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PIPELINE STABILISATION USING PRE-TRENCHING AND SAND BACKFILL

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ABSTRACT

Stabilizing large diameter natural gas pipelines on the seabed against extreme hydrodynamic loading conditions has proven to be challenging in the northwest of Australia. Tropical storms, which affect the area annually between November and April, can generate wave heights exceeding 30 m and on-bottom steady-state currents of 2 m/s or more. Consequently, in shallow water depths, typically less than 40 – 60 m, subsea pipelines can experience very high hydrodynamic loads, potentially causing significant lateral movement. If the seabed is rugged, or at locations where the pipeline approaches a point of fixity, this can lead to the pipeline suffering mechanical damage, which is undesirable.

In many places on the Northwest Shelf of Australia, there is a layer of minimum 3 m deep marine sediments. The sediments predominantly comprise of relatively stable, fine to medium sized carbonate silts and sands, sometimes with some clay content. Traditionally, in Australia and other parts of the world, post-trenching techniques such as ploughing and jetting have been applied in such areas. These techniques can successfully lower the pipeline into the seabed. However, in many situations on the Northwest Shelf of Australia, post-trenching has had limited success. This has in part been due to the unpredictable levels of cementation of the carbonate sand, which has often resulted in an insufficient trench depth, with the need to implement costly and time consuming remedial works to ensure pipeline stability.

The uncertainties in the success of post-trenching tools lead to the development of the pre-trenching and sand backfill method, which was first applied in Australia in 2003 on a 42-inch diameter natural gas trunkline. This technique has several advantages compared to post-trenching and other conventional pipeline stabilization methods such as rubble mound pipeline covers or gravity anchors.

This paper presents an overview of the pre-trenching and sand backfill method, its design principles, benefits, and risks and opportunities.

INTRODUCTION

Subsea pipelines are typically the most effective method for transporting hydrocarbons from deep water wells to shore for processing. Given the high consequence of pipeline failure, the potential for on-bottom instability during extreme metocean conditions and accidental external impact from shipping must be carefully considered in the design process.

It is common practice in the offshore industry to apply a concrete weight coating (CWC) to the pipeline to increase its submerged weight for on-bottom stability. The concrete coating, which is typically a few inches thick, also provides some degree of mechanical protection to the pipeline. However, there is a practical limit to how much weight coating can be applied to a pipeline, due to either the tension or handling capacity of the pipeline installation vessel or the handling capacity at the coating plant. In cases where the maximum coating thickness cannot provide the pipeline with a sufficient level of safety, a secondary stabilization method may have to be adopted.

Environmental conditions are particularly challenging along the Australian Northwest Shelf (NWS), an extensive oil and gas region off the North West Australia coast. The area is characterized by tropical cyclones, a wide continental shelf and highly variable seabed conditions. It is not uncommon for large diameter pipelines to require secondary stabilization from the shore crossing to approximately the 50 m water depth, which can cover tens and sometimes more than one hundred kilometers of pipeline route.

In the nearshore area, pipeline routes often cross shipping channels and tracks. This can place the pipeline at risk of damage from large ships. Consequently, pipeline stability and accidental external impact protection can contribute significantly to project capital expenditure (CAPEX).

The potential to significantly reduce capital expenditure without compromising safety and reliability of the system has provided the motivation to devote engineering resources to design optimization and innovation in this field. On each project, a detailed screening and selection process is performed to identify the most effective secondary stabilization solution from a range of options including:

- Gravity anchors
- Pre-trenching and backfill
- Rock dumping
- Rock trenching
- Ploughing
- Drilled (rock) anchors.

The feasibility of these methods are largely influenced by the level of exposure to tropical cyclones and shipping traffic, the geotechnical conditions and the availability of backfill material and quarry rock. Due to a particularly challenging set of design conditions that is prevalent in the Australian Northwest Shelf region, the pre-trenching and sand backfill method was developed and first applied in 2003 on a 42-inch diameter natural gas trunkline. The method has since been further developed to stabilize and protect other large diameter gas pipelines in the region.

