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◉ 論　文

Oil Spill Analysis Caused by Offshore Pipeline Damage

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해저 파이프라인 손상에 기인한 기름 유출 분석

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Key Words : Oil Spill(기름 유출), Pipe Buckle(송유관 좌굴), Spill Quantity(유출량)

Abstract

해저면에 설치되 있는 기름 송유관에 손상이 생겨, 송유관 내부에 흐르는 기름이 유출 될 경우 엄청난 환경오염 및 재난을 발생시킨다. 해저 송유관 손상에 의한 기름유출 원인은 여러 가지 경우에 기인한다. 선박의 바닥이 해저면에 끌려 해저 송유관을 손상시키는 경우, 선박의 엥커에 의해 손상되는 경우, 지진에 의해 좌굴 되는 경우, 자유 경간 (Free Span)에 의해 좌굴 되는 경우, 송유관 수리 시 사고로 인한 유출, 송유관의 부식에 기인한 유출 등으로 나누어 질 수 있다. 어떠한 경우이든 해저 파이프 손상시, 유출된 기름의 양을 예측하고 그에 따른 적절한 대비가 필요하다. 본 논문에서는 1차 유출 및 2차 유출을 정의하여 각각의 경우에 유출량 해석 이론을 소개하였다. 또한 이 이론을 실제 경우에 응용하여 해저 송유관 손상에 의해 방출되는 기름량을 손상면적에 따라 계산하였고, 최대 유출량 산출 법을 적용하여 손상 위치에 따른 부분별 유출량 계산법을 소개하였다.

INTRODUCTION

The oil leakage from a pressured offshore pipeline results in a tremendous cost and time to recover it from the environmental damage. Quite often, the damage can be only cured by the nature even some portion of the spilled could be retrieved. The offshore pipeline is designed to carry oil or gas in a hostile environment without failure for more than thirty years in general. The pipeline is protected by an anti-corrosion coating against the corrosive seawater and also covered with weight coating around to stabilize the pipeline against current and wave during the operation life. The high density concrete is commonly used for a weight coating which also protect the pipeline against the dropping objects. In many regions, the trenching or burial of pipe

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line is required to avoid any possible damage from dragging anchors, trawling boards, etc. Also trenching pipeline below the level of seabed can protect it from scouring and mechanical damages. If the pipeline is not buried, the possibility of being anchored increases, and also the large free spans caused by current and wave will result in a collapse of the pipeline.

The pipeline leakage can be divided into two categories; leakage with and without the pressure differential between inside and outside of pipeline. The first category is characterized by a relatively short duration and high leak rates. This category includes time to response and the pressure differential of the two liquids. The spill quantity for this case can be estimated relatively easier than the second case. The second category comprises loss of oil as a result of an exchange flow of oil and seawater, and is characterized by a long duration and relatively low leak rates. The loss of the second category can form a substantial part of the total loss, but can not estimated in a comparably simple way as the losses of the first category[1].

For the second phase spill, the flow interaction between seawater and oil takes place after the pressure differential of the two fluids becomes zero. The interaction occurs mainly due to the difference of the fluid specific gravities. The seawater having a heavier specific gravity intrudes into the pipeline through the damaged area. The spill quantity will depend on the following parameters;

- dimension of the damaged area
- specific gravities of oil and seawater
- viscosities of oil and seawater
- inclination of the pipeline
- pipe diameter

The intruding seawater will trap the inside fluid which is lighter than seawater in the areas that have the upward inclination. Therefore the spill quantity will be limited depending on the location and its inclination. However for the other case where it has downward slope, the seawater will flow down replacing the oil inside the pipeline. The shape of damaged area is not constant nor regular, but in this study the damaged shape is assumed as a circular and the total cut area was calculated. Figure 1 shows a schematic diagram of anchored pipeline. The vector represents the anchor force pulling the pipeline upward. The pipeline damage was investigated with a FEM program to simulate the anchor dragged pipeline. Figure 2 shows the schematic diagram of oil and seawater interaction after a damage.

