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Risk Assessment of Dropped Cylindrical Objects in Offshore Operations

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Risk Assessment of Dropped Cylindrical Objects
in Offshore Operations

A Thesis

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To whoever is reading this thesis.

Thank You

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List of Abbreviations

DROBS	Dropped object simulator
2D	Two-dimensional
3D	Three-dimensional
DNV	Det Norske Veritas
ABS	American Bureau of Shipping
LCG	Longitudinal center of gravity
ODE	Ordinary differential equation
MATLAB	Matrix laboratory
OS	Offshore standard
SAS	Statistical analysis system
PDF	Probability density function
CDF	Cumulative density function
SD	Standard deviation

List of Symbols

ϕ	Instantaneous Euler angle around the *x*-axis
θ	Instantaneous Euler angle around the *y*-axis
ψ	Instantaneous Euler angle around the *z*-axis
M_{44}	Moment of inertia in roll direction
M_{55}	Moment of inertia in pitch direction
M_{66}	Moment of inertia in yaw direction
m_{22}	Added mass in sway direction from strip theory
m_{33}	Added mass in heave direction from strip theory
m_{55}	Added mass in pitch direction from strip theory
m_{66}	Added mass in yaw direction from strip theory
m_{t2}	2D added mass coefficient in sway direction at the trailing edge
m_{t3}	2D added mass coefficient in heave direction at the trailing edge
x_t	Longitudinal position of effective trailing edge
g	Acceleration of gravity
ρ	Density of water
m	Mass of the cylinder
∇	Volume of the cylinder
X_G	Longitudinal center of gravity
U_1	Translational velocity of the local origin in the *x* direction
U_2	Translational velocity of the local origin in the *y* direction
U_3	Translational velocity of the local origin in the *z* direction
Ω_1	Rotational velocity of the local origin in the *x* direction (rolling frequency)
Ω_2	Rotational velocity of the local origin in the *y* direction (pitching frequency)
Ω_3	Rotational velocity of the local origin in the *z* direction (yawing frequency)
c	Decaying rate of rolling frequency
D	Diameter of the cylinder
ν	Kinematic viscosity of water
L	Length of the cylinder

C_{dx}	Drag coefficient in *x*-direction
C_{dy}	Drag coefficient in *y*-direction
C_{dz}	Drag coefficient in *z*-direction
Re	Reynolds number in the defined direction
δ	Cylinder's aspect ratio
m_p	Plastic moment capacity of the wall
δ	Pipe deformation, dent depth
t	Wall thickness (nominal)
σ_y	Yield stress
x_0	Penetration
b	Breadth of the impacting object
h	Water depth
$p(x)$	Probability of a sinking object hitting the sea bottom at a distance x
x	Horizontal distance at the sea bottom
δ_L	Lateral deviation
$P_{hit,r}$	Probability of hit within two circles around the drop point
r_i	Inner radius
r_o	Outer radius
$P_{hit,sl,r}$	Probability of hit to a pipeline with an object
L_{sl}	Length of subsea line within the ring
D	Diameter of subsea line
B	Breadth of falling object
A_r	Area within the ring
$F_{hitsl,r}$	Dropped object frequency
N_{lift}	Number lifted per year
f_{drop}	Drop frequency per lift
σ^2	Variance
μ	Mean
λ	Scaling factor
ρ_c	Mass density

Abstract

Dropped object are defined as any object that fall under its own weight from a previously static position or fell due to an applied force from equipment or a moving object. It is among the top ten causes of injuries and fatality in oil and gas industry. To solve this problem, several in-house tools and guidelines is developed over time to assess the risk of dropped objects on the subsea structures. This thesis focuses on compiling and comparing those methods in hope to improve the recommended practices available in the market. A simple modification is done on the in-house tools to better predict the landing point distribution of the dropped cylindrical objects on the seabed by imposing the random three-dimensional rotation around the water depth axis. This tool is then used to compare the result of annual hit frequency using the recommended practice and further compared with the available experimental data.

Keywords: Dropped cylindrical object, in-house tool, recommended practice, experimental data

Chapter 1

Introduction

Dropped objects may impose risk to the pipeline layout on the seabed. The impact may cause damage on the pipeline; thus, it is crucial to assess those risks to evaluate whether the pipeline had an adequate protection or not. To address this problem, several in-house tools, guidelines and studies was developed and performed over time.

1.1 Literature Review

DNV (2010) recommended practice assumed that the object excursions on the seabed follow a normal distribution. However, ABS (2013) guidelines suggested that a specialized technique to predict the trajectory of dropped objects and its excursion on the seabed is required. Xiang, G. (2016) has developed the in-house tool called DROBS from his paper.

1.2 Introduction to Experiments

Awotahegn (2015) performed a series of model tests to investigate the trajectory and seabed distribution of two drill pipes with diameter 8″ and 12″ falling from 1.2 meters above the water surface with depth of 3 meters. A model testing is preferred using Froude number scaling as it is rare to be able to achieve full Reynolds number scaling when other dimensionless parameters are also involved. Three levels of similarity used is geometric similarity, kinematic similarity and dynamic similarity. Data based on *ANSI/ASME* specification of steel pipe and *ISO General Purpose* stainless steel tube is used. For geometric similarity, the scale is taken based on water depth and the diameter, with all other parameters are scaled according to the scale law shown in Table 4.1. Two different water depths for real-life situation considered at 50 m (1:16.67) and 100 m (1:33.33) full scale.

Table 1.1 Pipe data and its corresponding model scale [2]

Type	Pipe 8"			Pipe 12"		
Scale	Full	1:16.67	1:33.33	Full	1:16.67	1:33.33
Diameter (m)	0.2191	0.0132	0.0066	0.3240	0.0194	0.0100
Length (m)	8.9600	0.5374	0.2690	8.9600	0.5374	0.2690
Mass (kg/m)	90.44	0.3250	0.0820	240.00	0.8640	0.2160
Thickness (m)	0.0183	0.0010	0.0017	0.0286	0.0017	0.0009
Grade	Carbon steel seamless			XS120		

The data was collected through manual observation, pictures and video recording. The pipe is dropped from the static point *oxyz* at coordinate (0, 0, 0) with dropped angle of varied at 0°, 30°, 45°, 60° and 90°. The test was conducted at least two to four times for each dropped angle to obtain the minimum and maximum excursion on the water basin floor.

1.3 Objectives and Scopes

This study focuses on compiling and comparing those methods in hope to improve the recommended practices available in the market. Main goal of this study is to obtain a basic knowledge about the motion of dropped cylindrical objects through water.

Chapter 2 reviews the literature about drop cylindrical objects by theoretical solution, industrial practice and experimental data. Some adjustment and comments were included for a better interpretation of the result. Chapter 3 discusses the output comparison between the three literatures. Chapter 6 gives conclusion and recommendation.

Chapter 2

Theories and formulas

2.1 Equation of motions and Monte Carlo simulation

Xiang et al. (2016) in his paper developed a numerical tool called Dropped Objects Simulator (DROBS). This tool was used to investigate various factors that may affect the trajectories, including drop angle, drag coefficient, rolling frequency, current and longitudinal centre of gravity. This tool is based on the newly proposed three-dimensional (3D) theory by modifying the equations of motion based on the maneuvering theory of slender bodies and rigid body dynamics and is stated as follows:

$$(m-\rho\nabla)g\sin(\theta)+F_{dx}=m(\dot{U}_1+U_3\Omega_2-U_2\Omega_3-X_G{\Omega_2}^2-X_G{\Omega_3}^2) \tag{2.1}$$

$$\begin{aligned}&-(m-\rho\nabla)g\cos(\theta)\sin(\phi)+F_{Ly}+F_{dy}=\\&\qquad\{m_{22}\dot{U}_2+U_1m_{t2}U_2-U_1(x_tm_{t2})\Omega_3\}+\\&\qquad m(\dot{U}_2+U_1\Omega_3-U_3\Omega_1+X_G\Omega_1\Omega_2+X_G\dot{\Omega}_3)\end{aligned} \tag{2.2}$$

