Predicting Pipeline Concrete Coating Impact Absorption

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Abstract

The primary functions of the concrete coating on a submarine pipeline are to give the pipeline additional weight to stabilize it on the sea floor, and to protect the external corrosion coating against mechanical damage. Pipeline integrity is a major concern where an impact may cause extreme denting of the steel pipe and at worst, cause leakage.

Recently (October 2002), Woodside Energy conducted full scale tests of a dropped object onto sample lengths of pipe from TSEP (Trunkline System Expansion Project) to confirm the safety of the pipeline during gravity anchor installations. These tests showed that the coated pipeline had at least one order of magnitude more capacity to absorb impact energy than predicted by design calculations. This project aims to remove some of the conservatisms from the design calculations in order that more realistic results can be achieved. This will be done by reviewing the design codes, analysing TSEP test results and comparing these results with experimental/modelling results.

1.0 Introduction

The new 42-inch North Rankin A Second Trunkline was installed on the North West Shelf as a supplement to the existing 40-inch Trunkline, which conveys gas and condensate from the NWS fields (North Rankin, Goodwyn and Wanaea / Cossack) to onshore treatment facilites located on the Burrup Peninsula near Dampier, Western Australia. The Second Trunkline was installed as part of the TSEP project and was stabilized on the sea bed using a combination of rock dump and dredging in shallow water, and gravity anchors in deeper water.

The instabillity of the gravity anchors, during installation, was identified during the FEED (Front End Engineering and Design) phase as being a key issue. In particular, the potential for damage to the pipeline weightcoat or denting of the pipeline were the overriding issues, primarily arising out of a vertical impact of the gravity anchor onto the pipeline during installation. To further understand the damage likely to occur, full scale drop tests on actual joints of TSEP pipeline were designed and performed in Batam, Indonesia.

Results from these tests proved analytical (FEED and detailed design) to be very conservative. That is, any damage resulting from a gravity anchor impact is significantly less than the analytical work indicates. For example, it was predicted that denting of the pipeline to a gaugeplate survey contractual limit of 3% OD (or 32mm) would required 80kJ of energy, but testing in Batam found that such a dent depth was more likely to occured from an impact energy of approximately 350kJ.

2.0 Background

The prediction of pipeline concrete coating impact absorption requires knowledge of; the code and its basis, concrete crushing behaviour and dropped object studies so that the type/size of impact can be determined.

2.1 Methodology of the Recommended Practice

The most commonly used code for the assessment of pipeline protection is Det Norske Veritas DNV-RP-F107. Section 4 of the code titled "Pipeline and protection capacity" classes accidental loading scenarios that can lead to damage on a pipeline as either an impact (due to dropped objects) or pullover/hooking (due to dragged trawl board or anchor). This project is concerned with impacts from dropped objects, so pullover/hooking loads will not be discussed any further. In the code (Section 4.6.1) are two equations that describe the energy absorbed by the concrete coating for two different cases, which is a function of the penetrated volume and crushing strength, Y. These equations are shown below.

$$E_K = Ybhx_o \quad \text{, or} \quad E_K = Yb\frac{4}{3}\sqrt{Dx_o^3} \qquad \text{(Eq. 1,2)}$$

Where: x_o denotes the penetration,
b and h are the breadth and depth of the impacting object respectively, and
D is the pipeline diameter.

For larger pipe diameters, Eq. (2) may give non-conservative estimates and a denting shape more like Eq. (1) should be considered.

Behind these equations lie assumptions that lead to conservative damage capacities calculated in the concrete coating. It is assumed that the concrete coating absorbs all of the available kinetic energy, and the steel pipe, external corrosion coating, soil and impacting object absorb no energy. In the case of soft soil conditions or a "non rigid" impacting object, such as containers, a considerable amount of energy will be absorbed by the soil and the impacting object.

The theory behind the absorbed energy equations in the recommended practice is found in Jensen (1978), where the analytical method for calculating the energy absorbed by concrete coating is described. The principle of impact loading is used to estimate penetration depth, x_o, into the concrete, which is deduced on the basis of the impulse law. For a perfect non-elastic impact, penetration and impact time, which assumes a linear decreasing velocity, can be found by the following relationships:

$$V_C = \frac{1}{2}\frac{MV_O^2}{Y} \quad \text{, and} \quad t_d = \frac{2x_O}{V_O} \qquad \text{(Eq. 3, 4)}$$

Where: V_C = Volume of penetration area,
M = mass of hitting object,
V_O= velocity of hitting object,
Y = crushing strength, and
t_d = impact time.

