The investigation of seabed stability history using simple geotechnical tools

L'étude de l'histoire de la stabilité du fond π.arin utilisant des outils géotechniques simples

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ABSTRACT: The design of offshore pipelines in areas affected by cyclonic storms needs to consider the effects of regional instability, when seabed sediments around the pipeline can fluidise under the effects of near bottom currents. The depth to which this fluidisation can occur is extremely important as it impacts the required burial depth of the pipeline. This paper presents a method of assessing the depth to which seafloor instability has occurred in the past, using the results of particle size distribution tests and static cone penetration tests. Whilst the former can provide evidence relating to previous seafloor instability, it is not conclusive evidence but, with the addition of CPT data, a reliable estimate of the depth of previous instability can be determined.

RÉSUMÉ:L'étude d'oléoducs situés dans des zones touchées par des dépressions cycloniques a besoin de considérer l'effet de l'instabilité régionale, quand les sédiments du fond marin autour de l'oléoduc peuvent se liquéfier sous les influences des courants prés du fond. La profondeur pour laquelle cette liquéfaction peut se produire est extrêmement importante car elle exerce une influence sur la profondeur nécessaire d'enterrement de l'oléoduc. Cet article présente une méthode d'évaluation de la profondeur à laquelle une instabilité antérieure du fond marin s'est produite, utilisant les résultats d'essais granulomètriques et d'essais du pénétromètre statique. Pendant que le précédent peut produire une évidence liée à des instabilités du fond marin préalables, ceci n'est pas une évidence conclusive mais, avec l'addition du datum du CPT, une estimation solide de la profondeur d'une instabilité préalable peut être déterminée.

1 INTRODUCTION

Following the discovery in 1990 of major scouring around sections of the existing 40" North Rankin Trunkline (NRT), studies indicated that there was a potential for major widespread instability of shallow sub-seabed sediments in the area traversed by the NRT. (See Figure 1)

This instability, which has been termed 'regional instability', results from shear forces, mobilised by near-bottom current, acting on the seafloor sediments and causing the transportation of near-surface sediments, which are termed *'tempestites'* in Seibold & Berger (1996). Under extreme conditions, such as during a major cyclonic storm, sheet flow of sediment occurs. This mechanism effectively causes the seabed sediments to 'fluidise' and behave as a liquid (Note that the term 'liquefaction' is not used, to avoid confusion with the better known geotechnical process resulting from the generation of high pore pressures).

It is important to recognise that this fluidisation process does not depend upon disturbing vortices, generated by interaction between the seafloor and neighbouring features and it is therefore independent of 'local scour', and should not be confused with this separate, more common occurrence. Unlike local scouring, regional instability occurs across a relatively wide seafloor area, with no requirement for any disturbing features to initiate sediment transport.

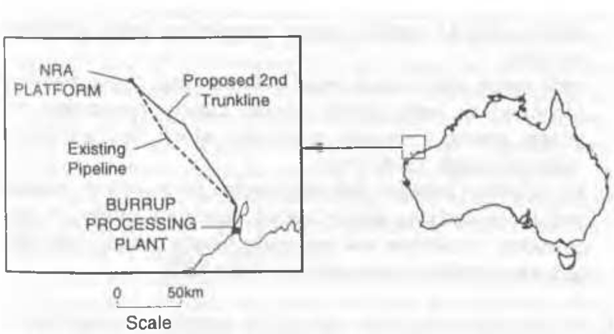
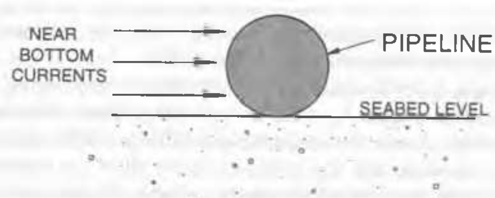


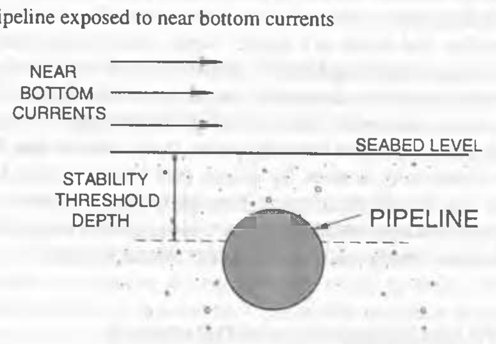
Figure 1: Location Diagram

However, if a pipeline has been buried to ensure its stability under the action of near bottom currents and regional instability occurs, some or all of the lateral restraint previously provided by the surrounding sand will disappear. (See Figure 2)