$$\begin{aligned}&-(m-\rho\nabla)g\cos(\theta)\cos(\phi)+F_{Lz}+F_{dz}=\\&\qquad\{m_{33}\dot{U}_3+U_1m_{t3}U_3-U_1(x_tm_{t3})\Omega_2\}+\\&\qquad m(\dot{U}_3+U_2\Omega_1-U_1\Omega_2+X_G\Omega_1\Omega_3-X_G\dot{\Omega}_2)\end{aligned} \tag{2.3}$$

$$\dot{\Omega}_1=c \tag{2.4}$$

$$\begin{aligned}&M_{Gy}+M_{Ly}+M_{dy}=\\&\qquad\{-U_1(m_{33}+x_tm_{t3})U_3+U_1{x_t}^2m_{t3}\Omega_2+m_{55}\dot{\Omega}_2\}+\\&\qquad M_{55}\dot{\Omega}_2+(M_{44}-M_{66})\Omega_1\Omega_3-mX_G(\dot{U}_3-U_1\Omega_2+U_2\Omega_1)\end{aligned} \tag{2.5}$$

$$\begin{aligned}&M_{Gz}+M_{Lz}+M_{dz}=\\&\qquad\{-U_1(m_{22}+x_tm_{t2})U_2+U_1{x_t}^2m_{t2}\Omega_3+m_{66}\dot{\Omega}_3\}+\\&\qquad M_{66}\dot{\Omega}_3+(M_{55}-M_{44})\Omega_1\Omega_2+mX_G(\dot{U}_2+U_1\Omega_3-U_3\Omega_1)\end{aligned} \tag{2.6}$$

Terms in curly brackets on Equations (2.2), (2.3), (2.5) and (2.6) are hydrodynamic force and moment derived from potential theory. Added masses and forces, m_{22}, m_{33}, m_{55} and m_{66} for the plane normal to the cylinder axis are derived using a strip-theory approach. M_{Gy} and M_{Gz} are the moments caused by the off-center weight. The drag forces, F_{dx}, F_{dy} and F_{dz}, and drag moments, M_{dy} and M_{dz}, are estimated using the Morison equation. Lift forces and moments F_{Ly}, F_{Lz}, M_{Ly} and M_{Lz} are all caused by the rolling motion of Kutta-Joukowski's lift theorem for a cylinder in ideal flow. After the translational velocity components, U_1, U_2 and $U_{3,}$are solved at each time step, the transformation between the local system (*oxyz*) and the global inertial system (*OXYZ*) can be expressed as:

$$\dot{X} = U_1 cos(\theta)cos(\psi) + U_2(-cos(\phi)sin(\psi) + sin(\phi)sin(\theta)cos(\psi)) + U_3(sin(\phi)sin(\psi) + cos(\phi)sin(\theta)cos(\psi)) \tag{2.7}$$

$$\dot{Y} = U_1 cos(\theta)sin(\psi) + U_2\left(cos(\phi)cos(\psi) + sin(\phi)sin(\theta)sin(\psi)\right) + U_3(-sin(\phi)cos(\psi) + cos(\phi)sin(\theta)sin(\psi)) \tag{2.8}$$

$$\dot{Z} = -U_1 sin(\theta) + U_2(-sin(\phi)cos(\theta)) + U_3(cos(\phi)cos(\theta)) \tag{2.9}$$

But a more ideal situation is when the object is dropped above the water level. The impact on water will cause unknown changes in drop angle, speed and rotation. These changes is difficult to model since it depend on many variables. Here, Monte Carlo simulation is used. The input variables includes orientation angle (ϕ_0, θ_0, ψ_0), translational velocities ($\dot{X}_0$, $\dot{Y}_0$, $\dot{Z}_0$) and rotational velocities (Ω_{10}, Ω_{20}, Ω_{30}) when the cylinder is just fully immersed. The sample size, N of 10000 is used to simulate the landing point distribution.

2.2 DNV simplified method

The document that will be used as the basis for this study is *Recommended Practice DNV-RP-F107, Risk Assessment of Pipeline Protection, October 2010*. The objective of this recommended practice is to provide a basis for risk assessment of accidental events which lead to eternal interference with offshore risers, pipelines and umbilical. The limits for the application of this document are on a fixed or floating platform and on a subsea installation.

2.2.1 Activity description

To evaluate whether the risk of an accidental event is acceptable or not, acceptance criteria are required. Alternatively, the structural failure probability requirements given in *Offshore Standard DNV-OS-F101, Submarine Pipeline System, October 2013* may be used as acceptance criteria, in which case no consequence assessment is required and only the frequency needs to be established. In lieu with the application of DROBS, only long shaped object will be considered in this study. This category further divided into three parts, those weighting less than 2 tones, between 2 to 8 tones and those weighted more than 8 tones.

Table 2.1 Object classification, typical load data [3]

Description	Weight (tones)	Typical object [1]	Angular deviation, α (°)
Flat/long shaped	< 2	Drill collar/casing, scaffolding	15
	2 – 8	Drill collar/casing	9
	> 8	Drill riser, crane boom	5

1 The classification in the table is based on platform activities to/from supply vessels. For other activities e.g. to/from subsea installations, an alternative classification may be more relevant.

2.2.2 Pipeline and protection capacity

DNV assumes that the given damage capacities of the pipeline can conservatively absorb all the available kinetic energy of the impacting objects. Most impacts are expected to result in a relatively smooth dent shape. The *dent – absorbed energy* relationship for steel pipelines are given in Equation (3.1) (Wierzbicki and Suh, 1988). Concrete coating may be used to shield pipelines from potential impact damage. The kinetic energy absorbed for two different cases may be expressed as given in Equation (3.2) and (3.3) (Jensen, 1978).

$$E = 16 \cdot \left(\frac{2\pi}{9}\right)^{\frac{1}{2}} \cdot m_p \cdot \left(\frac{D}{t}\right)^{\frac{1}{2}} \cdot D \cdot \left(\frac{\delta}{D}\right)^{\frac{3}{2}} \tag{2.10}$$

$$E_k = Y \cdot b \cdot h \cdot x_0 \tag{2.11}$$

$$E_k = Y \cdot b \cdot \frac{4}{3}\sqrt{D \cdot x_0^3} \tag{2.12}$$

Table 3.2 gives the proposed damage classification used for bare steel pipes. Material damage to the pipelines is classified by minor damage (D1), moderate damage (D2) and major damage (D3).

Table 2.2 Impact capacity and damage classification of steel pipelines and risers [3]

Dent (%)	Impact energy	Damage description	Conditional probability		
			D1	D2	D3
< 5	(2.10)	Minor damage	1.0	0	0
5 – 10	(2.10)	Major damage Leakage anticipated	0.1	0.8	0.1
10 – 15	(2.10)	Major damage Leakage and rupture anticipated	0	0.75	0.25
15 – 20	(2.10)	Major damage Leakage and rupture anticipated	0	0.25	0.75
> 20	(2.10)	Rupture	0	0.1	0.9

2.2.3 Failure Frequency

To assess the pipeline risk from accidental loading, it is necessary to establish the frequency of such event. The drop frequency is based on the accident data issued by the *UK Department of Energy* covering the period from 1980 to 1986 (DNV 1996b). The proposed dropped object frequency for ordinary lift to/from supply vessel with platform crane weighting less than 20 tones is 1.2e-05. The object excursion on the seabed are assumed to be normally distributed with angular deviations given in Table 3.1 defined as:

$$p(x) = \frac{1}{\sqrt{2\pi}\delta_L} e^{-\frac{1}{2}\left(\frac{x}{\delta}\right)^2} \tag{2.13}$$

The actual extent of the vulnerable items on the seabed within each ring can easily be incorporated by dividing the probability into several rings. The probability of hit to a pipeline with an object within each ring can be described as Equation (2.16). The impact frequency estimated with Equation (2.17) with the annual crane load data lifted to and from supply vessels.