This paper presents an overview of the pre-trenching and sand backfill method and its design principles, risks and opportunities for further optimization.

OVERVIEW OF METHOD

The term ‘Pre-trenching’ is used to refer to subsea trench excavation that is performed prior to pipeline installation. Conversely, ‘post-trenching’ involves cutting, ploughing or jetting a trench underneath the pipeline, such that it is lowered into the seabed.

Pre-trenching is typically performed using dredging equipment, such as a trailer suction hopper dredge, cutter suction dredge, or backhoe dredge.

Trench backfill is typically performed using a trailer suction hopper dredge. The backfill operation involves the dredge sailing to a designated sand borrow area, dredging seabed material into the hopper, sailing to the pipeline route and backfilling the open trench.

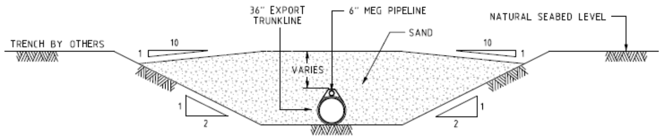

FIGURE 1: TYPICAL TRENCH & SAND BACKFILL DESIGN

DESIGN PRINCIPLES

The trench and sand backfill design must provide a appropriate safety level against any relevant modes of pipeline failure. In addition to considering the integrity of the pipeline, the impact of the design on the environment and third party activities such as shipping or fishing should be reduced as far as reasonably practicable.

In order to demonstrate that a design provides a sufficiently high safety level against failure, it is necessary to remove ambiguity by defining terms such as ‘failure’ and ‘sufficiently high safety level’. Since the purpose of a trench and sand backfill design is to ensure the stability and the protection of offshore pipelines, it is appropriate that the definition of such terms be consistent with offshore pipeline design. In Australia and several other parts of the world, the principal design reference for subsea hydrocarbon pipelines is the DNV Offshore Standard F101 [3], which is based upon a limit state and partial safety factor methodology, also called Load and Resistance Factor Design format (LRFD). The load and resistance factors depend on the safety class, which characterizes the consequences of failure.

A limit state is a condition where the pipeline no longer meets one or more design requirements. Serviceability limit states (SLS) are reached when normal operations are restricted. Ultimate limit states (ULS) are thresholds beyond which pressure containment, safety or the environment are threatened. Within each limit state category there can be many types of failure modes.

Failure modes for the SLS condition include problems that partially block the flow or prevent pigs from traveling along the pipeline, such as local ovalization of a given amount. Excessive lateral displacement due to the action of hydrodynamic loads is considered to be an SLS condition. In this case ‘excessive’ is not clearly defined; however the recommended practice for on-bottom stability design of pipelines [2] recommends that lateral displacement be limited to 10 pipe diameters.

For each of the limit state categories, the pipeline is designed to achieve target reliability levels that are specified by a safety class methodology. The pipeline system is classified into one or more safety classes based on failure consequences, normally given by the content and location. In the case of gas pipelines which are located away from populated areas such as the platform (safety class medium) the nominal failure probability per pipeline per year is 10^{-3} for SLS and 10^{-4} for ULS.

DESIGN LOADING CONDITIONS

The trench and sand backfill design must provide an acceptable margin of safety against any scenario that may result in failure of pipeline limit states.

The stability of a buried pipeline depends on the stability of the surrounding soil. Protection of a buried pipeline depends on the soil resistance to penetrating loads.

This section provides a high-level overview of the potential failure scenarios and how they are considered in the design process.

Scour

Scour of backfill material and/or the surrounding seabed material by wave and current action has the potential to expose a buried pipeline. If the entire backfill cover depth is scoured away, the pipeline may become exposed to direct hydrodynamic loading and subsequently break-out of the trench. Subsequent excessive displacement can lead to the pipeline exceeding the prescribed SLS or ULS limits.

