

## Vertical Load-Displacement Response of Untrenched Offshore Pipelines on Calcareous Sand

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### ABSTRACT

**A plasticity model is presented to describe the drained vertical load-displacement response of untrenched offshore pipelines on calcareous sand. The predicted plastic response during monotonic loading and elastoplastic behaviour during reloading is shown to compare well with experimental data. The model can be used to evaluate total settlement of a pipeline under both monotonic and cyclic loading conditions. Using the framework presented in this paper, it is possible to extend the model to simulate the vertical load-displacement response of other types of shallow foundations and to cover undrained conditions.**

### INTRODUCTION

The response of pipelines to monotonic and cyclic vertical loading is an important aspect of offshore pipeline engineering, as this response affects the on-bottom stability of untrenched pipelines. Previous investigations into pipeline behaviour under vertical cyclic loading have shown a minor increase in settlement and bearing capacity (Dunlap et al., 1990) compared to that deduced from cyclic horizontal loading (Morris et al., 1988). Hence the load-displacement response of pipelines under cyclic vertical loading has received relatively little attention, compared to that of pipelines under cyclic horizontal loading. However, with the development of analytical methods having a strong theoretical background (Zhang et al., 1999), accurate modelling of the vertical load-displacement response of pipelines becomes necessary.

While pipeline response under cyclic vertical loading has not been studied extensively, some progress has been made in the modelling of the vertical load-displacement response of shallow foundations. Results from model tests on a strip footing on dense ( $D_r = 86\%$ ) sand reported by Gottardi and Butterfield (1995) have shown very little hysteresis and an essentially linear response during a single unloading and reloading cycle. The general form of the footing load-displacement response mirrors the virgin compression and unloading-reloading response seen in soil compression tests. The stiffness of the footing's unload-reload line was about  $6 \times$  higher than that of the virgin loading (backbone) line. The reloading line rejoined the backbone line when the load was about  $1.1 \times$  the load at the point of starting unloading. Field tests (Al-Sanad et al., 1993) conducted on very dense calcareous sand using loading plates 0.3 m, 0.61 m and 1.28 m in diameter indicated an unload-reload stiffness only  $2$  to  $2.5 \times$  higher than that of the backbone line. Again, the unloading-reloading cycles show very little hysteresis and an essentially linear response. Results

from multiple-cycle loading tests indicated that the plastic displacement increment in each cycle decreased with an increasing number of cycles.

Sawicki et al. (1998) introduced compaction theory in the analysis of shallow foundation settlements due to cyclic vertical load. The empirical method proposed by Sawicki et al. did not include the settlement due to initial loading of the foundation, because this settlement was considered to be associated primarily with the phenomenon of plastic flow rather than compaction. Thus, while the method can enable an estimate of the increase in settlement due to cyclic vertical load, the settlement under initial loading must be evaluated separately.

In attempting to describe the vertical load-displacement response of pipelines and foundations within a theoretical framework, a new approach that follows strain-hardening plasticity theory is employed here in a way similar to that adopted by Pestana and Whittle (1995) in the construction of a compression model for cohesionless soils. The current model is different from the compression soil model in that an elastic range is assumed in this model. The unload-reload response is assumed to be partially elastic with a gradual elastoplastic transition during reloading. The gradient of the response curve at any point is taken as a function of the distance between the current loading point and the backbone line, and as this distance reduces, the proportion of plastic deformation increases.

A plasticity model that includes the above features is proposed in this paper to evaluate the total settlement of pipelines, which may be considered a type of shallow foundation, under both monotonic and cyclic vertical loading. This model is calibrated using experimental data. It is shown that predictions from the model agree very well with test data. Using the framework presented in this paper, it is possible to extend this model to perform settlement analysis of other types of shallow foundations under cyclic vertical loading.

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KEY WORDS: Offshore pipeline, plasticity model, vertical loading, calcareous sand, cyclic loading.

### EXPERIMENTAL OBSERVATIONS ON MODEL PIPELINES

A series of pipe tests has been conducted on the beam centrifuge at The University of Western Australia. Fig. 1 shows the general arrangement of the test apparatus schematically. The tests