$$P(x \leq r) = \int_{-r}^{r} p(x)\, dx = 2 \int_{0}^{r} \frac{1}{\sqrt{2\pi}\delta} e^{-\frac{1}{2}\left(\frac{x}{\delta}\right)^{2}}\, dx \tag{2.14}$$

$$P_{hit,r} = P(r_i < x \leq r_o) = P(x \leq r_o) - P(x \leq r_i) \tag{2.15}$$

$$P_{hit,sl,r} = P_{hit,r} \cdot \frac{L_{sl} \cdot (D+B)}{A_r} \tag{2.16}$$

$$F_{hitsl,r} = N_{lift} f_{drop} P_{hit,sl,r} \tag{2.17}$$

2.3 Half-folded distribution

By Equation 3.4, the object excursion on the seabed is assumed to be normally distributed with the mean, $\mu = 0$. To calculate the expected value, we could use the theory of folded normal distribution (Leone, F.C. et. all, 1961). It is used when the interest is only on the size of the random variables and not the direction or sign. When $\mu = 0$, $X \sim N(0, \sigma^2)$, then $Y = |X|$ follows a half-normal distribution. Thus, half-normal distribution is a fold at the mean of an ordinary normal distribution with mean zero. Using the σ parameterization of the normal distribution, the probability density function (PDF) of the half-normal is given by

$$f_Y(y; \sigma) = \frac{\sqrt{2}}{\sigma\sqrt{\pi}} exp\left(-\frac{y^2}{2\sigma^2}\right), \;\; y \geq 0 \tag{2.18}$$

The cumulative distribution function (CDF) is given by

$$F_Y(y; \sigma) = \int_{0}^{y} \frac{1}{\sigma} \sqrt{\frac{2}{\pi}} exp\left(-\frac{x^2}{2\sigma^2}\right) dx \tag{2.19}$$

The expectation is then given by

$$E(Y) = \mu = \sigma\sqrt{\frac{2}{\pi}} \tag{2.20}$$

Thus, from the estimation of lateral deviation, δ_L, mean of the half-normal distribution for object excursion on the seabed can be estimated using Equation (2.20).

Chapter 3

Case Study

3.1 Extended work of elemental rotation in 3D

The landing point distributions from DROBS is solved by assuming that the dropped cylinders' local coordinates *(oxyz)* are parallel as the main axis for the global coordinates *(OXYZ)*. In real life, this is not wholly true, since when being held on the crane boom, the dropped cylinder would possess a random rotation angle about the initial drop height. Thus, a basic rotation, or also called elemental rotation is used to rotate about one of the axes of the coordinate system, i.e. z-axis. After the excursion of the landing point from Monte Carlo simulation is obtained, at water depth $z = h$, using the right-hand rule, the following basics rotation matrices rotate vectors by generating a random angle, θ about the z-axis.

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \tag{3.1}$$

$$R_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \tag{3.2}$$

An example of the transformation using sample size, N of 10000 at drop angle 60° is as illustrated in figures below.

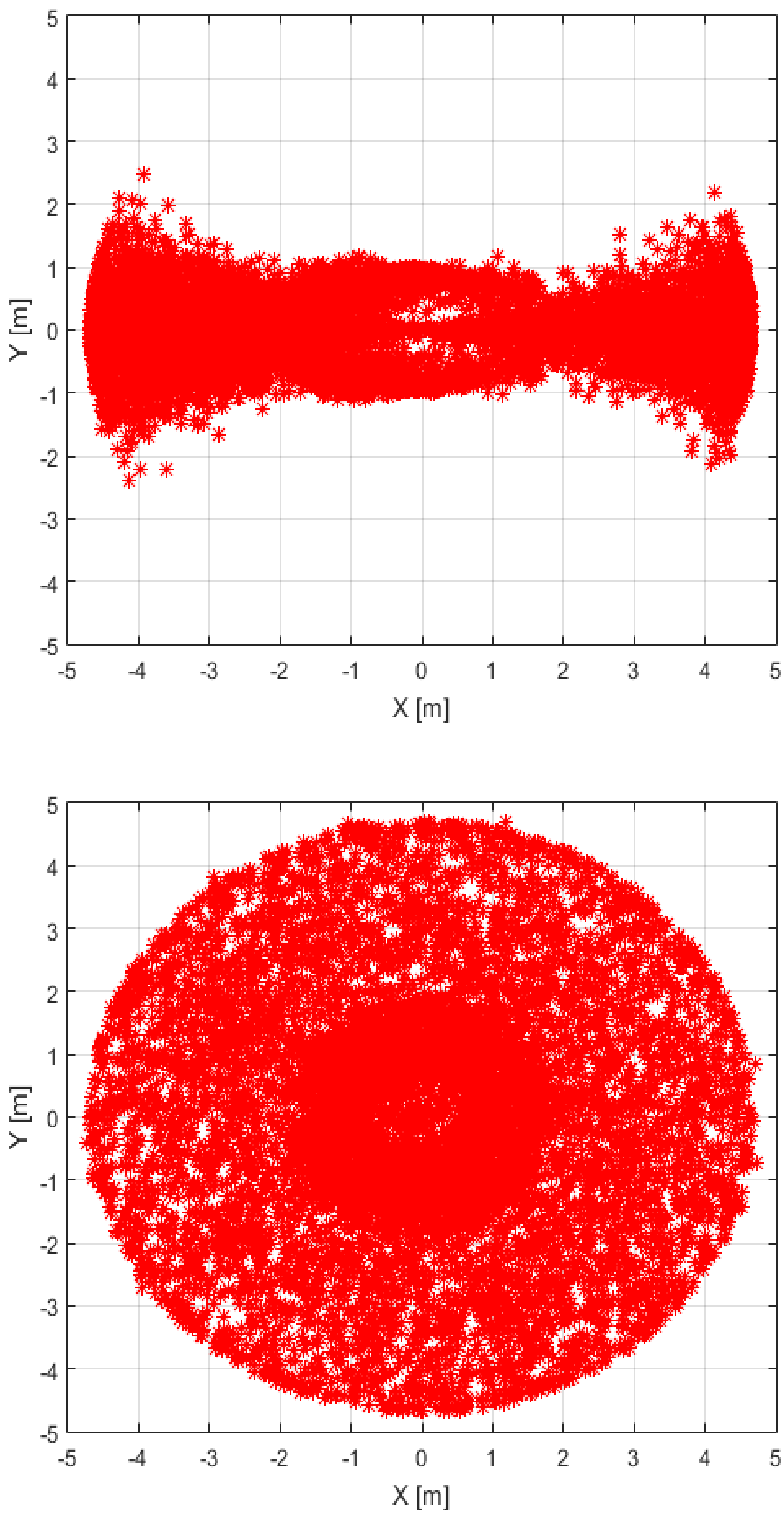

Figure 3.1 Landing point distribution before and after elemental rotation

3.2 DROBS vs DNV

For this project, the example of risk assessment procedure for dropped object proposed in DNV (2010) recommended practice is used as a baseline and try to simulate the same result using the DROBS. Consider the field layout with the pipeline approach and crane location as shown:

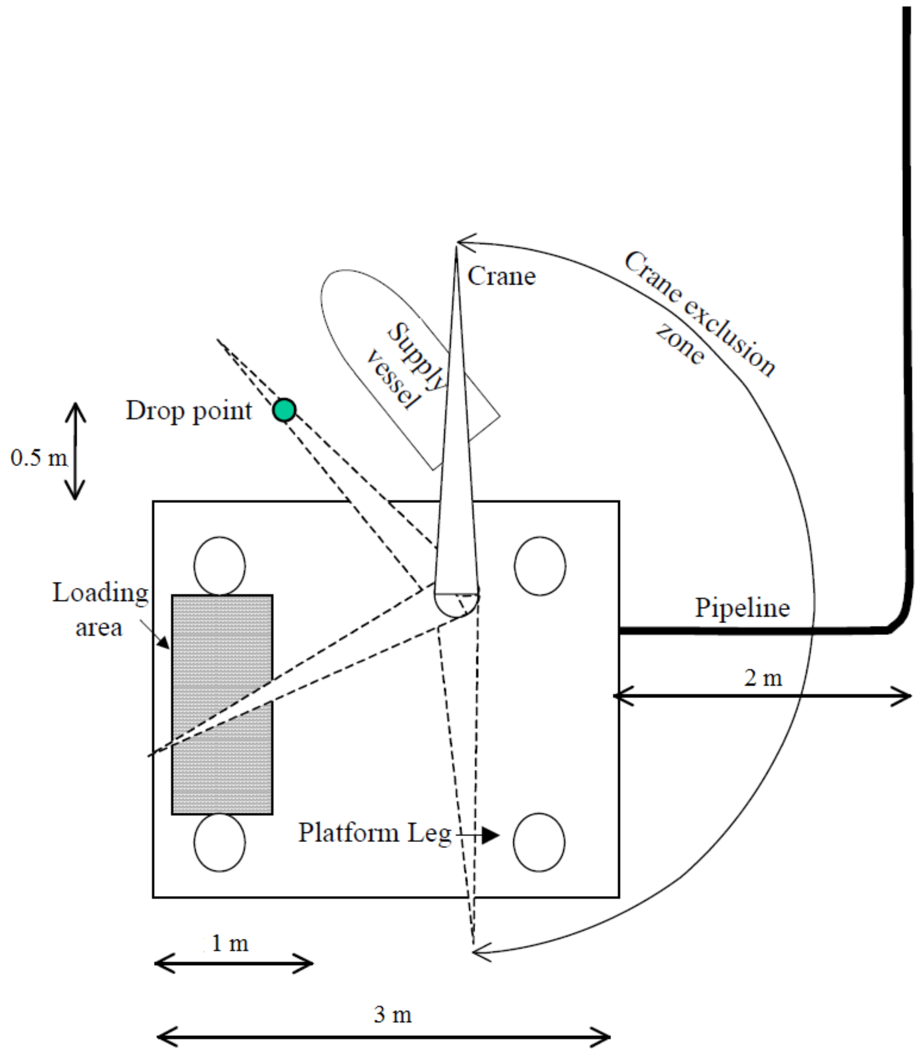

Figure 3.2 Field layout [3]

For the DNV simplified method, the object excursions on the seabed assumed to be normally distributed. Whereas for the DROBS simulation, data based on ANSI/ASME specification of steel pipe will be used to represent each weight groups with nominal size 8, 16 and 24 respectively as shown in Table 3.1. A 1:20 scale is used as a model.

Table 3.1 Properties of dropped cylinders

Case		1		2		3	
Properties	Unit	< 2 tones		2 – 8 tones		> 8 tones	
		Original	Scaled	Original	Scaled	Original	Scaled
Length *(L)*	m	10	0.5	10	0.5	10	0.5
Mass density *(ρ_c)*	kg/m^3	111.27	0.278175	365.35	0.913375	808.22	2.020550
Diameter *(D)*	m	0.2191	0.010955	0.4064	0.020350	0.6100	0.030500
Material grade	-	Schedule 160					

The excursion of dropped cylindrical object is a stochastic event. A normal distribution as given in Equation (2.13) is used to describe the fall pattern of the dropped cylindrical object. Due to the limited water depth, any currents will have limited effect on the excursion of the cylindrical objects and is therefore not accounted for. Thus, for DROBS simulation, there is no current velocity, $V_{current}$ and current heading, β is zero degree. From the drop point, concentric rings of increasing 0.5 meters radius are drawn up. The conditional probabilities of hit for cylinder to fall within these intervals on the seabed are given in Table 3.2. For DROBS simulation, at each case, the cumulative probability density is plotted from the landing point distribution and the corresponding probability is extracted at each 0.5 meters excursion interval. See Figure 3.3 and Figure 3.4. Whereas for simplified DNV method, using the Equation (2.13) to (2.16), the probability of Case 1 cylinder hitting within the first 0.5 meters ring is calculated in the following. This number can be found in Table 3.2 as the first item for Case 1 for DNV, within 0 to 0.5 meters interval. From this point onward, the procedure for the risk assessment is similar for both the simplified DNV method and the DROBS simulation. Table 3.2 to Table 3.7 compare the data obtained by the DNV simplified method and the DROBS simulation. Both shows a good agreement to each other.

$$\delta_L = 5\tan 15 = 1.3397$$

$$P(x \leq 0.5) = 2\int_0^{0.5} \frac{1}{\sqrt{2\pi}(1.3397)} e^{-\frac{1}{2}\left(\frac{x}{1.3397}\right)^2} dx = 0.2910$$

$$P_{hit,0.5} = P(0 < x \leq 0.5) = P(x \leq 0.5) - P(x \leq 0) = 0.2910 - 0 = 0.2910$$

$$P_{hit,Ar,0.5} = \frac{P_{hit,0.5}}{A_{0.5}} = \frac{0.2910}{0.7854} = 0.37052$$

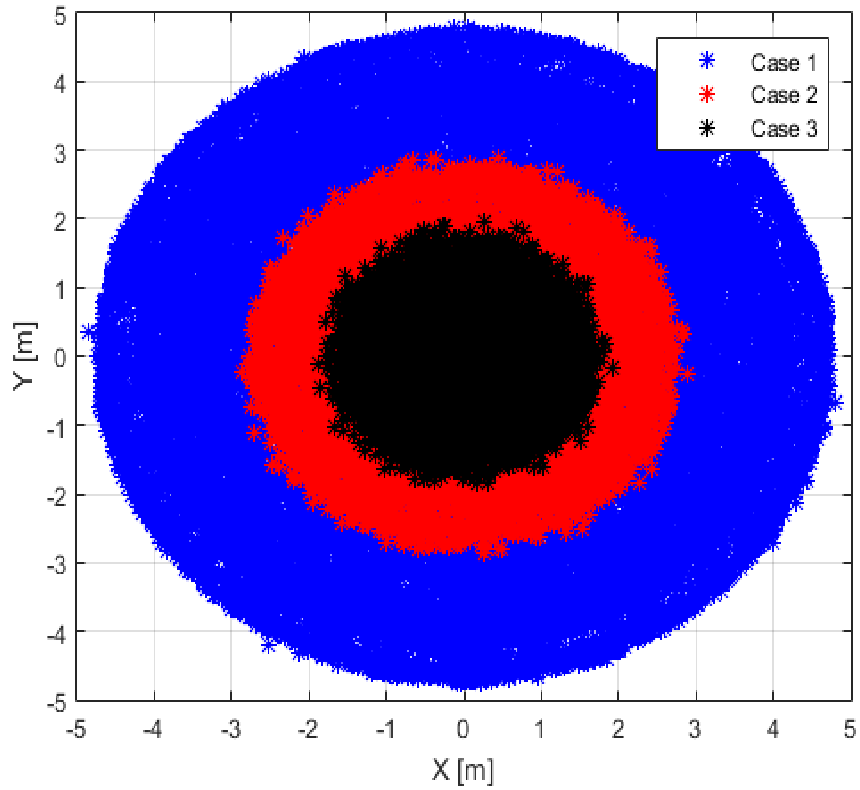

Figure 3.3 Distribution on the seabed for DROBS

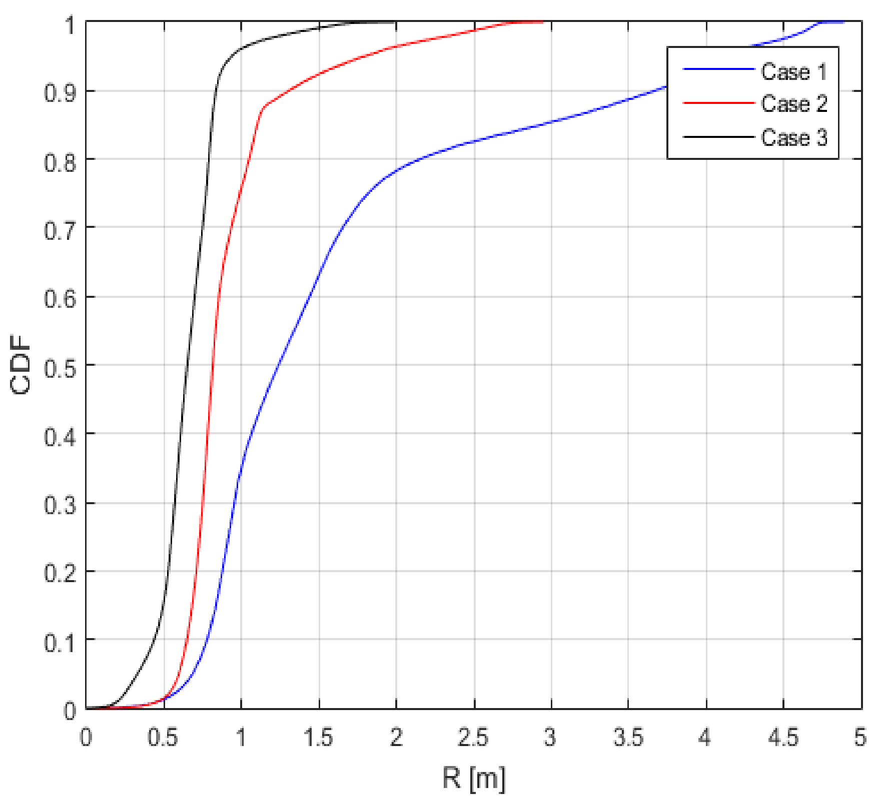

Figure 3.4 Cumulative distribution function for DROBS

Table 3.2 Conditional probability of hit for cylinder to fall within 0.5-meter intervals on the seabed