A simple impact hammer test was performed to validate the methodology, in which the impact time and penetration depths were recorded. As described in Section 3 of Jensen (1978), the test results closely resembled analytical results but give penetration depths lower than that estimated by the method. This is more than likely due to the composite behaviour between the steel pipe wall and the concrete coating and the idealistic assumption of a non-elastic impact.

2.2 Reinforced Concrete under Impact Loading

While much literature exists describing the behaviour of reinforced concrete under impact loads, little research has been done to examine pipeline concrete coating behaviour under impact loading. Being such a non-homogeneous material, it can be said that the concrete coating will fail in a similar manner where strength is greatly influenced by the concrete properties. Haldane & Maclean (1985) discuss how a concrete coatings compressive strength is dependent on the following parameters; the performance of the application process, the characteristics and relative portion of the constituent materials and the form of the reinforcement within the concrete.

2.2.1 Concrete Coating Application

The methods used to apply concrete coatings to subsea pipelines include casting, guniting, impingement and wrapping, all of which are detailed in Palmer's (1982) 'Concrete coating for submarine pipelines'. The most common application method used today is either the impingement or compression wrap method. Defects in the concrete coating, such as the occurrence of cracks and porous zones, reduce the impact resistance of a coating because they introduce paths of least resistance. Examination of the application process for concrete coatings is outside the scope of this project, but it's worth noting that defects need to be avoided.

2.2.2 Material Constituents

Aggregate is by far the largest single constituent within a concrete mix, hence is a significant parameter in terms of defining properties of the concrete coating. In order to eliminate the presence of defects in coatings, the aggregates must be well graded, angular in shape, rough in texture, strong in compression and have a restricted maximum particle size (Haldane & Maclean, 1985). The ultimate crushing strength, Y, of concrete is directly related to the characteristics of the aggregate it contains, and is generally somewhere in the order of 3 to 5 times the cube strength for normal concrete density (DNV-RP-F107).

Since the tensile strength of concrete is relatively small, reinforcement is needed to prevent failure due to the presence of tensile stresses. It also helps to absorb the energy and prevent breakdown of the concrete when subjected to impact loads. Traditional methods of reinforcement include the use of hexagonal wire mesh, commonly known as 'chicken wire', until it was found that significant damage to the concrete coating was occurring (Palmer, 1982). Conventional methods include the use of welded wire mesh and cage reinforcement (rebar). Rebar greatly increases bending strength and impact resistance capacities of pipeline concrete coating, but an area of weakness along the length of a pipeline is at the field joints where no reinforcement exists. Lengths of pipe are welded together on a lay barge and the joint simply covered with a corrosion coating and/or freshly applied concrete which offer little additional stiffness to the pipe (Mousselli, 1978).

As mentioned in Haldane & Maclean (1985) it should be noted that the anti-corrosion coating can also play an important part in limiting the development of cracking due to impact loading. The ability to develop a high shear stress between the interface of the anti-corrosion and concrete coatings is desirable.

2.3 Impacting Objects and Energies

To understand the energy absorbed in a pipeline concrete coating, the type of loads applied to the pipeline needs to be examined. The topic at hand is more concerned with impacts resulting from dropped objects, rather than trawl boards, so a review of the types of objects likely to be dropped and loads experienced by the pipeline is essential.

A dropped object study (Woodside, 2002) for the Taweelah Alpha (TA) platform in the Middle East reviews the frequency, consequences and risks associated with dropped objects and swinging loads in the near platform region during crane activities. A dropped load is considered to be the result of human error, mechanical failure or extreme environmental conditions.

The TA dropped object study identifies the type of objects lifted between the supply vessel and platform, and classifies them as either being a regular or exceptional lift. Regular lifts, including chemical tote tanks and barrels, are much more frequent and occur 260 times per year, whereas and exceptional lift for the replacement of a pump occurs only twice a year. Each object has a different shape and is simplified into either a box or cylinder (falling horizontally or vertically) for calculation of the impact velocities and energies. The method of calculation is quite extensive and can be found in Appendix 2 and 3 in the report (Woodside, 2002).