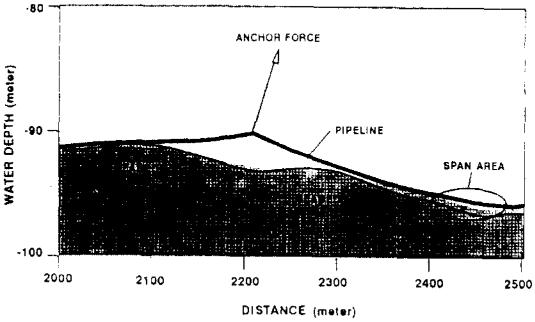

Fig. 1 Anchored Pipeline Simulation with FEM Method

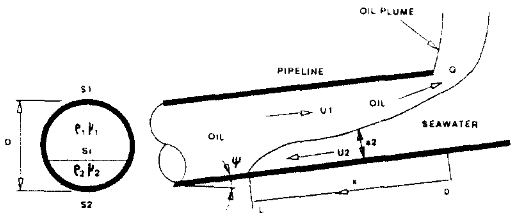

Fig. 2 Oil and Seawater Interaction

SECOND PHASE SPILL ANALYSIS

For the second category spill, the governing methods were the energy conservation and continuity equations. From Kranenburg[1], Schijf and Schonfeld[3], Officer[2] and Stommel and Farmer[4], the numerical model can be derived. From the continuity equation;

$$\frac{dA_2}{dt}+\frac{d}{dx}A_2u_2=0 \qquad (1)$$

$$A_1u_1+A_2u_2=0 \qquad (2)$$

Where, t = time
x = distance from pipe damage
A_1 = upper layer sectional area
A_2 = lower layer sectional area
A = total sectional area
u_1 = upper layer fluid velocity
u_2 = lower layer fluid velocity

Since the total cross sectional area of the pipe is the sum of upper and lower areas:

$$A_1+A_2=A \qquad (3)$$

The equations of the motion for nearly horizontal two-layered flow can be expressed as:

$$\frac{du_1}{dt}+u_1\frac{du_1}{dx}-gI+\frac{1}{\rho_1}\frac{dp}{dx}+\frac{S_1-S_i}{\rho_1A_1}=0 \qquad (4)$$

and

$$\frac{du_2}{dt}+u_2\frac{du_2}{dx}-gI+\frac{1}{\rho_2}\frac{dp}{dx}+\frac{S_i-S_2}{\rho_2}A_2+\varepsilon g\frac{da_2}{dx}=0 \qquad (5)$$

Where, ρ_1, ρ_2 = upper and lower liquid density
a_2 = hight of interface above the bottom of the pipe
ε = $(\rho_2-\rho_1)/\rho_2$
S = shear stress
1 = upper layer
2 = lower layer

The pressure p at the top of the cross section is as below:

$$p=\rho_1\,g\,I\,x+constant \qquad (6)$$

Where, I = tan ψ
ψ = inclined angle of the pipeline

Combing the equations (5) and (4):

$$\frac{d}{dt}(u_1-u_2)+\frac{1}{2}\frac{d}{dx}(u_1^2-u_2^2)+\varepsilon gI-\frac{\varepsilon g}{B}\frac{dA_2}{dx}+\frac{S_1-S_i}{\rho_1A_1}-\frac{S_i-S_2}{\rho_2A_2}=0 \qquad (7)$$

The B is the breadth of the interface and can be written as $B = (dA_2/dx)/(da_2/dx)$. As assumed by Kranenburg[1], in the analysis the existence of a laminar flow on the interface layer is applied. Also assuming that the friction on the interface layer is homogeneous, the equation (8) can be derived:

$$\frac{S_1-S_i}{\rho_1A_1}-\frac{S_i-S_2}{\rho_2A_2}=-\frac{A_2u_2}{A^2}\nu(\theta) \qquad (8)$$