Case		Probability per m^2									
		0.0 – 0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.0	2.0 – 2.5	2.5 – 3.0	3.0 – 3.5	3.5 – 4.0	4.0 – 4.5	4.5 – 5.0
1	DNV	3.71 e-01	2.69e -04	4.90e -02	2.32e -02	1.04e -02	4.27e -03	1.58e -03	5.23e -04	1.53e -04	3.97e -05
	DROBS	1.49 e-02	1.41e -01	7.18e -02	2.83e -02	6.10e -03	3.32e -03	3.20e -03	3.82e -03	3.28e -03	1.65e -03
2	DNV	6.01 e-01	3.41e -04	3.78e -02	8.49e -03	1.41e -03	1.67e -04	1.39e -05	8.02e -07	3.19e -08	8.72e -10
	DROBS	1.83 e-02	3.15e -01	4.27e -02	7.38e -03	3.28e -03	1.46e -03	0	0	0	0
3	DNV	9.51 e-01	2.45e -04	5.51e -03	1.09e -04	6.82e -07	1.27e -09	6.84e -13	9.42e -17	1.66e -17	0
	DROBS	1.96 e-01	3.42e -01	7.78e -03	1.59e -03	0	0	0	0	0	0

From Table 3.2, the probability for DROBS simulation is approximated to 0 for Case 2 from interval 3-metre and for Case 3 from interval 2-metre since for the sample size, N of 10000, none of the objects falls within this interval. However, for the DNV recommended practices, the dropped cylindrical object probability can still be approximated generally since it is based of Equation (2.6) rather than by the specific object hydrodynamics.

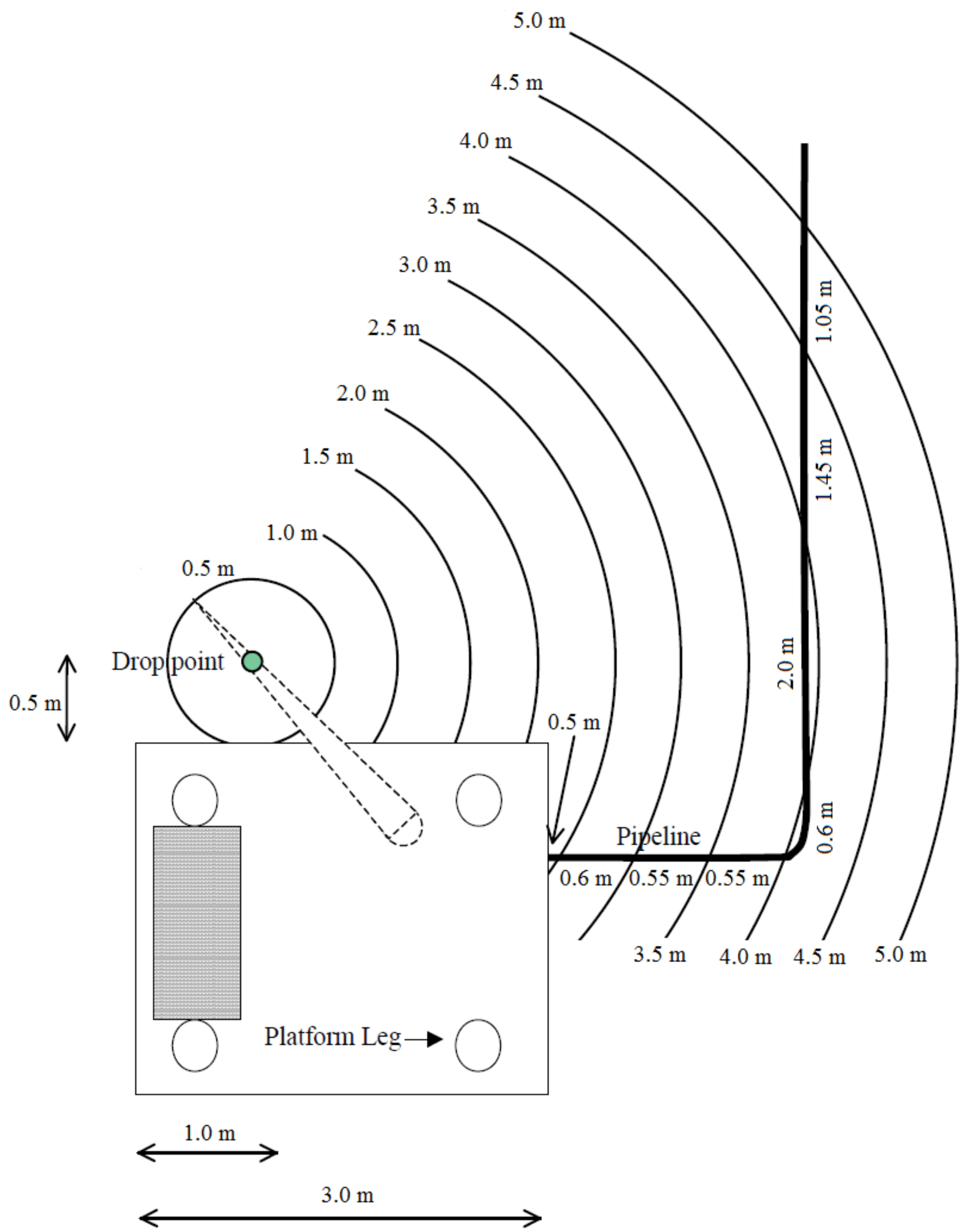

Figure 3.5 Field layout with indication of 0.5 meters interval rings [2]

The hit probability depends on the excursion of the objects as calculated in Table 3.2 and the length of pipeline within each ring and the pipeline diameter and object size. The length of the pipe within each interval is given in Figure 3.4 and Table 3.3. The pipeline diameter is 0.0315 meters including coating and the object size is assumed to be 0.6 meters long for the slender objects. The resulting conditional probability of hitting the pipeline is given in Table 3.4.

Table 3.3 Length of pipeline within each of 0.5-meter interval rings on the seabed

	Pipeline length within each ring									
	0.0 – 0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.0	2.0 – 2.5	2.5 – 3.0	3.0 – 3.5	3.5 – 4.0	4.0 – 4.5	4.5 – 5.0
Length (m)	0	0	0	0	0[1]	0[1]	0.55	2.55	2.05	1.05

1 Assumed shielded by the platform legs and bracing

Table 3.4 Conditional probability for each of the objects to hit pipeline within 0.5-meter intervals on the seabed

Case		Probability of hit									
		0.0 – 0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.0	2.0 – 2.5	2.5 – 3.0	3.0 – 3.5	3.5 – 4.0	4.0 – 4.5	4.5 – 5.0
1	DNV	0	0	0	0	0	0	5.49e-04	8.42e-04	1.98e-04	2.63e-05
	DROBS	0	0	0	0	0	0	1.11e-03	6.14e-03	4.25e-03	1.09e-03
2	DNV	0	0	0	0	0	0	4.82e-06	1.29e-06	4.13e-08	5.78e-10
	DROBS	0	0	0	0	0	0	0	0	0	0
3	DNV	0	0	0	0	0	0	2.37e-13	1.52e-16	2.15e-17	0
	DROBS	0	0	0	0	0	0	0	0	0	0

As an example, the conditional probability for the 3.0 to 3.5 meters radius ring for Case 1 DNV is calculated. The conditional probability of hitting the seabed within this ring is found in Table 3.2 to be 1.58e-03 per m^2. The length of the exposed pipeline is 0.55 meters as given in Table 3.3 and the breadth of the object is conservatively taken as the whole length of a pipe string, i.e. 0.6 meters. The conditional probability of hitting the pipeline then becomes

$$P_{hit,sl,3.5} = 1.58e^{-3} \cdot 0.55 \cdot (0.0315 + 0.6) = 5.49e-04$$

The value for each ring is summed up at the end to give a total conditional hit probability for each case. The final hit frequency is found by multiplying the number of lifts with the drop frequency of 1.20e-05 per lift and the sum of conditional hit probabilities given in Table 3.4 by Equation (2.8). The results are as shown in Table 3.5. The annual hit frequency is found to be 1.36e-05 for simplified DNV method and 1.06e-04 for DROBS simulation by adding up the hit frequency for Case 1, Case 2 and Case 3.