There are two forms of scour that are of relevance to hydrodynamic pipeline stability. These are:

- Free-Field Scour (also referred to as regional scour) – Scour or erosion of the seabed, in the absence of structures or obstructions.
- Local Scour – Scour caused by a change either in flow pattern due to the presence of a structure either on or in close proximity to the seabed or erodibility of seabed materials.

Free-field scour can be significant where the spatial variability of sediment transport rates is large. Local scour of sand backfill material can be significant where the adjacent seabed comprises unerodible material such as stiff clay or rock. The scour depth is a function of the bed shear stress relative to the critical shear stress for sediment mobility, and the duration of the hydrodynamic loading event.

Liquefaction

Liquefaction of backfill material is another phenomenon that may cause a buried pipeline to become unburied. Soil liquefaction results from an increase in the excess pore water pressure induced within the soil by transient or repeated ground motions or shocks. Pore water pressure increases may be induced by earthquakes or ocean waves. If the pore water pressure rises sufficiently high, then the soil grain to grain contact pressure drops temporarily to zero (i.e. liquefaction), and the soil mass will lose all shear stiffness and in some instances all strength as well, and therefore the soil acts somewhat like a fluid.

A pipeline may either float up or sink in liquefied soil, depending on the specific gravity of the pipeline relative to the density of the surrounding fluid. Large diameter gas pipelines generally have an operational density that is much less than the surrounding soil, making them sensitive to pipeline floatation. The risks of pipeline floatation and excessive scour are similar in that both processes result in a decrease in burial depth, making the pipeline susceptible to hydrodynamic loading and external impacts.

Pipeline floatation can occur when the buoyancy uplift force exceeds the soil resisting force. A general floatation equation can be defined in terms of the global force balance exerted on the pipeline as:

$$R_u = W'_{pipe} + F_{pull} \qquad (2)$$

Where,

R_u is the resultant uplift force acting on the pipeline due to excess pore pressures in the soil

W'_{pipe} is the submerged weight of the pipeline

F_{pull} is the soil uplift resistance

The combination of increased uplift force and a reduced soil resistance as excess pore pressures accumulate mean that the buried pipeline may reach an unstable state before the soil is fully liquefied. Hence pipelines may also float in soils that are not yet fully liquefied (Bonjean et al. [1]).

The most recent recommended practice for on-bottom stability design of pipelines [2] provides limited guidance on ensuring vertical stability of buried pipelines in soils which are or may be liquefied. It recommends that the specific weight of the pipe should not be less than that of the soil if burial is required, however, for large diameter pipelines this is often impossible to achieve. Fortunately the build-up of pore pressure tends to decrease with depth, such that for a given set of conditions there is a critical depth at which the forces acting on the pipeline are in equilibrium.

The burial depth required to prevent pipeline floatation can be estimated through a pipeline floatation assessment. A detailed overview of the assessment methodology is beyond the scope of this paper, and has already been presented by other such as Bonjean et al. [1]. The critical depth of cover, H, for pipeline floatation is a function of the specific gravity of the pipeline and the peak excess pore pressure gradient, i, and can be expressed diagrammatically as a pipeline floatation chart (Fig. 3).

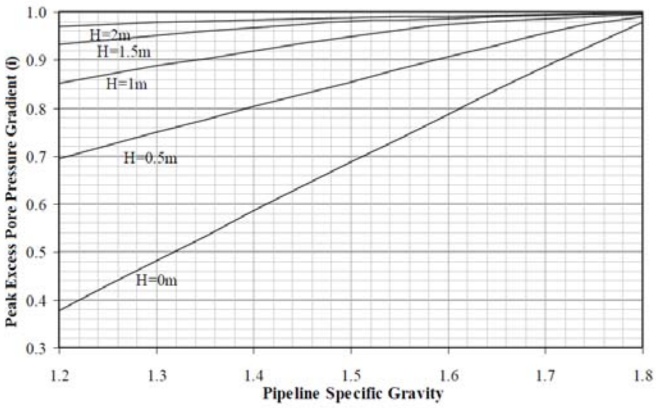

FIGURE 3: PIPELINE FLOATATION CHART

External Interference

Without sufficient depth of cover, a buried pipeline may be at risk of damage from the following external interference events:

- Vessel grounding or sinking
- Dragged anchors
- Dropped anchors
- Dropped objects

Of the above hazards, dragged anchors typically have the greatest influence on the trench and backfill design based on the interference frequency and the depth of soil penetration. The depth of anchor penetration is largely dependent on the anchor size and soil type.

The design of pipelines against external interference events involves the following tasks:

- Interference Scenario Frequency Assessment – aiming to quantify Interference Scenario Frequency along the pipeline route
- Pipeline Damage Assessment – aiming to quantify pipeline damage and associated Pipeline Failure Rate at sensitive locations identified in the Interference Scenario Frequency Assessment
- Quantitative Risk Assessment – aiming to quantify risk levels based on evaluation of expected frequency and consequences of accidental events.

As a risk reduction measure, the trench and backfill design must provide the pipeline with sufficient burial depth to reduce the probability and/or the consequence of external interference, such that the established acceptance criteria are met.

There is no known analytical model available to pipeline engineers to reliably predict the maximum penetration depth of ship anchors for a range of soil and anchor properties. Research into the behavior of dragged ship anchors have focused predominantly on the holding capacity rather than the maximum penetration depth. However, the literature does provide a rule of thumb for anchor fluke-tip penetration depth as being equivalent to the anchor fluke length for sand and stiff clay, and 3 to 5 times the fluke length in soft silts and clays [4].

Whilst this guidance may generally be considered adequate for conceptual design, for detailed design it may be prudent to conduct physical model testing to verify and potentially optimize the trench depth (Fig. 5).

FIGURE 5: ANCHOR DRAG MODEL TESTING

DESIGN ASPECTS

The trench design is defined by reference to its depth, bottom width and side slope angle, whereas the backfill material is defined in terms of its grain size distribution.

These dimensions are selected on the basis of the conflicting ensuring constructability and pipeline operability.

Design Trench Depth

Since the cost of trenching and backfilling increases considerably with trench depth, it is important that the design considers every hazard without combining allowances for extreme events that are mutually exclusive.

It is proposed that several trench depth cases be considered, with the worst governing:

- Hydrodynamic loading case
- Seismic loading case
- External interference case

A hypothetical example that is representative of conditions on the NWS of Western Australia is provided. A scour study recommended a 500 mm allowance for scour of backfill material. A backfill liquefaction and pipeline floatation study recommended allowances of 900 mm for the hydrodynamic loading case and 600 mm for the seismic loading case. An anchor drag testing program determined that a minimum cover of backfill material of 1200 mm was recommended. The minimum trench depth for each design case is presented in Table 1.

TABLE 1 – EXAMPLE OF TRENCH DEPTH DEFINITION

Design Allowance	Design Case		
	Hydrodynamic	**Seismic**	**Anchor drag**
Backfill Scour	0.5 m	0.5 m	0.5 m
Liquefaction	0.9 m	0.6 m	N/A
Anchor Penetration	N/A	N/A	1.2 m
Pipeline Diameter	1.2 m	1.2 m	1.2 m
Trench Depth	2.6 m	2.3 m	2.9 m

For the example above, a minimum trench depth of 2.9 m is considered necessary where protection from dragged anchors is required. Otherwise, a trench depth of at least 2.6 m is considered sufficient for pipeline stability under both extreme hydrodynamic and seismic loading conditions. In other cases the cover depth required to prevent pipeline floatation may be greater than the level required for protection.