The effective kinematic viscosity can be written as equation (9):

$$\nu(\theta)=3\,(E_1+E_2+E_3)/(E_4) \qquad (9)$$

The functions, E_1, E_2, E_3 and E_4 can be expressed as equations (10) to (13):

$$E_1 = \frac{c_1}{\rho_1}\theta^4 \mu_1^2 \tag{10}$$

$$E_2 = \theta(1-\theta)\left[\theta\frac{c_1(1+\theta)+2}{\rho_1} + (1-\theta)\frac{2+c_2(2-\theta)}{\rho_2}\right]\mu_1\mu_2 \tag{11}$$

$$E_3 = \frac{c_2}{\rho_2}(1-\theta^4)\mu_2^2 \tag{12}$$

$$E_4 = \theta^3(1-\theta)^3[\theta\mu_1 + (1-\theta)\mu_2] \tag{13}$$

From the above equations, θ is the ratio between total area and section 2 area expressed as A_2/A. The coefficient c_1 is $3-2\theta$, c_2 is $1+2\theta$. And the μ_1 and μ_2 are dynamic viscosity.

When there is oil spill caused by a rupture, the integral fluid phase can be considered critical. As introduced by Officer[2] and Stommerl and Farmer[1], the tow layer flow conditions can be applied to Equations (1), (3), (7) and the equation (14) satisfy the conditions:

$$\frac{u_1^2}{\varepsilon g\frac{A_1}{B}} + \frac{u_2^2}{\varepsilon g\frac{A_2}{B}} = 1 \tag{14}$$

Equation (14) can be considered the maximum spill condition and if a_1 is assumed as $D/2$ where D is inner pipe diameter, the maximum spill quantity can be derived as equations (15) and (16):

$$Q = -(A_1 u_1)x = 0 \tag{15}$$

$$Q = \frac{\pi^{\frac{2}{3}}}{32}D^2(\varepsilon gD)^{0.5} = 0.174D^2(\varepsilon gD)^{0.5} \tag{16}$$

As per the Kranenburg and Vegt[1], as the external fluid intrudes into the pipeline through the damage area, considering the contraction of internal fluid and the intrusion process effect, the maximum spill quantity will be less than the estimated quantity by the equation (16). From the lab experiments, the maximum quantity can be expressed as equation (17):

$$Q_m = 0.14D^2(\varepsilon gD)^{0.5} \tag{17}$$

FIRST PHASE SPILL ANALYSIS

Applying the energy conservation law, the energy in the pipeline should be conserved satisfying the following condition:

$$E_1 = E_2 \tag{18}$$

Equation (18) is expanded as:

$$\frac{P_1}{\gamma_1} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma_2} + \frac{V_2^2}{2g} + Z_2 + h_L \tag{19}$$

Having the same datum, Z_1 will be same as Z_2 and assuming that the vertical velocity inside the pipeline is zero, equation (19) can be rewritten as equation (20):

$$\frac{P_1}{\gamma_1} = \frac{P_2}{\gamma_2} + \frac{V_2^2}{2g} + h_L \tag{20}$$

$$V_2 = 2g\left(\frac{P_1}{\rho_2 g\ s.g} - h - h_L\right)^{0.5} \tag{21}$$

The s.g in the equations stands for the specific gravity of fluid, the "h" the water depth of damaged area, "h_L" head loss. The γ_1 is ρ_1 s.g.g, and γ_2 is ρ_2 s.g. g. Therefore, the spill quantity can be derived as:

$$Q = c\ A\ V_2 \tag{22}$$

For the head loss, h_L, the Darcy-Weisbach equation can be applied.

$$h_L = f \frac{L}{D} \frac{V^2}{2g} \tag{23}$$

The coefficient, f is dependent on the roughness of the pipeline and the Reynolds number. For the laminar fluid, the Reynolds number is less than 2,000 and independent on the roughness inside the pipeline. The coefficient can be calculated from a equation, $f = \frac{64}{R}$ and for the Reynolds number is in between 3000 and 100,000, the coefficient can be expressed as $f = \frac{0.316}{R^{0.25}}$.