Table 3.5 Resulting hit frequency

Case		Number lifted per year	Drop frequency per lift	Conditional hit probability	Hit frequency
1	DNV	700	1.20e-05	1.62e-03	1.36e-05
	DROBS			1.26e-02	1.06e-04
2	DNV	50	1.20e-05	6.16e-06	3.69e-09
	DROBS			0	0
3	DNV	5	1.20e-05	2.36e-13	1.42e-17
	DROBS			0	0

To find the failure frequency, the energy of the objects and the capacity of the pipeline need to be considered. In lieu of accurate information, the result of hit frequency from Table 3.5 is split into several energy bands. The division for the conditional probabilities is proposed for a pipeline with normal protection requirement and a normal distribution of the impact energies. Table 3.6 gives the resulting hit frequency for different impact energy levels and Table 3.7 gives the resulting accumulated hit frequency. See also Figure 3.4.

Table 3.6 Hit frequency for different impact energy levels

Case		Energy level (J)					
		< 6.61	13.21	26.42	52.85	105.69	> 105.69
1	DNV	4.09e-06	2.45e-06	1.91e-06	1.64e-06	1.50e-06	2.04e-06
	DROBS	3.17e-05	1.90e-05	1.48e-05	1.27e-05	1.16e-05	1.59e-05
2	DNV	1.85e-10	2.96e-10	5.54e-10	7.02e-10	9.24e-10	1.03e-09
	DROBS	0	0	0	0	0	0
3	DNV	0	0	1.42e-18	2.13e-18	4.26e-18	6.38e-18
	DROBS	0	0	0	0	0	0

Table 3.7 Accumulated hit frequency for different impact energy levels

Case	Energy level (J)					
	> 0	> 6.61	> 13.21	> 26.42	> 52.85	> 105.69
DNV	4.09e-06	2.45e-06	1.91e-06	1.64e-06	1.50e-06	2.05e-06
DROBS	1.06e-04	7.41e-05	5.50e-05	4.02e-05	2.75e-05	1.59e-05

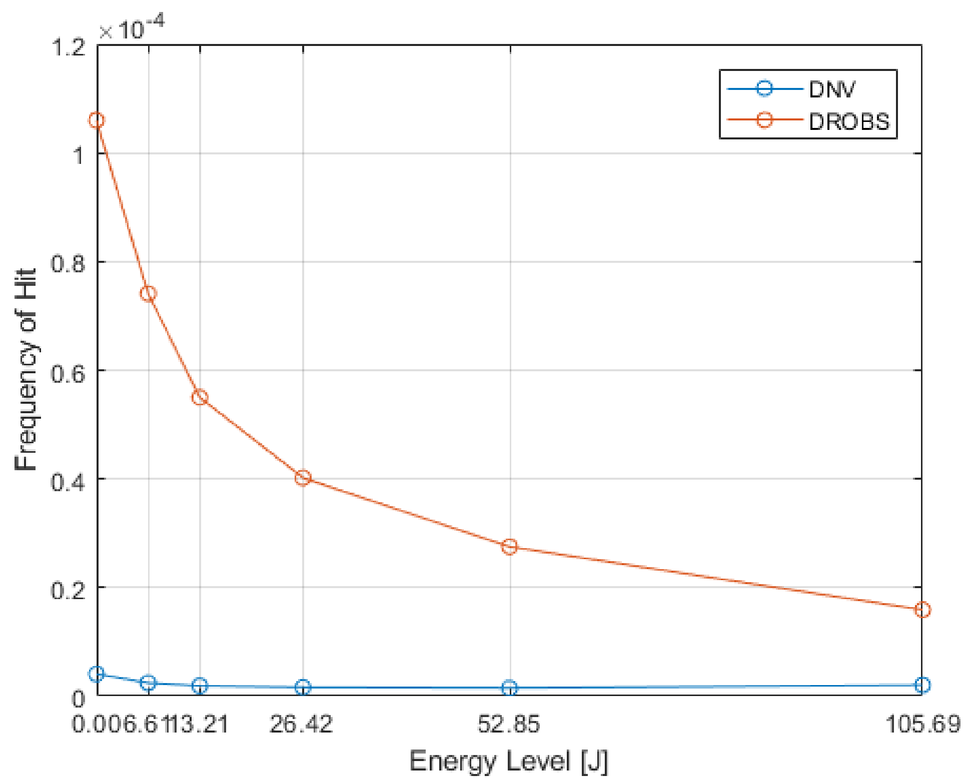

Figure 3.6 Accumulated annual hit frequency for different impacts energy level

From Figure 3.5, we see that the accumulated annual frequency of hit for DNV is way below the accumulated annual frequency of hit for the DROBS. The DNV recommended practice clearly underestimated the hit frequency. This is because the DNV calculated the hit probability generally without considering the hydrodynamic properties of the cylinder and water as what DROBS did. For each of the damage classes defined in Section 3.2, i.e. *D1*, *D2*, *D3*, conditional probabilities for damage to the pipeline can be determined as proposed in Table 2.2. The impact energy required to create a dent of 5 % is found by Equation (3.1):

$$E = 16 \cdot \left(\frac{2\pi}{9}\right)^{\frac{1}{2}} \cdot 91.125 \cdot \left(\frac{0.0254}{0.0009}\right)^{\frac{1}{2}} \cdot 0.0254 \cdot \left(\frac{0.05}{0.0254}\right)^{\frac{3}{2}} = 1.8379\, J$$

The result for larger dents are given in Table 3.8. In addition, the 0.0015 mm breadth, b and 0.015 mm height, h, concrete coating has impact resistance. According to Section 2.2.2, the impact capacity of the coating is taken as the average between Equations (2.2) and (2.3). Here, the crushing strength, Y of concrete is 35e06 with penetration, x_0 of 0.003 m. The total capacity of the pipeline and coating is given in Table 3.8.

$$E_k = Y \cdot b \cdot h \cdot x_0 = 3 \cdot 35e06 \cdot 0.0015 \cdot 0.015 \cdot 0.003 = 7.0875\, J$$

$$E_k = Y \cdot b \cdot \frac{4}{3}\sqrt{D \cdot x_0^3} = 3 \cdot 35e06 \cdot 0.015 \cdot \frac{4}{3}\sqrt{0.0254 \cdot 0.003^3} = 6.1243\, J$$

$$E_k = \frac{7.0875 + 6.1243}{2} \approx 6.6059\, J$$

Table 3.8 Conditional impact energy of pipeline and coating

Dent (%)	Impact energy (J)		Damage description	Conditional probability		
	Steel pipe	Total		D1	D2	D3
< 5	< 1.84	< 8.44	Minor damage	1.0	0	0
5 – 10	1.84 – 5.20	8.44 – 11.80	Major damage	0.1	0.8	0.1
10 – 15	5.20 – 9.55	11.80 – 16.16	Major damage	0	0.75	0.25
15 – 20	9.55 – 14.70	16.16 – 21.31	Major damage	0	0.25	0.75
> 20	> 14.70	> 21.31	Rupture	0	0.1	0.9

Damage versus frequency can be determined by combining the Table 3.7 and Table 3.8. For example, at 5 % dent, the frequency of hit for DNV simplified method can be obtained by projecting the corresponding value from energy level of 8.44 J to 1.84 J from Figure 5.4. The resulting hit frequency at this impact energy intervals is 4.77e-06, then to obtain the frequency, this value is multiplied with the conditional probability as in Table 3.8. The result for frequency versus damage is shown in Table 3.9 and Table 3.10 for DNV and DROBS, respectively.