The risk of pipeline damage from a dropped object is a combination of the frequency of dropped loads and probability of impact on the sea floor. Falling paths of these dropped objects are more closely examined in Aanesland & Marintek (1987) and Katteland & Oygarden (1995). The first of which gives extensive detail of the dynamic motion of freely falling drilling pipes that can obtain high maximum velocities and large excursions posing a critical threat to subsea equipment. Katteland & Oygarden (1995) investigate the falling paths of tubular, compact and boxed shaped objects in deep water and produce a probability of impact versus excursion for each object. This information is crucial to the development of accurate risk analysis and is outside the scope of this project.

3.0 TSEP Testing

3.1 Methodology

A total of 16 test drops were done on 2 joints of linepipe from TSEP. Both were 1.067m (42") OD x 23.9 WT and nominally grade X65 (SMYS = 450Mpa). The main test pipe had 70mm of concrete coating and was used to do most of the tests, the other 90mm of concrete and was used for high energy free-fall tests in the event that the first joint had been too severly damaged for further tests. The second joint also had an anode removed at the mid point of its length, leaving 600mm of "bare" pipe which is representative of a field joint, a weak point in the pipeline.

Impact testing required the design of a suitable drop weight that would be representative of a gravity anchor hitting the pipeline during installation. This was based on a 30 tonne gravity anchor weight and 10 tonnes added mass under water. Effective impact mass (static submerged weight) was taken as half of this and given that the geometry of the gravity anchor meant that it would not be possible to impact the pipeline at a single location with the full mass, an impact weight of 10 tonnes was calculated. The drop weight was in the form of a reinforced concrete block, impacting surface area 2m x 1.5m with an actual certified weight of 10.4 tonnes (Woodside, 2003).

Testing was broken down into 3 series of tests. Series 1, Tests 2 to 7, was done on the 70mm concrete coated pipe and involved dropping the mass from 0.1m and height increased incrementally to a maximum height of 2m. All drops were done at the same location so as to capture the effect of multiple impacts in one area to measure the effect of concrete degradation. The block was level to give a bluff impact over the full 2m width. The second series of tests, also done on the 70mm pipe, were inclined tests with the impacting block tilted at 6.5°. This angle was based on the maximum installed out-of-level installation specifications and was considered an extreme limit during lifting operations. Impact heights varied from 0.4m to 5m, each occurring at 'fresh' locations along the pipe's length. Series 3 tests were high energy drops onto the 90mm concrete coated pipe, two of which were located in the middle of the pipe either side of the 'bare' pipe, replicated field joint. The impacting block was again dropped at an incline of 6.5°.

3.2 Results and Discussion

Results from the impact testing are shown in Table 1 below.

Test N°	Test Series	Pipe	Block Angle	Impact Location	Drop height (m)	Impact Energy (kJ)	Maximum Vertical Dent Depth Ovalisation (mm)	Energy Absorbed by Steel Pipe (kJ)	Energy Absorbed by Concrete Coating (kJ)
0	n/a	70	n/a	n/a	n/a	n/a	0		
1	n/a	70	Flat	2 - 4	0	0	1		
2	I	70	Flat	1.5 - 3.5	0.1	10.20	1	0.21	10.00
3	I	70	Flat	1.5 - 3.5	0.2	20.40	0.5	0.07	20.33
4	I	70	Flat	1.5 - 3.5	0.4	40.81	1	0.21	40.60
5	I	70	Flat	1.5 - 3.5	0.8	81.62	3	1.08	80.54
6	I	70	Flat	1.5 - 3.5	1.2	122.43	8	4.69	117.74
7	I	70	Flat	1.5 - 3.5	2	204.05	14	10.86	193.19
8	II	70	**6.5°**	12.5	0.4	40.81	1	**0.21**	**40.60**
9	II	70	**6.5°**	11.5	0.8	81.62	4	**1.66**	**79.96**
10	II	70	**6.5°**	11	1.2	122.43	6.5	**3.44**	**118.99**
11	II	70	**6.5°**	10	2	204.05	7.5	**4.26**	**199.79**
12	II	70	Flat	5 - 7	5	510.12	64	106.17	403.95
13	II	70	**6.5°**	4.5	5	510.12	72	**126.68**	**383.44**
14	III	90	**6.5°**	7.5	5	510.12	58	**90.90**	**419.22**
15	III	90	**6.5°**	7	5	510.12	68	**115.40**	**394.72**
16	III	90	**6.5°**	11	3.5	357.08	40	**52.06**	**305.02**
17	III	90	**6.5°**	2	3.5	357.08	34	**40.80**	**316.28**

Table 1. TSEP Drop Test Results and Absorbed Energy Calculations.

