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Uplift mobilisation resistance of subsea pipelines in loose sand

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Upheaval buckling (UHB) is a well-known phenomenon associated with buried high-pressure high-temperature pipelines. A large number of research studies have been undertaken in the last two decades on developing reliable uplift resistance mobilisation models from which the current standards and recommendations are based. This paper examines Technip's extensive database consisting of experimental and numerical studies concerning sandy backfills only. The peak uplift mobilisation distances obtained are compared with the current DNV recommendations and a recent experimental study undertaken at the University of Cambridge. The trends obtained indicate differences associated specifically with the lower backfill cover depths and suggest that the current recommendations need to be updated. A new improved peak mobilisation distance model, which is able to capture the relevant data with a distinction made between very loose and loose sand backfill, is offered.

KEYWORDS: buried structures; offshore engineering; pipelines; sands; standards

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NOTATION

D	pipe diameter
H	cover height, defined as vertical distance from top of backfill to top of pipe
δ_f	mobilisation distance
δ_{peak}	peak mobilisation

INTRODUCTION

The transport of hydrocarbon products offshore in shallow water is generally through trenched subsea pipelines. These pipelines are typically at higher temperatures and pressures than the ambient surrounding environment. This causes the pipeline to expand, which induces an axial compressive force along the pipeline as the backfill on top of the pipeline restrains its movement. This force and any imperfections in the pipeline can result in vertical upheaval buckling (UHB) where, in the worst case, the pipeline can protrude above the seabed.

Imperfections in a pipeline trench are defined as vertical out-of-straightness (OoS) events, which indicate the locations where UHB is most likely to occur as the force required to buckle at an imperfection is less than that for a flat pipeline. OoS events can be caused by natural imperfections such as initial seabed conditions, boulders and sand waves. However, the main cause of OoS events is from the trenching operation due to variations in trencher performance (e.g. stop/start plough operation and collapsed or slumped material from the trench walls getting under the pipeline).

Figure 1 shows the effective axial force developed along a length of a pipeline. At the ends, where the pipeline is free to expand, the axial force reduces to zero. It can be seen from the plot that, in sections, the effective axial force is greater than the critical force for various prop height imperfections and hence these would be susceptible to UHB. UHB mitigation can be effective when backfill is placed on top of the pipeline within the trench. The backfill material will provide a resistance to pipeline movement, which will depend on the type of backfill used and how it is placed in the trench. The main methods of pipeline burial offshore are

- jet trenching, in which a series of high-pressure water jets liquefy the soil and the pipeline sinks
- pipeline ploughing, where a tool with a cutting share is towed along the seabed to form an open trench which is then backfilled upon installation of the pipeline.

Sand backfill formed through jet trenching will be in a very loose condition with relative density (RD) typically $< 10\%$. On the other hand, mechanically placed sand backfill will typically be in a loose to medium dense condition, represented as $10\% < RD < 40\%$.

The uplift resistance offered by a sand backfill depends on the upward movement of the pipeline. This vertical pipeline movement required to fully mobilise the uplift resistance is an important parameter for UHB, as the critical buckling force depends on the vertical upward stiffness of the sand backfill (Randolph & Gourvenec, 2011). This peak mobilisation distance also adds to the imperfection height mentioned earlier. Hence, the greater the mobilisation distance – or the lower the upward stiffness – then the lower the critical buckling force and the longer the length of pipeline susceptible to buckling. As such, underestimating the mobilisation distance could result in an unsafe design as the resistance provided by the backfill at critical sections along the pipeline may not be sufficient to resist the buckling force. Expensive remedial measures (e.g. rock dump or concrete mattresses placed on top of the backfill) would therefore be required to mitigate the excess buckling force.

The topic of mobilisation distance of sand backfill has attracted significant research interest. This has resulted in a number of small-scale centrifuge studies (e.g. Dickin, 1994; White *et al.*, 2001), 1***g*** laboratory studies (e.g. Schaminee *et al.*, 1990; Bransby *et al.*, 2002) and numerical modelling approaches (e.g. Dickin & Laman, 2007; Cheuk *et al.*, 2008).