Table 3.9 Failure frequency versus damage category (DNV)

Dent (%)	Impact energy (J)		Damage description	Frequency		
	Steel pipe	Total		D1	D2	D3
< 5	< 1.84	< 8.44	Minor damage	4.77e-06	0	0
5 – 10	1.84 – 5.20	8.44 – 11.80	Major damage	1.25e-07	9.98e-07	1.25e-07
10 – 15	5.20 – 9.55	11.80 – 16.16	Major damage	0	7.11e-07	2.37e-07
15 – 20	9.55 – 14.70	16.16 – 21.31	Major damage	0	1.86e-07	5.58e-07
> 20	> 14.70	> 21.31	Rupture	0	5.92e-07	5.33e-06
				4.90e-06	2.49e-06	6.25e-06

Table 3.10 Failure frequency versus damage category (DROBS)

Dent (%)	Impact energy (J)		Damage description	Frequency		
	Steel pipe	Total		D1	D2	D3
< 5	< 1.84	< 8.44	Minor damage	3.70e-05	0	0
5 – 10	1.84 – 5.20	8.44 – 11.80	Major damage	9.69e-07	7.75e-06	9.69e-07
10 – 15	5.20 – 9.55	11.80 – 16.16	Major damage	0	5.52e-06	1.84e-06
15 – 20	9.55 – 14.70	16.16 – 21.31	Major damage	0	1.44e-06	4.33e-06
> 20	> 14.70	> 21.31	Rupture	0	4.59e-06	4.14e-05
				3.80e-05	1.93e-05	4.85e-05

The total failure frequency versus damage category is then calculated for both DROBS and DNV and is compared with the acceptance criteria as given in the DNV-OS-F101, where the annual failure frequency shall be less than 1e-5, i.e. safety class high, for the system to be considered as having an adequate pipeline protection. The failure frequency is obtained by adding the results for damage class D2 and D3 only since the damage class D1 is not considered to give damage leading to failure. For DROBS, the annual hit frequency is 6.7808e-05 from Table 3.9 whereas for DNV, the annual hit frequency is 8.7344e-06 from Table 3.10. DNV indicate that the pipeline protection was adequate but DROBS estimated the annual hit frequency to exceed the acceptance criteria, thus the pipeline protection is not adequate.

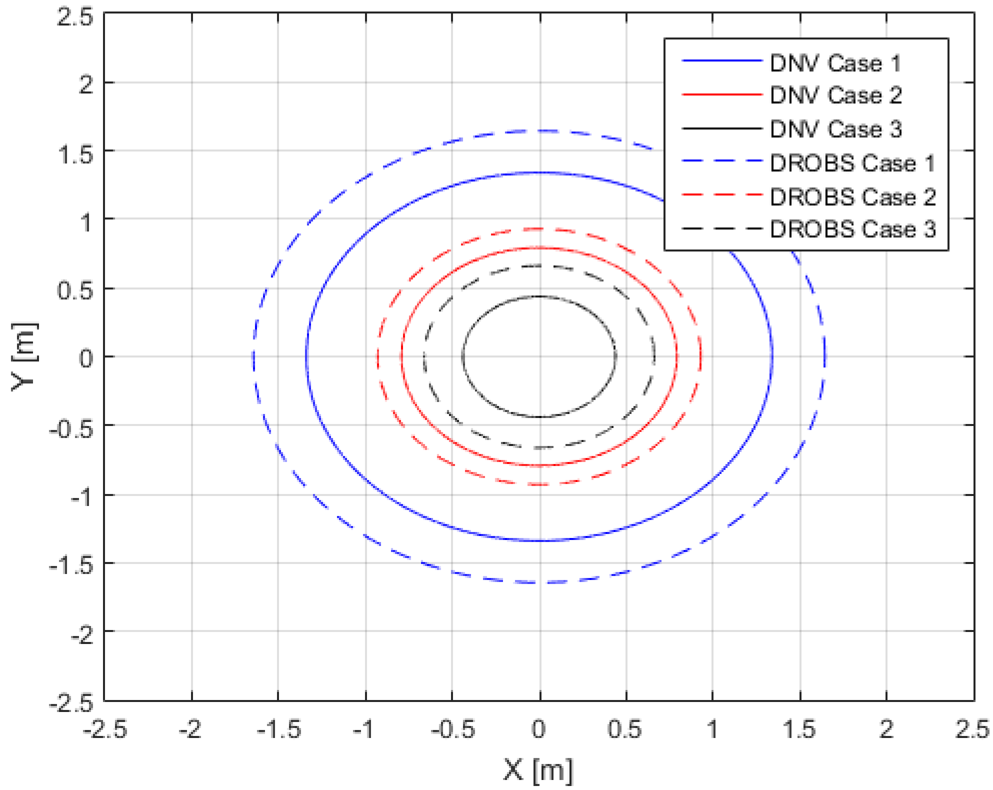

Figure 3.7 Mean radius comparison between DROBS and DNV

If we see from Figure 3.6, it can be easily concluded that DNV underestimate the mean radius in all the three cases, thus supporting the idea that the protection for the pipeline on the seabed is not adequate. Any piping system outside the mean radius of DNV calculation is subjected to risk from dropped objects which can distribute to damage or rupture. Xiang, G. (2016) also mentioned that the result from the DNV underestimate the possible excursion of a landing point on the sea bed. As quoted from Awotahegn (2015), this underestimation happens since DNV only gave an initial estimate since it's based on a general category, i.e. water depth, rather than a specific dropped object hydrodynamics, i.e. length, diameter, density, etc. Thus, adjustment should be made on the DNV recommended practice to avoid undesirable offshore accident.

3.3 DROBS vs DNV vs Experimental Data

For the water depth, d of 50 metre full scale, the model is experimented using a 3-metre water depth towing tank. Thus, the scaling factor used is 1:16.67. Model drop height, h is estimated at 1.2 metre above water level. To reduce the computation time, sample size, N used to simulate DROBS is 10,000. Table 3.11 shows the properties of the dropped pipe used by Awotahegn (2015) in his experiment.

Table 3.11 Properties of dropped pipe (scale 1:16.67)

Case		1		2	
Properties	Unit	Original	Scaled	Original	Scaled
Nominal size	inch	8		12	
Length *(L)*	m	8.96	0.5376	8.96	0.5376
Mass density *(ρ_c)*	kg/m	90.44	0.325584	240.00	0.864000
Diameter *(D)*	m	0.2191	0.013146	0.3240	0.019440
Amount needed *(N)*	-	10		10	
Material grade	-	Carbon steel seamless		XS120	

Table 3.12 Dropped pipe distribution at tank bed (scale 1:16.67)

Angle *(°)*	No of sample	Case	DROBS		DNV		Experimental Data	
			Mean R *(m)*	SD R *(m)*	Mean R *(m)*	SD R *(m)*	Mean R *(m)*	SD R *(m)*
0	2	1	1.7283	0.8543	0.6414	0.8038	0.1520	0.1040
30	3		1.5300	0.9655	0.6414	0.8038	0.2600	0.1240
45	2		1.4572	0.8364	0.6414	0.8038	0.2720	0.0960
60	2		1.6272	1.0103	0.6414	0.8038	1.1340	0.4190
90	2		1.9169	0.8676	0.6414	0.8038	1.0380	0.3700
Mean			1.6519	0.9068	0.6414	0.8038	0.5712	0.2226
0	2	2	1.3487	0.6513	0.3791	0.4752	0.2140	0.1030
30	1		1.2238	0.7628	0.3791	0.4752	0.3620	0.1470

45	1		1.1399	0.6995	0.3791	0.4752	0.7570	0.2600
60	3		1.2865	0.7909	0.3791	0.4752	1.1340	0.3080
90	1		1.7218	0.7071	0.3791	0.4752	0.3480	0.1750
Mean			1.3442	0.7223	0.3791	0.4752	0.5630	0.1986

For DNV recommended practice, dropped pipe in Case 1 weights less than 2 ton ($\cong 0.8932\ ton$), thus the angular deviation, α is equal to 15°. While the dropped pipe in Case 2 weights between 2 to 8 ton ($\cong 2.3704\ ton$), thus the angular deviation, α is equal to 9°. Then the mean standard distribution for radius, SD R, is calculated using the lateral deviation, δ. Refer to Equation (2.4).

