Back analysis of measured as-laid pipeline embedment in soft clay

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ABSTRACT
Pipeline designs such as on-bottom stability, lateral buckling and axial walking analyses require reliable predictions of the as-laid pipeline embedment. The as-laid embedment is usually significantly larger than that predicted by its submerged self-weight alone. This is mainly attributed to the effects of the stress concentration in the touchdown zone and soil remolding caused by the pipeline dynamic motions during the laying process. Quantification of these effects is often made difficult by the lack of field observations. This study presents a detailed back-analysis of the observed pipeline as-laid embedment in soft clayey soils in the shallow waters of Bengal Bay. Statistical analysis is performed to characterize the inherent variability of the observed embedment. The observed dynamic embedment factor is found to be between 1.08 and 1.96. The degradation of the soil resistance to the pipeline during the dynamic laying process is back-analyzed by a sophisticated method in which the reduction of the stress concentration with the increased embedment of the pipeline is well considered. The remolded soil resistance to the pipeline is found to be 0.48~0.74 of the intact soil in the dynamic laying process. And the degree of soil resistance degradation is found to be smaller when the pipeline static embedment is larger.

KEY WORDS: field observations; as-laid pipeline embedment; soft clay; soil softening; stress concentration.

INTRODUCTION
Subsea pipelines represent a significant expenditure for the offshore oil and gas development. The pipeline is usually preferred to be laid directly on the seabed without other specific actions, however the feasibility for doing this is strongly depended on the design values of pipe-soil interaction and the prediction of the pipeline as-laid embedment (Bruton et al., 2007). The parameter of the pipeline as-laid embedment is important, which could influence the soil resistance to the as-laid pipeline, exposure to external loadings and thermal insulation (Randolph & White, 2008).

However, the estimation of the as-laid pipeline embedment is much complicated by the dynamic laying process and remains a great challenge to engineers. The observed pipeline embedment is usually larger than that calculated by its submerged self-weight only. This is mainly caused by two factors: (a) Stress concentration in the TDZ (touchdown zone). The contact force between the pipe-soil in the TDZ is much larger than the pipe self-weight; (b) Dynamic effect. Soil resistance to the pipeline would decrease as the pipeline is laid dynamically.

To estimate the pipeline embedment, theoretical solutions for soil resistance have been developed for a rigid pipe penetrated into soft clayey soils (Aubeny et al., 2005; Merifield et al., 2008; Merifield et al., 2009). Centrifuge modeling has also provided further insights (Gaudin & White, 2009). But, it is much more difficult to incorporate the soil strength softening properly in the theoretical solutions, and the centrifuge modeling was operated under ideally controlled conditions. The complexity of the real dynamic laying process can hardly be simulated.

This study presents the detailed back-analysis of the pipeline as-laid embedment field observations in the shallow waters of Bengal Bay. Based on the plasticity solutions for partially embedded pipeline into the soft sediments, the dynamic factor is back-analyzed from field observations to compare with the recommended values in designing. The dynamic effects during the laying process are quantified by estimating the degree of soil resistance degradation from the field observations.

FIELD STUDIES
The investigated pipeline, located in the shallow waters of Bengal Bay, Asia, was developed to transport the produced gas from offshore platform to land terminals. The pipeline was directly laid on the seabed using S-lay method. The investigation of the pipeline as-laid embedment was carried out about one month later after pipeline installation using sonar scanning and ROVs (remotely-operated vehicle) visual recordings.

Soil Properties
This paper studies pipeline as-laid embedment field observations in the region of soft clay sediments on top of the seabed. The pipeline is nearly 45km long in the investigated region.

To investigate the soil properties, methods including drilling, sampling, piezocone penetration test (PCPT) and offshore laboratory testing were carried out in the upper 0.5m. Gravity core samples were used for the laboratory testing. The shear strength was measured by the vane tests, which were cross-calibrated by the results of field PCPT tests. According to the investigated soil strength profile, the distribution of soil shear strength in the analysis is assumed to increase linearly in the shallow depth with zero intercept at the mudline.

The soil properties are summarized in the Table 1, and four sections are divided along the investigated pipeline route.