Current design guidelines for uplift resistance suggest that the peak uplift resistance in sandy backfill is mobilised

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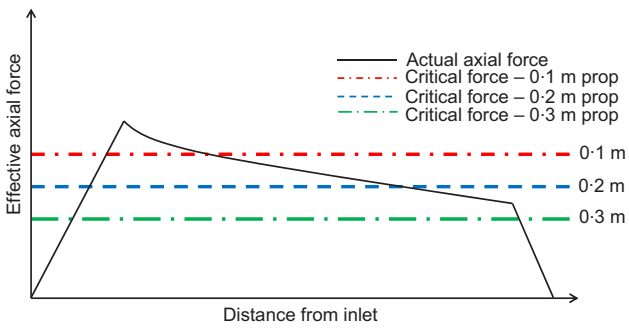

Fig. 1. Critical buckling force profile

when the upward movement of the pipe reaches 0·5–0·8H%, where H is the cover height defined as the vertical distance from the top of the backfill to the top of the pipe (DNV, 2007).

Palmer *et al.* (2003) reported that the peak uplift resistance shows good agreement between centrifuge and 1***g*** modelling tests but indicated inconsistencies in the dimensionless mobilisation displacement because of localised shear zone formation. As a result, caution should be taken when centrifuge data of mobilisation distances are used for design purposes.

A few studies have investigated rate effects associated with how quickly water drains from the sediment. Bransby & Ireland (2009) indicated that if uplift speeds are less than 0·167 mm/s, then saturated loose clean sand will behave as dry loose sand (i.e. fully drained condition). However, when the rate of testing exceeds this limiting value, partially drained conditions will apply and this will affect the peak mobilisation displacement. Williams *et al.* (2013) showed that the mobilisation displacement will increase for speeds in the range 0·002–5 mm/s.

A recent full-scale experimental study was undertaken at the University of Cambridge in sandy backfill (Thusyanthan *et al.*, 2010; Wang *et al.*, 2012) to investigate the uplift stiffness response of pipelines buried in both saturated and dry sand. The results showed that the ratio of mobilisation distance to peak uplift resistance depends on H/D and exceeds the recommendations stated in DNV-RP-F110 (DNV, 2007). Based on experimental data obtained from their study and a few studies found in the literature, Thusyanthan *et al.* (2010) proposed a new equation for peak mobilisation in loose sand as a function of H/D

$$\frac{\delta_f}{D} = 0{\cdot}02\exp\left(0{\cdot}5\frac{H}{D}\right) \tag{1}$$

Thusyanthan *et al.* (2010) compared their test data with centrifuge experiments (Dickin, 1994), results from strip anchor plates (Dickin & Laman, 2007) and the study undertaken by White *et al.* (2001). As mentioned before, Palmer *et al.* (2003) indicated that centrifuge test data may not be representative of the mobilised displacement associated with upheaval bucking. Although Dickin & Laman (2007) suggest that similar behaviour may be expected for both anchor plates and pipelines, they also highlight that 'significant differences do exist in displacements to failure'. In addition, the data presented by Thusyanthan *et al.* (2010) are on a log scale, which minimises any discrepancy between the datasets for large values of H/D than if a linear scale was used. The majority of the tests undertaken by Thusyanthan *et al.* (2010) focused on loose sand with 10% < RD < 40%. A few tests on very loose sand with RD < 10% were undertaken by Schaminee *et al.* (1990). More recently, studies reported by Byrne *et al.* (2013) and Williams *et al.* (2013) have provided a comprehensive dataset of approximately 60 tests performed on very loose sand (0% < RD < 17%).

This paper attempts to address the lack of clear and consistent guidelines related to the vertical distance required to fully mobilise the peak uplift resistance of a pipeline for shallow burial depths of $H/D < 3{\cdot}5$ and very loose and loose sand backfill for dry and saturated conditions.