From the maximum vertical dent depths for each test, the energy absorbed by the steel pipe could be calculated using the dent-absorbed energy relationship for steel pipelines from DNV-RP-F107. This equation, shown below, is based on a knife-edged load perpendicular to the pipeline where the indenting object covers the whole cross section/pipeline diameter. For conservatism, the effect of internal pressure is not included. Assuming a perfect non-elastic impact, the energy absorbed by the concrete coating is equal to the total impacting energy minus the energy absorbed by the steel pipe. Photographs from the TSEP testing show that the impacts are far from perfectly non-elastic with the impacting block 'bouncing' off the pipe after impact.

Dent-absorbed energy relationship for steel pipelines (DNV-RP-F107):

$$E = 16 \cdot \left(\frac{2\pi}{9}\right)^{\frac{1}{2}} \cdot m_p \cdot \left(\frac{D}{t}\right)^{\frac{1}{2}} \cdot D \cdot \left(\frac{\delta}{D}\right)^{\frac{3}{2}} \qquad \text{(Eq. 5)}$$

Where: m_p = plastic moment capacity of the wall ($= {}^1/_4 \sigma_y t^2$),
δ = pipe deformation (dent depth),
t = wall thickness (nominal),
σ_y = yield stress, and
D = steel outer diameter.

The relationship between impact energy and maximum vertical pipe denting/ovalisation was plotted and can be seen in Figure 1 below.

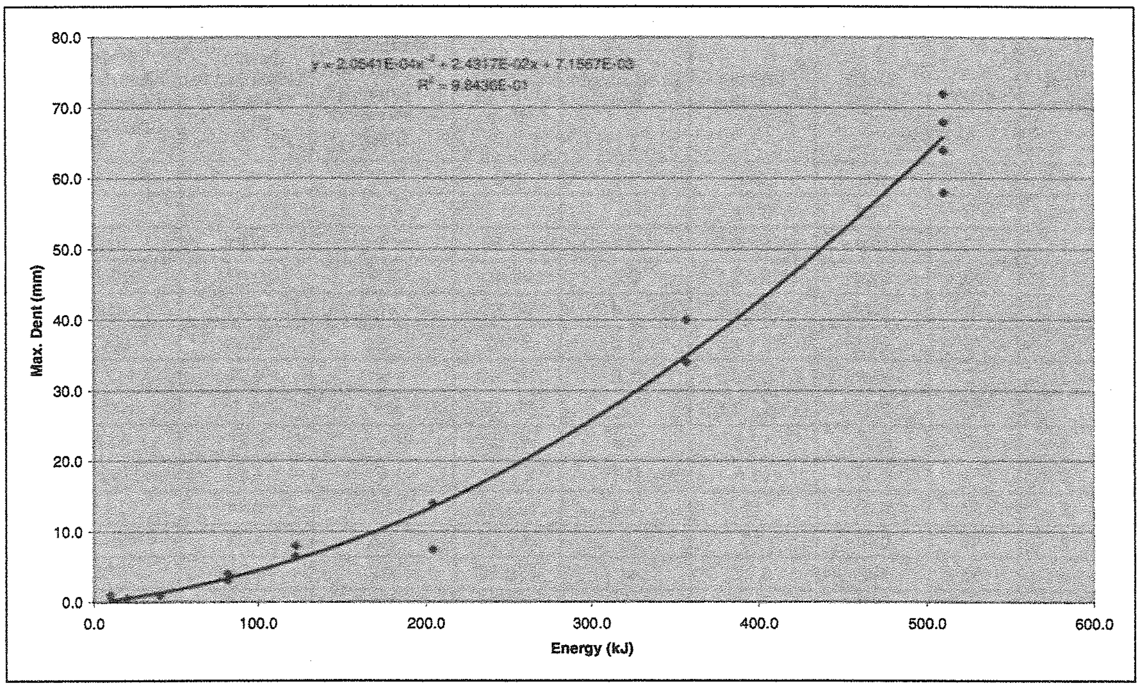

Figure 1. TSEP Drop Test – Results Correlation

A clear and consistent correlation is evident in Figure 1. The most apparent initial observation is that the degree of pipeline damage is relatively insensitive to impact attitude (i.e. whether flat to give a flat impact, or inclined to give a knife-edge impact). On the other hand, weightcoat damage was much more sensitive to impact attitude of the block. The inclined impacts gave rise to a more concentrated and severe area of coating damage.

