Pipe-soil Interaction Test Database Study

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Introduction and Executive Summary

API funded a project to perform a review of low normal stress interface shear tests performed over the past two decades as part of an effort to update industry guidance on pipe-soil interaction (PSI) testing, interpretation, and analysis. The work builds on efforts by laboratories to develop standardized approaches to PSI testing in relation to quantifying parameters used in calculations of axial resistance of seabed pipelines. This report presents the updated database and recalibrations of relevant model parameters, as well as guidance for best practice applications of testing and interpretation.

The API Subcommittee on Offshore Structures (SC2), Research Group 7 (RG7) identified a knowledge gap in the current API 2GEO related to axial pipe-soil interaction (PSI) testing, interpretation, and analysis. From this, API SR3 was initiated by contracting the Norwegian Geotechnical Institute (NGI) to address these knowledge deficiencies through a project titled “Design Guidelines for Axial Pipe-Soil Interaction Analysis”. This report presents the work completed as part of these efforts, culminating in an updated interface shear test database, recalibrations of relevant model parameters, as well as guidance for best practice applications of testing and interpretation.

The scope of work comprised four tasks: (1) collecting and cataloging project-specific low normal stress shear test data from various laboratories to establish an updated database of fine-grained interface shear test data and supplementary soil parameters, (2) review of the updated test database to establish a framework for data set definition, (3) recalibration and refinement of existing models using the updated data sets, and (4) development of best practice guidance.

As part of the database interpretation and analysis, four data sets (A, B, C, and D) were identified and characterized including development of statistically derived descriptive parameters and judgement-based selection of model parameters to account for effects of (i) normal stress, (ii) overconsolidation, (iii) interface surface roughness, and (iv) drainage during shear. Each data set was sequentially filtered for specific categories of soil types and surface materials from the database to narrow the statistical range of derived model parameters. This generally achieved coefficient of variation values as low as 0.15 but began to reach a point of diminishing returns due to the small sample sizes in the most restrictive data set. While it is the most restrictive and filtered data set, it is recommended that Data Set D is used for all high plasticity, fine-grained, non-carbonate soils, which are typical of deepwater Gulf of Mexico sites. for all data sets, parameters were developed for smooth, intermediate, and rough surfaces sheared under undrained and drained conditions. Limitations of the database and interpretation of design values are described.

Best practice guidance is presented for test planning, execution, and interpretation, largely based on previous guidance provided in the public domain including technical publications developed as part of the SAFEBUCK Joint Industry Project. New insights are included based on more recent testing performed over the past several years. Collectively, these comprise:

— **Sampling and supplementary testing**: Box coring is recommended to obtain surficial soils for interface shear testing. Batch samples are recommended to be created using sub-samples from individual box cores. Separate batch samples on surficial layers may be warranted, particularly if the expected pipe embedment range extends into both layers. Batch samples are remolded to a (salt) water content value at or slightly higher than the liquid limit, accounting for effects of salt water on measured liquid limits. Supplementary laboratory testing performed on the batch samples is recommended to include water content, unit weight, particle size distribution, specific gravity, and Atterberg limits tests.

— **Test program design:** Normal stress values are recommended to cover the full range of empty through flooded pipeline submerged bearing pressures including wedging effects where appropriate. A minimum of three normal stress values is needed to capture the curvature of the stress effect. for projects where changes in pipe weight during pre-commissioning are significant, it may be useful to perform tests at overconsolidation ratios (OCR) > 1 on the same sample material and the same interface to derive the OCR *m* parameter to apply the SHANSEP approach for undrained strength derivation. A minimum of three OCR values is recommended, using the best estimate (BE) normal stress during shear for all three tests.

— **Interface surfaces selection and characterization:** Testing is ideally performed on representative pipeline coatings provided by the coating supplier. In the absence of actual coatings, plastic surfaces provide a practical substitute, selected to match the planned coating roughness. Sandpaper may be used as a proxy for a roughened surface, but for roughness significantly greater than 10 μm, soil-soil shear (i.e. direct shear) tests generally show less scatter compared with rough interface testing. Bare steel coatings create potential physicochemical interactions between the soil and the steel. Extremely smooth surfaces may induce bonding variations for high plasticity soils. It may be necessary to resurface interface plates throughout the testing program to avoid variations in roughness from test to test. Surface roughness measurements are recommended to be taken parallel to the direction of shearing before and after each test, or at a sufficient frequency to ensure consistency across the test program.