DATA ANALYSIS

The Technip database comprises both experimental and numerical data gathered from research studies undertaken since 1995. The database contains the published studies undertaken by Matyas & Davis (1983), Trautmann *et al.* (1986), Schaminee *et al.* (1990), Dickin (1994), Ng & Springman (1994), White *et al.* (2001), Martindill (2005), Cheuk *et al.* (2008), Thusyanthan *et al.* (2010), Wang *et al.* (2012) and Byrne *et al.* (2013). It also contains test results commissioned directly by Technip, called Technip A and Technip B (Technip OED, 2003).

The general relationship used for design is defined through the tri-linear uplift resistance model defined in DNV-RP-F110 (DNV, 2007), which is based on the mobilisation distance δ_f and parameters α and β shown in Table 1; DNV-RP-F110 further indicates that δ_f is independent of H/D. The peak mobilisation δ_f was examined for the Technip database over a range of H/D values. In order to observe the data for shallow depths, δ_f was normalised with diameter D.

RESULTS AND DISCUSSION

The data obtained from the Technip database were analysed using only complete datasets. Peak mobilisation values for some datasets were not available and consequently these were not included. Table 2 gives an overview of the data used in this analysis, giving an indication of the condition of the soil, RD, number of tests undertaken and rate of pipeline displacement (where available).

Tests undertaken on loose sand only were included in this analysis. Centrifuge test results were not included following the recommendation of Palmer *et al.* (2003) as they are not representative of the peak displacements found in 1***g*** tests.

Figure 2 presents a complete set of the data available for loose sand (RD < 40%) compared with the current DNV-RP-F110 (DNV, 2007) recommendations. Some data are also marked 'sub' and 'dry', indicating tests undertaken in

Table 1. DNV-RP-F110 (DNV, 2007) parameters for sand

Backfill	Condition	Mobilisation distance, δ_f: mm [a]	α	β	Limitations
Sand	Loose	0·5–0·8H%	0·75–0·85	0·2	$3{\cdot}5 \le H/D \le 7{\cdot}5$
Sand	Medium/dense	0·5–0·8H%	0·65–0·75	0·2	$2{\cdot}0 \le H/D \le 8{\cdot}0$

[a] δ_f given in the code as 0·005–0·010H

Table 2. Summary of data

Source	Test	Number of tests	Soil	D_{10}: mm	D_{50}: mm	RD	Pipeline/anchor plate Submerged/ dry	Uplift speed: mm/s	Comment
Schaminee *et al.* (1990)	Full scale	3	Very loose soil	0·15	0·25–0·3	0·05–0·14	Pipeline/submerged	0·027	
Schaminee *et al.* (1990)	Full scale	4	Loose soil	0·15	0·25–0·3	0·17–0·21	Pipeline/submerged		
Technip A	Full scale	5	Sand	0·2	0·25–0·3	0·24–0·29	Pipeline/submerged	0·0011	
Technip A	Centrifuge	5	Fine sand	0·08	0·1–0·15	0·2	Pipeline/submerged		Centrifuge tests not included
Cambridge University/ White *et al.* (2001)	Centrifuge	5	Sand			>0·35	Pipeline/dry		No loose soil test result – should not be included in loose soil calculation
Technip B	Scale model	4	10% silt, 90% sand	0·1	0·25–0·9	0·17–0·21	Pipeline/submerged	0·005–0·012	
Technip B	Scale model	4	10% silt, 90% fine sand	0·06	0·1–0·15	0·2–0·31	Pipeline/submerged		
Trautmann *et al.* (1986)	Full scale	6	Loose clean sand	0·2	0·5	0·321	Pipeline/dry	0·333	
Trautmann *et al.* (1986)	Full scale	2	Medium clean sand	0·2	0·5	0·321	Pipeline/dry	0·333	
Matyas & Davis (1983)	Scale	3	Sand	0·2	0·35	0·22–0·28	Pipeline/dry		
Byrne *et al.* (2013)	Scale model	19	Red Hill 110 sand				Pipeline/submerged	0·002	
Byrne *et al.* (2013)	Scale model	20	LB14/25			0·172	Pipeline/dry	0·17–1·8	
Martindill (2005)	Scale model	30	Leighton Buzzard 15/25 sand, loosely packed			0·297	Pipeline/dry	0·35–0·95	
Wang *et al.* (2012)	Full scale	8			0·18	0·35	Pipe/submerged	0·005	
Wang *et al.* (2012)	Full scale	2			0·18		Pipeline/dry	0·005	
Dickin (1994)	Centrifuge	4	Loose clean fine quartz sand				Pipeline	0·067	Comment from Palmer *et al.* (2003) – should not be included
Dickin (1994)	Centrifuge	7	Loose clean fine quartz sand			0·067	Anchor plate	0·067	Anchor plate tested instead of pipe, should not be included as some issues were raised