Design Trench Width

The base width of the trench should be as narrow as possible without risking any length of the pipeline being laid outside the trench base. Pipelay contractors can typically install the pipeline in a trench with a bottom width of 5.0 m, in water depth less than 50 m. This is dependent upon the horizontal lay tolerance of the pipelay barge. Consequently a design trench bottom width of 5.0 m has been adopted on past projects in the NWS region, although it is recognized that a narrower trench bottom width can sometimes be accepted.

Trench Side Slopes

To minimize CAPEX the trench side slopes should be as steep as possible without risking slope collapse that would effectively reduce the trench depth. The critical trench side slope for stability is governed by the stability of the seabed material, the length of time that the trench is exposed to environmental conditions and the severity of those conditions. As a general rule of thumb, it is assumed that the side slope will need to be 1v:2h in medium density sand and 1v:1h in areas of cemented material.

Backfill Material Specification

Another task of the pipeline engineer is to specify the required properties of the backfill material. The ideal backfill material should exhibit a high level of resistance to liquefaction and erosion, and it should be easy to source a sufficient quantity within close proximity to site.

The factors that affect the occurrence of liquefaction are soil type, grain size distribution, compactness of the soil, soil permeability, and the magnitude and number of load cycles applied. Fine sand or fine cohesionless soils comprising non-clay minerals (eg. carbonate silt and mud) are most susceptible to liquefaction. Fine grained soils that include a significant fraction of clay minerals are generally less susceptible to liquefaction.

The susceptibility of backfill material to erosion is primarily governed by grain size distribution. The relationship between grain size and the threshold velocity for erosion is illustrated by the Hjulström curve (Figure 6). Fine material with a high clay content typically has a greater resistance to erosion than sands due to the cohesive forces. However, these cohesive forces also make clay an impractical backfill material because a Trailer Suction Hopper Dredger cannot easily dredge this material unless it has a low shear strength.

For the reasons mentioned above, coarse sand with a low proportion of fines is generally sought after for backfill material. Whilst there is no definitive requirement, on recent projects in the NWS region sand with a median grain size (D50) of greater than 200 - 300 microns and a low fines content (less than 5-10% by weight) has been specified as the limits for suitability.

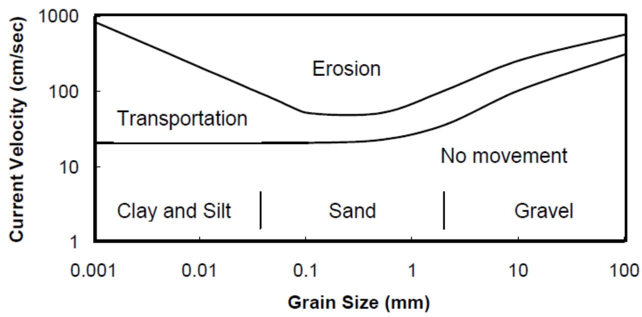

FIGURE 6: HJULSTROM CURVE [5]

Sand Sourcing

The economic feasibility of the trench and sand backfill method is dependent on obtaining a suitable source of sand backfill material. Ideally the sand borrow ground is located in close proximity to the pipeline route in order to minimize the cycle time of backfilling operations. The source will need to be located in a water depth within the operating limits of dredging equipment. The source should also be located in an area that will minimize impact on marine flora and fauna.

An investigation to identify potential sand borrow sites typically commences with a review of publically available marine sediment sample database and benthic maps. This information can assist with selecting areas to perform a reconnaissance survey using multi-beam echo sounders, pinger sub-bottom profilers and/or side scan sonar. In-situ samples are also collected with a vibrocorer to determine the mean grain size, fines content and the thickness of the sand layer.

Trenchability Assessment

A trenchability assessment is performed to determine what type of equipment is required for trench construction. Whilst this decision is ultimately made by the dredging contractors, it is necessary to assess the technical feasibility of trenching early in the design process.

The assessment considers the strength of the seabed material, the water depth, typical seastate conditions, and the limitations of available equipment. A trailing suction hopper dredger is the most effective vessel for dredging unconsolidated sediment in moderately deep water, although it is typically unable to excavate well consolidated material. A cutter suction dredge is capable of dredging through most material from clay to hard rock, but its workability limited to water depths of less than 25 meters and relatively calm seastate conditions.