— **Test procedure:** Monitoring sample settlement during the consolidation phase, which may be performed in multiple increments of stress, allows estimation of the coefficient of consolidation of the soil. To measure the residual undrained shear resistance, fast shearing rates (no less than 0.1 mm/s) are recommended. Monotonic testing and cyclic testing with short displacement limits may overestimate the residual value due to lack of sufficient strain accumulation. It is recommended to maximize shearing displacement as much as practical within the constraints of the equipment and consideration of potential soil loss during shear. for cyclic testing, episodic consolidation periods between cycles or pairs of cycles allows for calibration of drainage models that capture the effects of pipeline startup and shutdown events. However, episodic consolidation may prohibit measurement of the minimum undrained residual strength. Gapping between the shear box/ring may promote soil loss and development of additional machine friction. Machine friction correction tests are recommended using an empty shear ring for each interface tested, which is then subtracted from the measured soil-interface resistance. To measure the drained shear resistance, tilt table testing is recommended, performing multiple shearing episodes to ensure the residual shear strength is attained. In the absence of tilt table testing, ISB testing can be performed at slow shearing rates (no greater than 0.001 mm/s). Repeat tests performed for a given set of project conditions allow assessment of how consistent (or inconsistent) the results are.

— **Test interpretation and design parameter derivation:** The residual resistance is selected from portions of the tests where a stable value is observed, averaging across enough data points to eliminate noise. for cyclic tests, the absolute values of shear resistance in each direction are averaged to remove any asymmetry in the data. Machine friction corrections in both forward and backward directions may be appropriate depending on the nature of the surface tested. Epistemic uncertainty and aleatoric variability influence quantification of low estimate (LE) and high estimate (HE) shear resistance from shear test programs. In the absence of explicit assessments of epistemic uncertainties, the coefficient of variation for a given data set in this study may be used to derive LE and HE shear resistance values using the local mean value of a given parameter from site-specific testing on a batch sample.

Suggested future studies to reduce interface shear resistance uncertainty could include (i) comparisons of cyclic testing with and without episodic consolidation periods to determine the number of cycles required to attain minimum undrained shear strength, (ii) modifications/development of low normal stress ring shear devices to achieve true undrained residual shear resistance and avoid cyclic effects of machine friction and berm development, and (iii) investigations using a single soil sample and surface type to refine model calibrations.

Pipe-soil Interaction Test Database Study

1 Scope

1.1 General

The scope of work is divided into four tasks:

a) Collect and catalog project-specific interface shear test data from various laboratories to establish an updated database of fine-grained interface shear test data and supplementary soil parameters;

b) Review of the updated test database to establish a framework for data set definition and refinement;

c) Recalibrate and refine existing design models to the updated data sets, and

d) Develop guidance for best practice.

1.2 Motivation

The interface frictional response of subsea pipelines subject to cycles of expansion and contraction has gained considerable interest over the past two decades as developments are increasingly using subsea tie-back pipelines to existing infrastructure. Energy developers are now routinely testing shallow seabed soils in a variety of custom-built modified direct interface shear box (ISB) devices and tilt table devices designed to apply low normal stresses to fine-grained or coarse-grained soils sheared against a structural surface representing the pipeline coating. The range of interface shear strength measured for a given soil type and interface surface combination is influenced by several factors, for which there is no standardized investigation approach. As a result, ranges in interface shear strength derived from site-specific testing can vary by a factor of 3 (or more) and may be only marginally narrower or even wider than published trends from large databases of both fine-grained soils (Westgate et al. 2018) and coarse-grained soils (Westgate et al. 2021).

The scatter in data are due to sensitivity in measured shear resistance to specimen preparation, testing procedure and equipment, variability of surface seabed soils, and surface roughness effects. These factors affect selection of design interface shear strength values. As a result, shear test program outcomes often present operators and their pipeline contractors with wide ranges of axial PSI inputs to pipeline design, leading to expensive solutions to mitigate pipeline expansion and associated lateral buckling. The lack of guidance means that the application of axial PSI in design will continue to vary based on operator experience. This may increase future risk of unplanned axial pipeline behavior including rogue buckle formation, excessive buckle feed-in, end expansion and through-life walking, resulting in potential buckle pullout and compromising the reliability of a project's controlled lateral buckling strategy. Current approaches to mitigate these issues using strategies such as rock dumping, concrete mattresses, and hold-back anchoring are expensive, but can be used to avoid the significant environmental and financial consequences of excessive axial pipeline movements and their impact on structural pipeline system integrity.

1.3 Objectives

This research focuses on addressing gaps in current practice and improving the recommended practice for PSI under axial loading. The outcome is a set of design and assessment guidelines related to safe operation of new and existing pipelines as well as input to inspection, maintenance, and evaluation for life-extension/continued-service to support. The 2025 updates to ISO 19901-4 include discussion on testing and analysis methods for derivation of axial friction parameters for subsea pipelines in fine-grained soil, inspired by work performed within the SAFEBUCK Joint Industry Project (Atkins 2015). Much of the SAFEBUCK output is now included in the DNV Recommended Practice F114 (DNV, 2021); however, it is referred to as an 'alternative method'. An axial PSI testing database used to calibrate SAFEBUCK PSI models has been published (Westgate et al. 2018). The objective is to update current guidance to include guidance on axial PSI testing and analysis, including the statistical database presented in Westgate et al. (2018) and recently re-examined in Westgate (2022). Reducing uncertainty in the axial PSI inputs through improved code-based guidance can accelerate deployment of resilient