It is therefore critical to ensure that, if a pipeline is installed in an area susceptible to regional scour, it is installed with its crown below the depth to which regional instability can be expected. Consequently, the maximum depth to which regional instability can occur must be determined. This depth is known as the Stability Threshold Depth (STD).



a) pipeline exposed to near bottom currents



b) pipeline shielded from near bottom currents (unless regional instability were to occur)

Figure 2: A Buried Pipeline Affected by Regional Instability

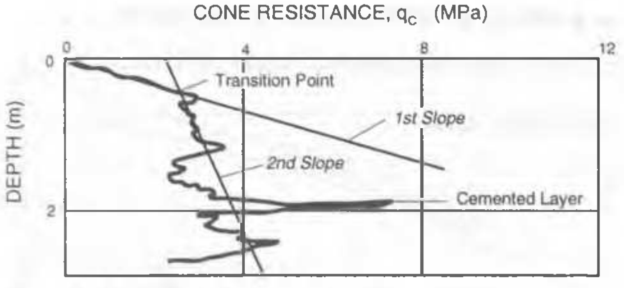


Figure 3: Typical Cone Resistance Response

This process is complicated by the fact that regional instability is likely to peak at the height of the event causing the disturbance and that, after the event has occurred, there may be no visible signs on the seafloor that such an extreme event has occurred.

Waterton & Price (1994) described studies into the regional scouring mechanism and its contribution to scouring mechanisms that impacted the NRT after the passage of a major cyclonic storm. They also postulated possible methods of identifying the STD. Subsequently, during the early stages of design of the proposed Second Trunkline (See Figure 1), it was recognised that further studies of this matter were required as the pipeline burial depth requirements could be significantly impacted by the occurrence of regional instability, with a consequent major effect on project economics.

2 PREVIOUS STUDIES

As reported in Waterton & Price (1994), studies undertaken to that time comprised:

- a series of static Cone Penetration Tests (CPTs) carried out along the existing pipeline alignment;
- evaluation of a large quantity of Particle Size Distribution (PSD) data that had been recovered in the late 1970s during the geotechnical investigation for the pipeline;
- soil fabric studies carried out on undisturbed samples recovered from locations along the pipeline route.

A set of criteria were developed from these studies and the application of these criteria allowed the accurate hindcasting of those areas of the NRT where seabed instability problems had occurred, thus giving good correlation between the various facets of the study and observed areas of instability.

Of particular interest was the CPT behaviour noted during these earlier studies. Figure 3, which is reproduced from Waterton & Price (1994), shows the characteristic bilinear CPT cone resistance, q_c, response that was noted in nearly all of the tests in the area known to have been previously unstable. In this earlier paper, it was postulated that the upper relatively smooth linear section, may represent a relatively uniform, normally consolidated layer, possibly laid down in a single 'event', overlying a more irregular response resulting from the penetration of multiple layers of materials deposited separately as a result of normal, non-extreme marine processes. It was thus postulated that the transition point between these two responses could define the STD. However, laboratory studies by others (see Pearce *et al*, 1992) suggested that the depth of sheet flow instability would be limited to a depth of not more than 50mm; bioturbation being identified as the most likely cause of the upper, linear section.

3 SCOPE OF CURRENT INVESTIGATIONS

Whilst the previously established correlation between seabed instability and scoured areas established was strong, it was also recognised that this correlation was possibly arbitrary and that there was no direct correlation linking the soil fabric observations with the interpretations of instability made from the CPT and PSD data sets.

Therefore, when work on the Second Trunkline project commenced, it was recognised that if reliable pipeline stabilisation were to be achieved by trenching or burial, it would have to be buried below the Stability Threshold Depth. This was because not only would the stabilising effect of surrounding sediments be lost if these materials became affected by sheet flow processes but also because earlier studies had shown that an exposure of as little as 5% of the pipeline's diameter could initiate local scouring around the pipeline.

In view of the constancy of geological conditions during the lifetime of the seafloor sediments (which are less than 18,000 years old) and the low rate of sediment deposition (0.07 to 0.1mm/year), it seemed likely that the material down to the STD would act as record of past major storm events and also be an indicator of likely instability in the future. Thus the thickness of this storm signature layer defines the STD. In view of the age of the sediment (<20,000 years), there is only a low risk (of the order of 0.01 – 0.0025) of the maximum storm experienced to date being exceeded during the new pipeline's service life (say 40 – 50 years). Consequently, the storm signature layer is not only a record of past storm events but is also an indicator of likely instability in the future.

Previous studies had shown that the effects of significant regional instability appeared to be mostly confined to a 20km section of pipeline with water depths ranging from approximately 30m to 50m. Clearly this observation is a function of local geography and storm behaviour and also required verification.