NUMERICAL EXAMPLE AND MODELING

The numerical analysis was applied to an actual pipeline named "Saratoga Passage" in U. S. A. The Saratoga Passage was 4 km long with the maximum water depth of 85 meter. The pipe grade was x-65 with the outer diameter of 0.9 meter and the wall thickness of 0.938 cm. Considering the wave and current actions, the pipeline was weight coated to be stable under the 100 year return period condition. The specific gravity of the liquid inside the pipeline was 0.89 which was lighter than the surrounding fluid, seawater. The specifications of pipeline and liquid inside the pipeline are summarized in Table 1. The damage situation was modelled that the pipeline was buckled by a ship anchor. Actually, this type of accident has been reported in the past.

The accident associated with ship anchors occurs at a greater frequency than any other cases not only to the subsea pipeline but also to the underwater facilities such as PLEM (pipeline end manifold), well heads, mooring lines, etc. Once a buckling occurs in the pipeline, the inside material will be spilled out through the damaged area. The spill quantity will depend on many factors (specific gravity of inside and outside fluid., pressure gradient, buckled area, inclination of pipeline, pipe size, friction, etc.). However, in this study, the damage area is assumed as a circular shape. Even the shape of the damaged area is not a circular, this analysis still can be applied to any shape of damage as long as the total damage area is known.

Table 1. Pipeline and Fluid Specification

DESCRIPTION	SPECIFICATION
pipe diameter m (in)	0.914(36)
wall thickness cm (in)	2.38(0.94)
max. concrete thickness cm (in)	7.62(3)
max. flow rate (BPD)	605,000
max. pressure kg f/㎠ (psi)	68(975)
receiving temperature (°F)	16-32(60-90)
API grade	27.2
specific gravity at 16℃	0.89
viscosity(c.s.) at 40℃	14.3

The five various diameters of the damage area (2 cm, 4 cm, 6 cm, 8 cm and 10 cm) were applied in the study. The spill duration of up to three day was considered in the modelling. The external force to cause a buckling in the pipeline protected by concrete coating was approximated by a FEM program called "OFFPIPE". The criteria for buckling was set for the case where the SMYS (specified maximum yield strength) percentage exceeds 100 %. The situation where an anchor is pulling the pipeline perpendicular to its axis was simulated. The vertical angle of anchor pull can be estimated once the breaking force of the pipeline is obtained from the model. The breaking load can be divided into horizontal and vertical vectors and the associated vertical angle can be approximated. The program is able to calculate the vertical separation of pipeline and free span caused by the external force vector and also to estimate the stress distribution along the pipeline.

RESULTS FROM NUMERICAL MODELLING

Figures 3 to 5 show the spill quantity estimated by the derived equations for five various damages. From the results, it is noted that as the damage area increases the spill quantity also increase. Figure 4 is a seabed profile of the Saratoga Passage. The width of the Passage was around 4000 m with the maximum water depth of 85 meter.

The sectional spill quantity was estimated as shown in Figure 5 for the modelled pipeline. From this figure, the maximum spill quantity can be approximated for each location along the pipeline. Once the around damage location is found, the maximum amount of spill can be estimated. As mentioned earlier, the inclination of pipeline also affects the spill quantity. For instance, as a damage occurs at 2200 meter in Figure 5, the inside oil will be trapped by the sea water which is heavier than the inside fluid so the spill quantity will be limited. However the spill will increase as the damage location travels to the end of pipeline where the elevation becomes higher. This is explained with the same concept that the heavier seawater will intrude down to the lower part replacing the inside fluid.