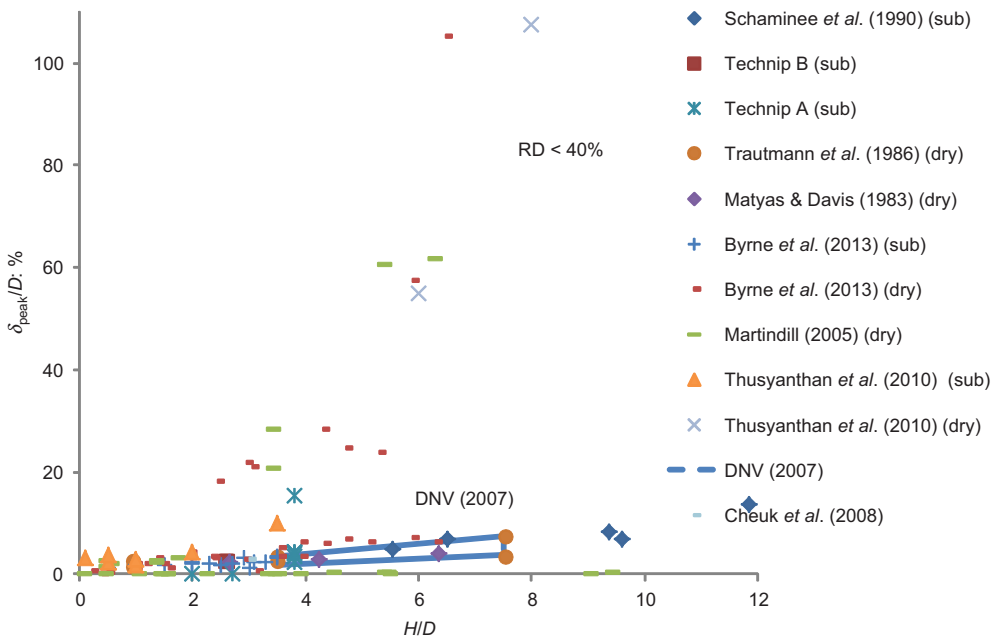

Fig. 2. Recommended mobilisation distance for loose sands normalised with pipe diameter (RD < 40%) – all data

submerged and dry soil conditions, respectively. Figure 2 shows that the majority of the data obtained from the Technip database fall within the shallow depth region ($H/D < 3{\cdot}5$) for which DNV do not give recommendations. It is also clear from the results that higher values of mobilisation displacement are evident for dry conditions than submerged conditions

The sand used in all the studies was clean sand, apart from Technip B data where 10% of silt was present, in which case fully drained conditions may not have been realised. Bransby & Ireland (2009) and Williams *et al.* (2013) comment on the importance of the test rate and the presence of the fines content in sand.