As noted previously, CPT response could be providing a direct indication of STD and studies were put in hand to investigate this matter further. The geotechnical investigation programme was therefore extended to include:

- CPT work along the pipeline route;
- recovery of high quality undisturbed tube samples, recovered using a sampler deployed from the CPT test rig, thus allowing the direct comparison of the CPT data with a corresponding sample;
- geotechnical and sedimentological logging of these samples
- laboratory testing of recovered samples.

3.1 *Sedimentological studies*

The bulk of the sedimentological studies were carried out on undisturbed tube samples, which were found to provide high quality samples, which had been subjected to minimal disturbance. These studies involved the examination of 316 tube samples, which were logged in terms of sediment-type categories and features such as soil structures. 215 of these samples were obtained from the same locations as CPTs were carried out, thus allowing direct comparison of the results of the sedimentological examination with CPT data.

The detailed reporting of the results of these sedimentological studies is outside the scope of this current paper, but it was found that:

- out of the 215 samples examined, the previous (in)stability of 202 samples could be assessed with a reliable degree of certainty, with 44 samples being assessed as being previously unstable;
- well sorted, clean sands were common and could readily be identified as being storm driven, clearly contrasting with poorly sorted, fines-rich materials, which had accreted in more quiescent conditions;
- the interface between the well-sorted, storm-driven materials and the underlying poorly sorted, materials formed in more quiescent conditions was generally clearly visible and sharp and was therefore representative of the STD.

It was also noteworthy that most of the samples received had not been affected in any major way by bioturbation processes.

Whilst such activity is very common in the region, it was apparent that the recovered samples had not been affected to any major degree by bioturbation and it is therefore very unlikely that the CPT response would be affected by such processes.

3.2 *Cone penetration testing*

CPTs are finding increasing use during offshore pipeline investigations, providing data for various aspects of pipeline design, including stabilisation, ploughing, on-bottom friction, sub-sea structure foundation design. However, as noted previously, a hypothesis regarding the identification the depth of previous storm driven instability using CPT data has been put forward and was tested during these studies.

215 CPTs were carried out during the investigations for the proposed Second Trunkline. These tests were carried out to depths of up to 3m below seabed and provided information on the nature and condition of shallow sub seabed materials.

The results of these CPTs were analysed in a similar manner as reported in Waterton & Price (1994), with the apparent STD being indicated by the point of inflection in an observed bilinear q_c response.

3.3 *Sample grading*

Earlier work indicated a likely relationship between grading and previous instability, with instability being correlated against Percent Fines (-75 micron) and Uniformity Coefficient, the latter parameter being modified to d_{80}/d_{40} to allow its computation from the results of conventional sieve analysis. The results of this previous work showed that previously unstable materials in the North West Shelf area have a –75 micron value of less than 12% and a (modified) Uniformity Coefficient ($C_{u(mod)}$) of less than 3.7. It must be emphasised that these limiting values are only being postulated for the region crossed by the NRT. Limiting values in other areas are likely to be different. However, a similar rationale should apply to their derivation.

A total of 156 grading analyses were carried out on samples recovered from within 0.5m of the seafloor during the CPT investigation and, using the limiting grading parameters previously deduced, the results of these tests were compared with the results of the sedimentological studies carried out on the same samples.

4 RESULTS

4.1 *Assessment With Grading Characteristics*

Out of the 156 seafloor samples that were subjected to grading analysis, sedimentological examination showed that 31 samples had experienced previous instability and all of these samples had a %fines value of less than 12% and a $C_{u(mod)}$ value of less than 3.7. In addition, of the remaining 125 samples assessed as stable, only 7 had a %fines content of less than 12% and a $C_{u(mod)}$ value less than 3.7.

This would appear to indicate that seabed materials that had previously experienced the effects of regional instability would display the proposed limiting grading values described in Waterton & Price (1994). However, it is also clear that other effects could cause the particle size distribution of seabed materials to fall within the postulated limits, even though they have not previously experienced regional seabed instability. Therefore any relationship between sample grading and its stability history is complicated by other near-bottom effects, such as scouring, high energy sedimentation or saltation processes, which can also cause sorting of seafloor sediments.