The criteria for assessing the amount of weightcoat damage was whether reinforcing was exposed. All flat impacts, performed on the same length of 70mm concrete coated pipe, resulted in very minimal weightcoat damage. The repeated testing in Series 1 up to a height of 2m on the same location resulted in no spalling of the concrete and insignificant cracking. Similarly, the single flat drop of 5m yielded a comparable level of minor concrete damage. Reinforcement was not exposed until the inclined tests were performed. This occurred once impact energy exceeded 100kJ on the

70mm pipe and 500kJ on the 90mm pipe, with rebar often bent or broken. In summary, the critical damage threshold for the concrete coating is the exposure of the reinforcement, and the minimum impact energy that can cause this is 100kJ. Inclined impact on the 70mm coated pipe is the governing case, and should the impact be flat or on a 90mm section of coated pipe, there is virtually no likelyhood of critical coating damage. It should also be noted that during all the drop tests, the pipeline corrosion coating was never exposed by an impact.

The worst case scenario for a gravity anchor impacting the pipeline is a free fall situation in the case of a snapped crane hoist wire or rigging during the final positioning over the pipeline. The terminal velocity of the gravity anchor was calculated to be approximately 6.1m/s, and the associated energy 389kJ (Woodside, 2003). Figure 1 indicates that such a free fall impact would result in approximately a 40mm dent. This is slightly outside the 3 % gauge plate limit (32mm), but within the 5 % integrity limit (53mm). Intial design work indicated that denting the pipe to 97 % OD would require an impact energy of 80kJ, 40kJ to dent the steel pipe and 40kJ as the threshold for concrete weightcoat damage. Testing showed that in order to create such a dent (32mm), an impact energy of approximately 350kJ would be needed. This shows that the concrete coating has almost 8 times more capacity to absorb energy than previously determined. Although this is not entirely correct due to the assumption of a perfect non-elastic impact, it is representative of the conservatism in design calculations.

4.0 Future Work

As a comparison to the TSEP testing and a means of gathering a second set of results, impact testing is being carried out at UWA on sample lengths from the Wanaea / Cossack pipeline. Two 12m lengths of the 12.75" (323.8mm) OD x 12.7mm WT pipeline were sent down from Karratha to be cut into eight 3m lengths for testing. A geometric scale of 1:10 for diameter to length is regarded as high enough to eliminate any 'open end' effects during testing. Each length of pipe has 30mm of concrete coating

As a worst case scenario, the pipe will be tested on hard ground (concrete) and impacted with a steel weight. To cause severe concrete damage and pipe deformation, a sharp edged impact is needed. Initial testing will use a 100kg steel mass with a spherical (rounded) impacting face. The weight will be lifted vertically by the use of a forklift, suspended by some chain and a quick release shackle will be used to release the weight smoothly. This quick release mechanism was purchased from Whitworth's Marine and Leisure, and has a functional limit of 1,100kg and breaking load 1,500kg. The shackle was tested using the 100kg weight and released quite easily. The maximum drop height that can be achieved from the forklift is approximately 5m which gives an initial impact energy of 4.9kJ. With a 'sharper' impact, this is expected to cause spalling to the concrete coating but minimal deformation to the steel pipe. Alterations are planned to the drop weight to give it more of a point load and increase its weight so as to cause more damage to the pipe. After each drop test, the damage to the concrete coating and steel pipe will be individually measured. These results will then be compared to those predicted by DNV calcutations and finite element analysis (FEA).

Modelling of the testing is being attempted through Abaqus, FEA Modelling Software, using two types of shell elements to represent the two materials (steel pipe and concrete coating) and introducing a rigid body as the impacting object. No results have been computated from the simulation to date, but it is hopeful that further development of the model will provide a means to validate test results.

5.0 Conclusion

The TSEP drop tests demonstrate the potential for pipeline concrete coating to absorb impact energy. In the case of creating a 3 % OD dent depth, the impact energy required was several orders of magnitude larger than those predicted in design calculations. A considerable amount of this inconsistency is due the assumption of a perfect non-elastic impact, the issue of which needs to be addressed. Work is continuing on the project to produce some results that can be used to compare/verify those found from TSEP testing. The results of these findings will be included in the final honours report.

6.0 References

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