The curve proposed by Thusyanthan *et al.* (2010) and Wang *et al.* (2012) (equation (1)) takes into account test results from both dry and submerged conditions. As can be seen from Fig. 2, the dry condition data of Thusyanthan *et al.* (2010) are significantly higher for $H/D=6$ and $H/D=8$ and match only a few points obtained from other studies. This would suggest that if the proposed curve was recommended for design, the data for $H/D > 3{\cdot}5$ would be overly conservative.

From Fig. 2 it is also clear that the experiments of Trautmann *et al.* (1986) and Matyas & Davis (1983) undertaken in dry sand conditions are similar to those undertaken in saturated conditions. However, the studies undertaken more recently in dry conditions (Martindill, 2005; Thusyanthan *et al.*, 2010; Byrne *et al.*, 2013) indicate higher mobilisation displacements when compared with those undertaken in earlier studies.

The speed effect for the tests undertaken in saturated soil was examined and showed no significant influence on the peak mobilisation (Fig. 3). Since all the tests performed in saturated conditions were undertaken in loose soil and at

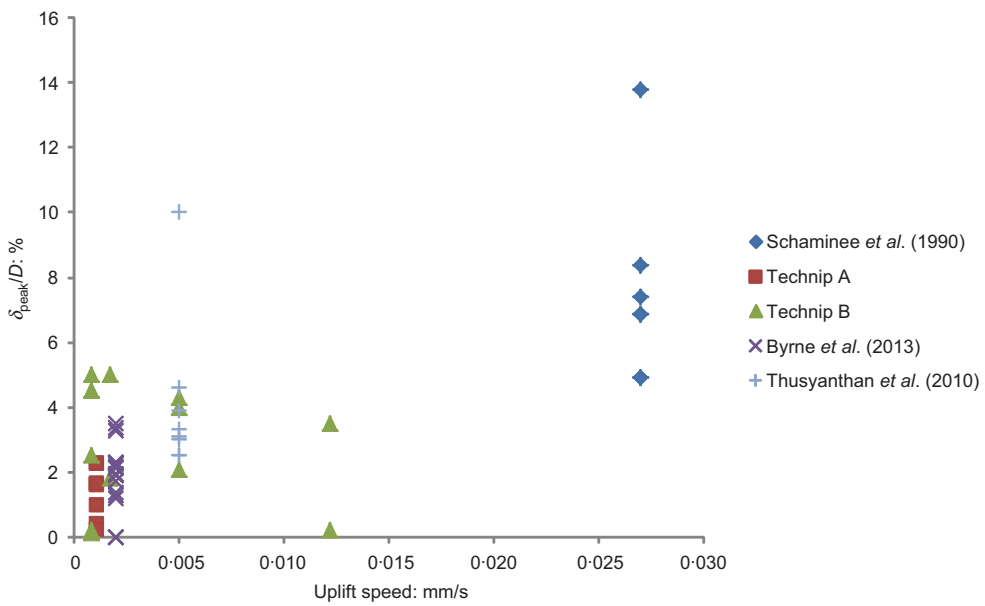

Fig. 3. Influence of uplift speed on mobilisation displacement for the cases undertaken in saturated sand