Furthermore, subsequent deposition over previously unstable materials would indicate that there has been no instability since the deposition of the upper material. Whilst the grading of the underlying stratum may be indicative of previous storm-driven

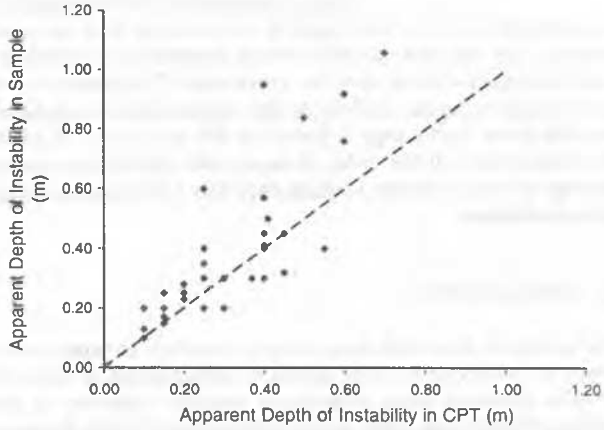


Figure 4: Stability Threshold Depth Measured in CPT *versus* Sample

instability, the thickness of the overlying layer and its rate of deposition can be used to assess the risk of pipeline exposure to regional instability processes. For example, at one location along the proposed Second Trunkline route, there is a surficial silty layer, 0.5m thick, overlying a sand that had the characteristics of having been previously unstable. Since deposition rates in the area are known to be of the order of 10mm/century, the destabilising event occurred more than 5000 years ago and is therefore not relevant in STD determination.

It is therefore considered that identification of areas affected by previous regional instability cannot be reliably identified by the grading characteristics of seafloor materials alone and that other identifying measures should be included in the assessment of previous stability.

4.2 *Assessment Using CPT Data*

The results of 215 CPTs carried out along the proposed Second Trunkline routes were also examined to identify the response postulated in Waterton & Price (1994) as being characteristic of previous seabed instability. In the samples associated with 16 of these tests, variation of material grading was evident along the sample length but no clear, distinct interface was visible. These tests were therefore excluded from further consideration.

Of the remaining 199 tests, there was only a single instance where an interface was clearly visible in the sample tube but not discernable in the CPT results. Comparison of the results of the remaining 198 tests with their associated samples showed either:

- (in 39 tests) a clear interface, both in the CPT plot and in the associated sample; or
- (in the remaining 159 tests) the absence of an interface in either.

This would seem to verify that the CPT should be able to be relied on to identify this interface. However, the depth of this interface below seabed should be the same for both methods of determination.

Figure 4 shows the Stability Threshold Depth, as determined directly from sedimentological inspection of undisturbed samples plotted against the STD, assessed from interpretation of the CPT carried out immediately adjacent to the corresponding sample location.

Figure 4 shows good agreement between data from the sedimentological examination of the undisturbed tube samples recovered from each CPT location and the results of the CPT itself, with a variation in depth of the order of 0.2m. Since the resolution limits in measuring depth in this situation are probably at least 0.1m, this variability is considered acceptable.

This figure also shows that, in general, STD values measured from the tube samples are 0.1 – 0.2m deeper than those deduced from the CPT results. Although the tube sampler is mounted on the side of the CPT package, system errors could well give rise to this discrepancy. For example, for the CPT, 0m is defined as the point when an electrical signal is first received from the cone whereas, for the tube sampler, 0m is defined as the point at which penetration of the sampler commences. The presence of a very soft layer on the seafloor or the pushing aside of surficial material when the package is placed on the seafloor could result in a discrepancy of the order of magnitude observed, as could package tilting or denser seafloor materials preventing package skirt penetration.

5 CONCLUSIONS

The results of this study have shown a reliable correlation between the observations made during a sedimentological study of samples recovered along a proposed pipeline alignment in the offshore North West Shelf region offshore from North Western Australia. Whilst all previously unstable seabed materials do display certain grading characteristics, they do not uniquely do so and so it is not possible to precisely define the extent of previous instability from sample grading alone. However, when considered in conjunction with the CPT results, a consistent set of data were derived which allowed the identification of the depth of previous seafloor instability and thus the determination of a safe minimum pipeline burial depth, so as to avoid the pipeline becoming exposed to unexpected lateral forces resulting from fluidised sand flow. The density of such a 'liquid' could, at the height of a major storm, exert forces on the pipeline considerably in excess of those predicted by the designers.

It is considered that the observed point of inflection in the CPT plot, together with the relatively smooth cone resistance response above the point of inflection, should provide a reliable indicator of the depth of previous instability at any location. However, the derived grading correlations are likely to be site specific and should therefore be verified by further studies if required to be used outside the North West Shelf area of Western Australia.

In selecting the actual pipeline burial depth, the decision was taken to locate the obvert of the pipeline beneath the derived Stability Threshold Depth. However, if project economics dictated it, statistical evaluation of:

- seabed sediment age;
- sedimentation rate;
- storm return periods; and
- pipeline design life

could provide a more rational basis for the selection of pipeline burial depth.

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