, T., 1992. A soil resistance model for pipelines placed on sandy soils. Proc. Offshore Mechanics and Arctic Engineering Conf, Vol V-A pipeline technology: 123–131.

Verley, R.L.P. and Lund, K.M., 1995. A soil resistance model for pipelines placed on clay soils. Proc. Offshore Mechanics and Arctic Engineering Conf, Copenhagen, 18–22 June 1995, Vol V: 225–232.

Sahdi, F., Tom, J.G, Watson, P.G., Gaudin, C. and Bransby, M.F. 2020. Effect of water entrainment on seabed soils during cyclic pipe-soil interaction. Proc. ISFOG 2020.

Watson, P.G., Bransby, M.F., Delimi, Z.L., Erbrich, C., Finnie, I.M.S., Krisdani, H., Meecham, C., O'Neill, M.P., Randolph, M.F., Rattley, M., Silva, M.F., Stevens, R., Thomas, S. and Westgate, Z., 2019. Foundation design in offshore carbonate sediments – building on knowledge to address future challenges. Proc. XVI PCSMGE 2019.

Westgate Z.J., White D.J., Randolph, M.F. and Brunning, P., 2010a. Pipeline laying and embedment in soft fine-grained soils: field observations and numerical simulations", Proc. Offshore Technology Conf., Houston. Paper OTC 20407.

Westgate, Z.J., Randolph, M.F., White D.J. and Li, S., 2010b. The influence of seastate on as-laid pipeline embedment: a case study, Applied Ocean Research, Vol. 32, No. 3, pp 321-331.

Westgate, Z.J., White, D.J. and Randolph, M.F., 2012. Field observations of as-laid pipeline embedment in carbonate sediments. Géotechnique 62 (9), 787-798.

White, D.J., Campbell, M.E., Boylan, N.P. and Bransby, M.F., 2012. A new framework for axial pipe-soil interaction, illustrated by shear box tests on carbonate soils. Proc. SUT Conference, London.

White, D.J., Westgate, Z.J. and Tian, Y., 2014. Pipeline Lateral Buckling: Realistic Modeling of Geotechnical Variability and Uncertainty. Proc. Offshore Technology Conf., Houston, OTC25286.

White, D.J., Westgate, Z., Ballard, J.C., de Brier, C., and Bransby, M.F., 2015. Best Practice Geotechnical Characterization and Pipe-soil Interaction Analysis for HPHT Pipeline Design. OTC 26026.

Zhang, J., 2001. Geotechnical stability of offshore pipelines in calcareous sand. PhD thesis, University of Western Australia.