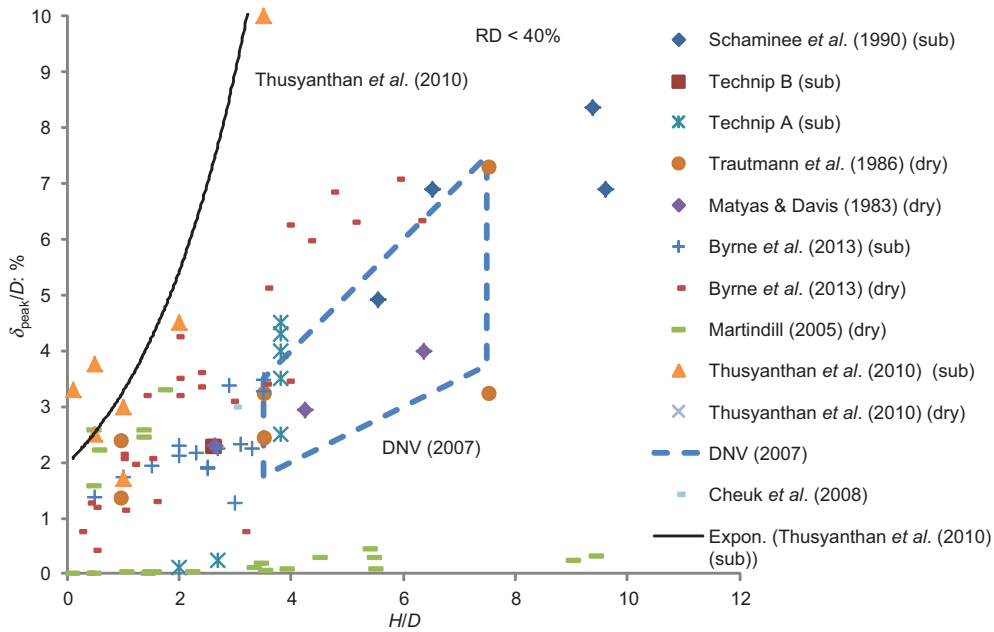

Fig. 4. Recommended mobilisation distance for loose sands normalised with pipe diameter (RD < 40%)

uplift speeds less than 0·167 mm/s, according to Bransby & Ireland (2009) and Williams *et al.* (2013) the speed effect should not have been influential. Byrne *et al.* (2013) give 60 datasets for very loose sand (RD < 10%), representative of post-jetted sand providing strong evidence for the separate categorisation of very loose and loose sand.

RECOMMENDATION

It is clear that equation (1), proposed by Thusyanthan *et al.* (2010), does not best represent the data obtained from other studies for $H/D < 3{\cdot}5$. It is clear that, for shallow depths, the mobilisation distance is different from that found for deeper trenching depths. It is also clear from Fig. 4 that very loose sand performs differently from loose sand. Consequently, the loose sand classification can be further separated into loose (10% < RD < 40%) and very loose sand (RD < 10%), associated with mechanically placed sand and post-lay jetting, respectively.

Figure 5 proposes an extension to the DNV zone where only data within the 'loose' sand range were considered. Figure 6, on the other hand, proposes an extension to the DNV zone where only data for very loose sand are presented. Here, the extension zone mainly captures the data reported by Byrne *et al.* (2013), currently the most comprehensive study in terms of very loose sand. The zone suggested goes beyond the recommended DNV zone for $3{\cdot}5 < H/D < 7{\cdot}5$ to include these data and also gives an extension for shallow depths.

This indicates that a further distinction within the DNV recommended practice is required in which very loose sand could follow a more conservative upper bound limit. This