A detailed site investigation, comprising geophysical surveys and collection of borehole samples along the pipeline route corridor, provides vital input data for assessing trenchability and minimizing construction risk. Seismic refraction can provide an indication of the change in material strength with depth, making it an effective survey method in areas where seabed strength often has high spatial variability. Physical sampling should be carried out to check the correlation with the geophysical data. Borehole samples are collected using vibrocoring or other suitable methods. To maximize the benefit of physical sampling, boreholes should be performed in locations where trenchability appears uncertain based on the geophysical data.

BENEFITS

The use of pre-trenching and sand backfill for pipeline stabilization can provide an attractive alternative to the more traditionally used methods.

One of the more traditional methods is to dump quarried and graded rock over a pipeline that is either laid in a trench or on the natural seabed level. In cases where a suitable sand borrow area within close proximity to the site is available, engineered sand is far more economical to supply and install than the equivalent quantity of quarried and graded rock. It is also possible to backfill a trench in far less time using sand than with quarried rock, resulting in an earlier start-up date.

The method also offers benefits compared to post-trenching methods such as ploughing and mechanical trenching. Pre-trenching is performed using proven dredging equipment that is widely used in other fields of offshore engineering.

Given that the appropriate dredging spread is selected for the site location based on a thorough trenchability assessment, pre-trenching is less sensitive to variable geotechnical conditions compared to post-trenching.

Pre-trenching also has the advantage of being able to easily accommodate changes to the trench dimensions, whereas for post-trenching the trench dimensions are limited by the dimensions of the plough or trenching tool. In some cases the maximum trench does not allow for sufficient burial depth of a large diameter pipeline.

RISKS

As is the case for other pipeline stabilization methods, the pre-trenching and sand backfill method carries a number of design and construction risks primarily due to uncertainties in the marine environment. These risks must be carefully managed to ensure a successful project.

Design risks during the installation period between pre-trenching and trench backfill should be considered in the design and construction schedule. The open trench may partially infill with fine sediment, which may increase the risk of pipeline floatation. There may also be potential for pipeline instability and partial collapse of the trench side walls during extreme seastate conditions. These risks can be reduced by additional allowances to the trench depth or by having equipment on standby to perform trench maintenance dredging.

Installation period design risks can also be reduced by minimizing the duration between pre-trenching and pipeline installation; however, this will increase the schedule risk associated with trenching works not being completed on schedule.

Delays in trenching are typically caused by latent geotechnical or seastate conditions that result in reduced trenching productivity rates. In the worst case where the design trench depth cannot be achieved, the pipeline may need to be backfilled with quarried rock as a contingency stabilization measure.

The supply of quarried rock can carry long lead times and requires a suitable marine load-out facility. Schedule risk can be minimized by ensuring the availability of a contingency stockpile of quarried rock, a rock dump vessel and load-out facility, although this comes at a cost.

Another construction risk is the possibility that the design trench depth or width is not achieved in some areas due to inaccuracies of trenching and survey equipment. This risk can be mitigated by specifying allowable construction tolerances.

OPPORTUNITIES FOR IMPROVEMENT

The design process described in this paper has been successfully used on several major projects in the NWS area. It has generally proven to be effective to achieve CAPEX savings whilst demonstrating a sufficient margin against pipeline failure. However, it is likely that opportunities for further CAPEX savings exist through an improved understanding of the sensitivity of the reliability of the pipeline system to the pipeline burial depth and key design inputs.

Theoretically, a life cycle cost-benefit assessment should be the preferred way for determining the optimum target reliability. The total life cycle cost is taken to be the initial investment (CAPEX) and the maintenance cost (OPEX), subtracted by the failure cost. Estimation of the failure cost requires quantification of the failure probability and the likely failure consequence. This requires quantifying the probability and/or the consequences of pipeline response to the design loads.