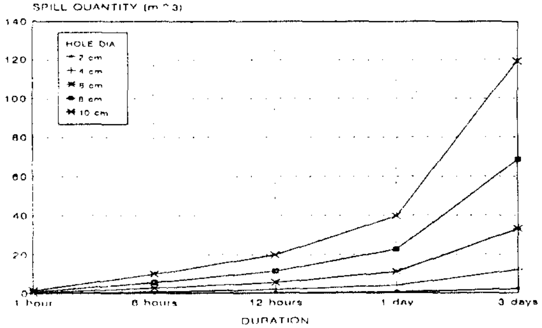

Fig. 3 Static Oil Spill Quantity vs. Duration

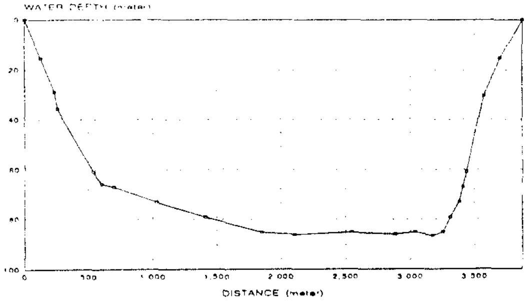

Fig. 4 Saratoga Passage Seabed Profile

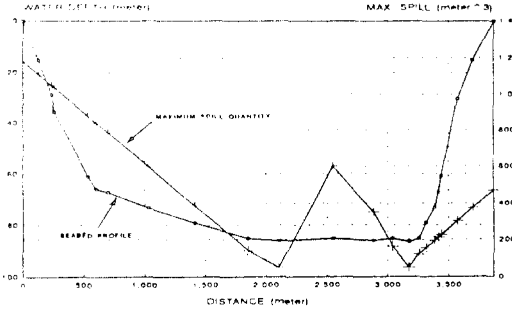

Fig. 5 Maximum Spill Quantity as per Seabed Profile

Figure 6 shows the relationship between time

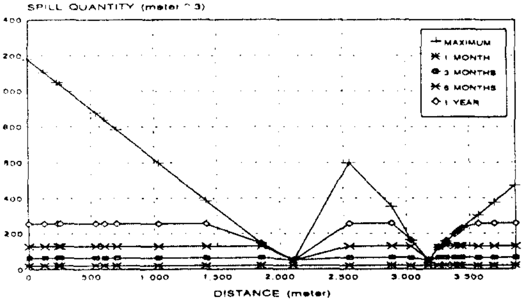

Fig. 6 Oil Spill Quantity at 2cm Hole Diameter

and the maximum spill quantity. The diameter of 2 cm was applied for a study. As depicted in figure 6, after three months, most oil will be escaped in the upwardly inclined section. Figure 7 shows that most oil will be replaced by seawater after three months when the damage diameter is 6 cm.

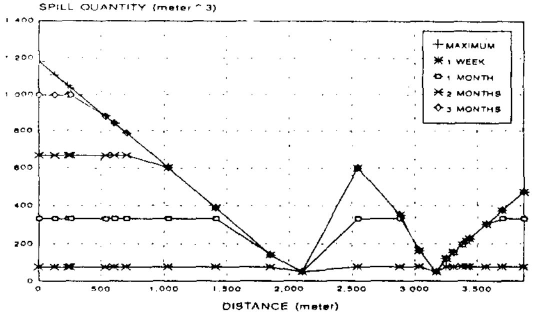

Fig. 7 Oil Spill Quantity at 6cm Hole Diameter

CONCLUSION

The oil spill can be quantified for two different cases; the first phase and the second phase. The first phase occurs during the intial stage after the damage. The driving forces for spill is the pressure gradient of two fluids. After the pressure reaches an equilibrium, the oil spill will be mainly due to the difference of fluid specific gravity and the size of damage. The spill chart can be produced in the region where the subsea pipeline is installed and would give a valuable information to approximate the maximum spill quantity for each location. The duration of spill also can be estimated with the damage size known. It is shown that The maximum spill quantity is heavily dependent on the inclination of location.

The numerical modelling also can be applied as to predict the pulling force to damage the pipeline and the anchor size for that. This estimation would be very important to regulate the vessel size over the region where a pipeline is installed. When a buckling occurs, the size of the anchor and the winch capacity which might be able to cause the damage could be approximated.

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