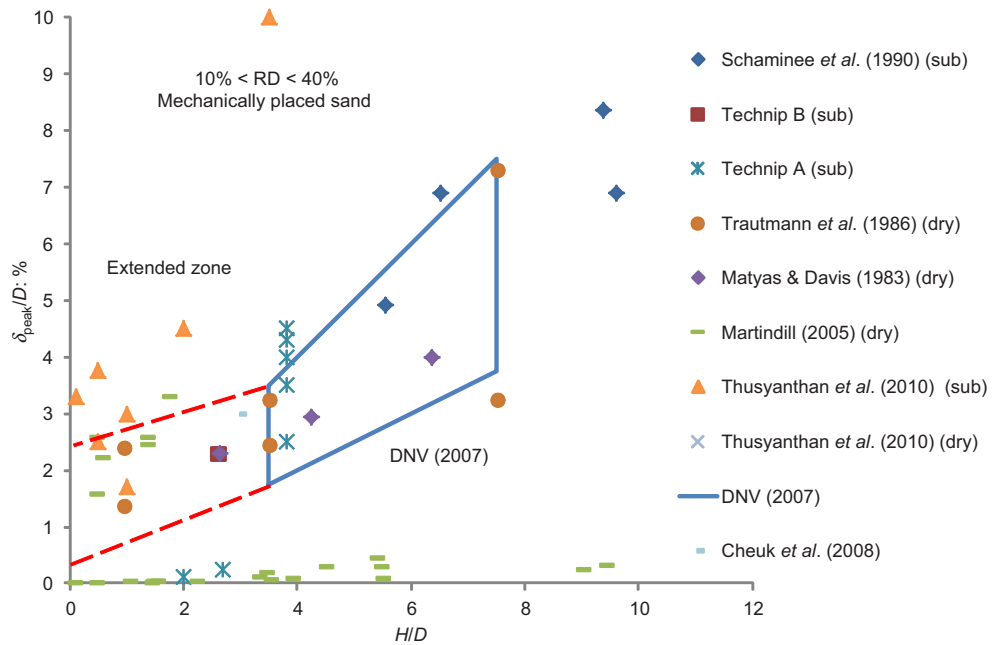

Fig. 5. New proposed mobilisation distance zone for loose sand, 10% < RD < 40% (mechanically placed sand)

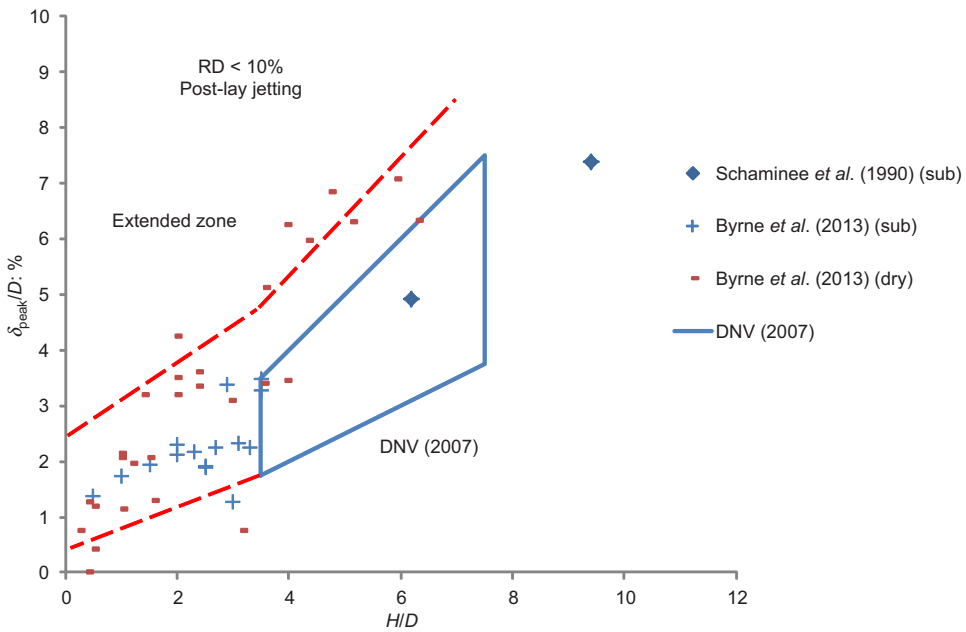

Fig. 6. New potential mobilisation distance zone for very loose sand, RD<10% (post-lay jetting)

assumes that the results of tests in dry conditions are sufficiently representative of the submerged soil conditions found in the field.

CONCLUSIONS

Mobilisation displacements associated with the uplift resistance of buried pipelines were examined and a comparison of the Technip database and the DNV recommendations was undertaken. The results of recent laboratory studies were taken into account, indicating the trends for shallow depths and a clear distinction between sets of tests undertaken in dry and submerged conditions. Following the analysis, it appears that the DNV code still provides suitable recommendations for higher *H*/*D* values while some modifications are required for lower values, in particular to capture data from studies undertaken in recent years. A distinction is made between very loose and loose sand and new recommended peak mobilisation curves are proposed that better represent the two cases. It was also shown that, in the tests undertaken in saturated conditions, the uplift speed used should not influence the mobilisation displacement.

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