The current approach is essentially deterministic in that the trench depth combines allowances for the different failure modes which are determined by separate studies. The cover depth allowances for scour, pipeline floatation and external interference are provided as deterministic values, despite the considerable levels of uncertainty.

The pipe-fluid-soil interactions that cause scour and pipeline floatation are highly complex and not fully understood. There is also considerable uncertainty in the characteristic environmental loading conditions and geotechnical conditions, as the design input values are interpolated or extrapolated from a limited data set.

For external interference events, it is common to quantify the failure probability of an unprotected pipeline as part of a QRA. It is less common to quantify the reduction in risk as a result of burying the pipeline.

Optimization of the design trench depth could be performed by quantifying the failure probability due to each failure mode as a function of cover depth. King et al. [6] have outlined a method to quantify the pipeline failure probability due to ice scour as a function of burial depth (Figure 8).

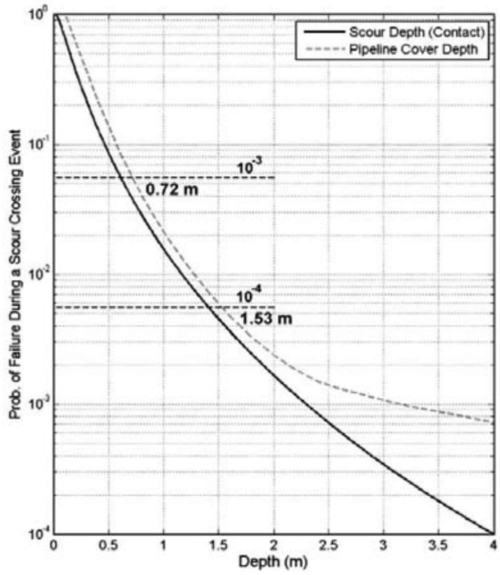

FIGURE 8: PROBABILITY OF FAILURE AS FUNCTION OF PIPELINE COVER DEPTH [6]

A similar design approach could also be used to quantify the probability of pipeline limit state failure caused a particular sequence of unlikely events, such as the process by which a buried pipeline may fail either under SLS or ULS conditions over the duration of an extreme storm.

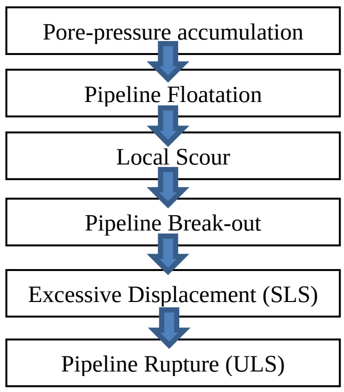

FIGURE 9: PIPELINE FAILURE SCENARIO

As part of the design approach described in this paper, a pipeline floatation assessment provides estimates of the critical burial depth required to prevent pipeline floatation. It would be useful if pipeline engineers were provided additional information on the pipeline response during and after floatation. The probability of pipeline floatation could be estimated as a function of cover depth, with details on the expected vertical pipeline displacement and bending strain on the pipeline.

CONCLUSION

The pre-trenching and sand backfill method can offer significant benefits over other secondary stabilization measures. This method can be a particularly attractive option in challenging and remote locations where it is very expensive to stabilize the pipeline using quarried rock, or where post-trenching equipment may not achieve the required trench depth.

It is necessary to have a thorough understanding of the site conditions and the processes that can cause instability of the backfill material and the pipeline system. Studies of the potential for scour, liquefaction of backfill material and pipeline floatation are required to produce a cost-effective and robust design trench and backfill design.

A detailed site investigation and trenchability assessment is required to minimize the risk of being unable to achieve the design trench depth in some areas. Similarly, a sand sourcing study must be performed to secure a sufficient quantity of suitable sand backfill material. Where this risk is unacceptably high, a quantity of quarried rock may need to be made available for contingency.

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