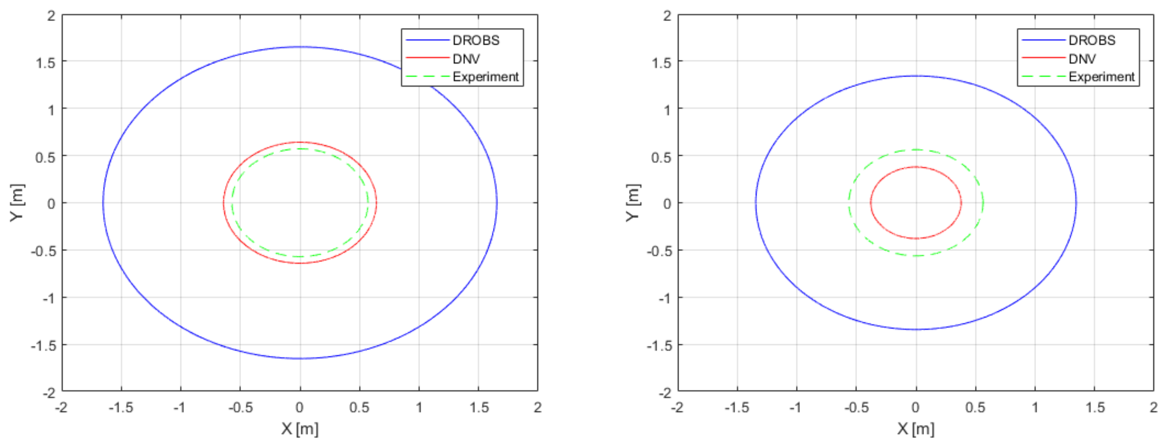

Figure 3.8 Mean radius comparison between DROBS, DNV and experiment (scale 1:16.67)

For the water depth, d of 100 metre full scale, the model is experimented using a 3-metre water depth towing tank. Thus, the scaling factor used is 1:33.33. Model drop height, h is estimated at 1.2 metre above water level. Same sample size is used to simulate DROBS.

Table 3.13 Properties of dropped pipe (scale 1:33.33)

Case		1		2	
Properties	Unit	Original	Scaled	Original	Scaled
Nominal size	inch	8		12	
Length *(L)*	m	8.96	0.2688	8.96	0.2688
Mass density *(ρ_c)*	kg/m	90.44	0.081396	240.00	0.2160
Diameter *(D)*	m	0.2191	0.006573	0.3240	0.00972
Amount needed *(N)*	-	10		10	
Material grade	-	Carbon steel seamless		XS120	

Again here, for the DNV recommended practice, dropped pipe in Case 1 weights less than 2 ton ($\cong 0.8932\ ton$), thus the angular deviation, α is equal to 15°. While the dropped pipe in Case 2 weights between 2 to 8 ton ($\cong 2.3704\ ton$), thus the angular deviation, α is equal to 9°.

Table 3.14 Dropped pipe distribution at tank bed (scale 1:33.33)

Angle *(°)*	No of sample	Case	DROBS		DNV		Experimental Data	
			Mean R *(m)*	SD R *(m)*	Mean R *(m)*	SD R *(m)*	Mean R *(m)*	SD R *(m)*
0	2	1	0.7787	0.4982	0.6414	0.8038	0.1760	0.0770
30	2		1.0038	0.6609	0.6414	0.8038	0.0830	0.0430
45	3		1.1882	0.7228	0.6414	0.8038	0.4430	0.1500
60	3		1.2964	0.6823	0.6414	0.8038	1.0370	0.3300
90	4		1.6259	0.6061	0.6414	0.8038	0.6400	0.2930
Mean			1.1786	0.6341	0.6414	0.8038	0.4758	0.1786
0	2	2	0.5627	0.3603	0.3791	0.4752	0.1270	0.0660
30	2		0.7706	0.5141	0.3791	0.4752	0.3580	0.1330
45	2		0.9220	0.5666	0.3791	0.4752	1.0000	0.2300
60	2		0.9712	0.5483	0.3791	0.4752	1.7860	0.2860
90	2		1.1015	0.4746	0.3791	0.4752	0.4960	0.1170
Mean			0.8656	0.4928	0.3791	0.4752	0.7534	0.1664

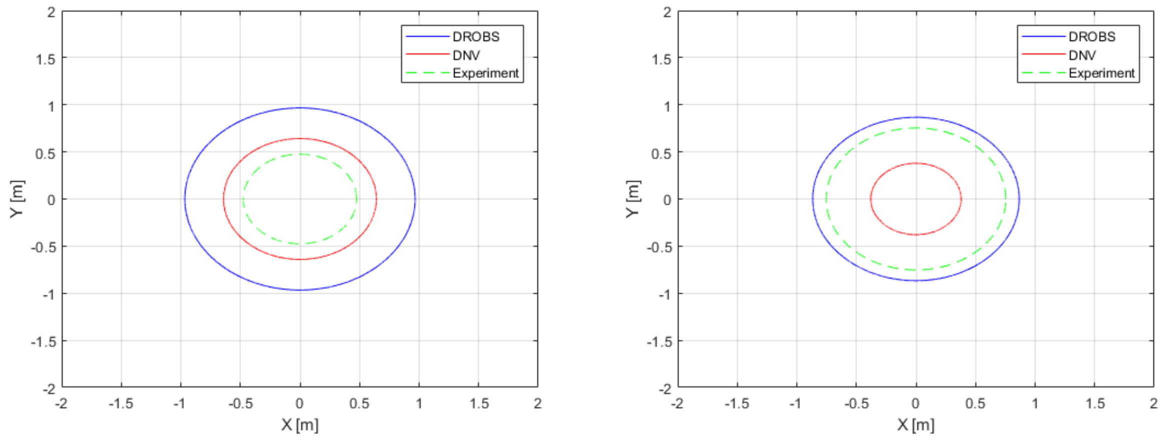

Figure 3.9 Mean radius comparison between DROBS, DNV and experiment (scale 1:33.33)

DROBS result would be considered to give a more accurate mean radius since the sample size used to run the Monte Carlo distribution is 10000 compared to experimental data which is carried out only 10 times. From Figure 3.8, we can see that for both Case 1 (less than 2 tones) and Case 2 (between 2 to 8 tones), the mean radius for DROBS is larger compared to the mean radius for the experimental data. The mean radius for DROBS is consistent regardless the scale ratios differences and it resembles more of that for the experimental data.

Chapter 4

Conclusion

In this thesis, the in-house tools DROBS which is developed to predict the trajectories and landing point of the dropped cylindrical object is modified by imposing the 3D transformation on rotation at z-axis, i.e. water depth. This gave a better interpretation on the landing point distribution of the dropped cylindrical object on the seabed, where it is found to be symmetric around the x- and y-axis. Two cases were then studied: in Case 1, DROBS were used to obtain the mean radius of the landing point distribution at each interval and was used to compare the annual hit frequency obtained by using the recommended practice by DNV, whereas in Case 2, DROBS were used again to compare the mean radius of landing point distribution between DNV and experimental data. The following conclusions were drawn from the results:

I. The annual hit frequency for DROBS is 6.7808e-05 from whereas for DNV, the annual hit frequency is 8.7344e-06. This means that DNV conclude the pipeline protection was adequate but DROBS estimated the annual hit frequency to exceed the acceptance criteria, thus the pipeline protection is not adequate

II. DNV underestimate the mean radius in all the three cases, thus supporting the idea that the protection for the pipeline on the seabed is not adequate

III. Any piping system outside the mean radius of DNV calculation is subjected to risk from dropped objects which can distribute to damage or rupture, thus a modification is should be done to better improve the recommended practice

IV. DROBS result would be considered to give a more accurate mean radius since the sample size used to run the Monte Carlo distribution is 10000 compared to experimental data which is carried out only 10 times

V. DROBS predicted the mean radius to be larger compared to the mean radius for the experimental data but is consistent regardless the scale ratios differences and it resembles more of that for the experimental data.

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Vita

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