Sinking Behavior of Pipeline in the Ocean*

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Sinking behavior of a very long pipeline installed on the sea floor which transports the cold water and the resources in the deep sea is analysed.

In the application of the subsurface tow method, the effects of a horizontal tension caused by a barge and a removing rate of buoys along the pipeline upon the maximum landing velocity and the maximum bending moment of the pipeline are examined by the theoretical and numerical analyses.

As a result, it is shown that the maximum landing velocity of the pipeline and the maximum bending moment produced in the pipeline can be decreased by removing the buoys from the shore-side to the offshore-side and by increasing the removing rate and the tension caused at both ends of the pipe.

Key Words : Ocean Engineering, Fluid Mechanics, Ocean Thermal Energy Conversion, Cold Water Pipe, Dynamic Behavior of Pipeline

1. Introduction

In order to transport many kinds of resources to the shore or the cold water to the thermal energy conversion plant on the shore, it is necessary to install a very long pipeline on the sea floor from the shore to the offshore. In this study, the sinking behavior of this sort of pipeline during the installation is analysed.

On this problem, there are a few studies about the stress caused in the pipeline during its installation by a lay barge for the marine pipeline on the sea floor⁽¹⁾⁽³⁾, or by the subsurface tow⁽⁴⁾. However, these studies dealt with the static problems and there is no study treating the dynamic problem.

In the installation of a very long pipeline on the sea floor from the shore to the offshore, the long pipeline which is assembled at the shore is at first pulled out from the shore to the offshore under the sea surface, and then is sunk to the sea floor through loss of its buoyancy. One of the ideas to pull out the pipeline to the installation location is to tow the pipeline with many buoys by the barge, and this is named the subsurface tow method. The method, though economical and convenient using no large crane barge nor lay barge, has been used in few cases because the sinking behavior of the pipeline is not clear.

In this study, the sinking behavior of a very long pipeline with a horizontal tension from the subsurface of the sea to the sea floor when the buoys are removed analysed and the maximum landing velocity and the maximum bending moment produced in the pipeline are examined by an analytical method and a numerical simulation.

2. Nomenclature

- b : Buoyancy per unit length of the buoy in N/m.
- C_D : Fluid drag force coefficient.
- D_p, D_r : Outer diameters of the pipeline and the rope, respectively, in m.
- EI : Bending stiffness of the pipeline in Nm^2 .
- L : Length of the pipeline in m.
- L_1, L_2 : Lengths of the shore-side and the offshore-side ropes, respectively, in m.
- n : Division number of the pipe in the finite difference method.
- T : Horizontal tension in N.
- t : Time variable in s.
- $u_{i,j}$: The finite difference expression of $z(x,t)$ in m.
- V_1, V_2 : Shearing forces at the pipeline ends caused by the shore-side rope and the offshore-side rope, respectively, in N.
- v : Removing rate of the buoys in m/s.
- w_p, w_r : Gravitational forces per unit length of the pipeline and the rope, respectively, including the buoyancy in N/m.
- x : Horizontal position of the pipeline in m.
- $z(x,t)$: Vertical displacement in m.
- α : Equivalent linearization coefficient in m/s.
- ρ_p, ρ_r : Masses per unit length of the pipeline and the rope,

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respectively, including the added mass of the sea water in kg/m.
 ρ_w : Density of the sea water in kg/m³.

3. Analytical Model

3.1 Assumptions

(1) As shown in Fig.1, the pipeline has a uniform cross section, and its motion is two-dimensional in a vertical plane.

(2) The pipeline has a small inclination and it is represented the Euler-Bernoulli's beam. And the horizontal displacement of the pipeline is neglected.

(3) The buoys are distributed uniformly and continuously.

(4) A constant horizontal tension is exerted on the pipeline by the barge.

(5) The ropes affect the pipeline ends as shearing forces V_1, V_2 .

(6) The buoy of the shore-side rope is removed at the same time as the removal of the buoys of the pipeline begins. The buoys of the pipeline are removed continuously from the shore-side to the offshore-side with a constant rate. The buoy of the offshore-side rope is removed at the same time as the removal of the buoys of the pipeline finishes.

(7) Since the pipeline, ropes and buoys have been under the sea surface at first, there is no change of buoyancy during the sinking of the pipeline.

(8) At first, the pipeline is straight and horizontal, and has no initial sinking velocity.

(9) Effects of the sea wave and the ocean current are neglected.

3.2 Equation of motion

From the assumptions, the equation of motion of the pipeline is given as follows:

$$\rho_p \frac{\partial^2 z(x, t)}{\partial t^2} + \frac{1}{2} C_D \rho_w D_p \left| \frac{\partial z(x, t)}{\partial t} \right| \frac{\partial z(x, t)}{\partial t} + EI \frac{\partial^4 z(x, t)}{\partial x^4} - T \frac{\partial^2 z(x, t)}{\partial x^2} - w_p + bH(x - vt) - V_1 \delta(x) - V_2 \delta(x - L) = 0 \quad (1)$$

where $H(\)$ = Heaviside's step function,
 $\delta(\)$ = Dirac's delta function. The first term of Eq.(1) represents the inertia force of the pipeline including the added

mass, the second term represents the drag force, the third term represents the elastic force, the fourth term represents the vertical component of the tension caused by the barge, the fifth term represents the gravitational force including the buoyancy of the pipeline, and the sixth term represents the buoyancy of the buoys which are removed from the shore-side to the offshore-side with a constant rate and $b = w_p$ from the assumption (7). The seventh and eighth terms represent the shearing forces at the pipeline ends caused by the shore-side rope and the offshore-side rope, respectively, which are given by the following expressions:

$$V_1 = \frac{1}{2} w_p L_1 H(t) - T \left(\frac{z(x, t)}{L_1} - \frac{\partial z(x, t)}{\partial x} \right) \Big|_{x=0} - \frac{1}{8} C_D \rho_w D_p L_1 \left| \frac{\partial z(0, t)}{\partial t} \right| \frac{\partial z(0, t)}{\partial t} - \frac{1}{3} \rho_p L_1 \frac{\partial^2 z(0, t)}{\partial t^2} \quad (2)$$

$$V_2 = \frac{1}{2} w_p L_2 H(vt - L) - T \left(\frac{z(x, t)}{L_2} + \frac{\partial z(x, t)}{\partial x} \right) \Big|_{x=L} - \frac{1}{8} C_D \rho_w D_p L_2 \left| \frac{\partial z(L, t)}{\partial t} \right| \frac{\partial z(L, t)}{\partial t} - \frac{1}{3} \rho_p L_2 \frac{\partial^2 z(L, t)}{\partial t^2} \quad (3)$$

where the first terms of Eq.(2) and Eq.(3) represent the gravitational forces including the buoyancies of the ropes, the former acting at $x = 0$ simultaneously with the beginning of the removal of the buoys and the latter acting at $x = L$ simultaneously with the finishing of the removal of the buoys from the assumption (6), the second terms represent the vertical components of the tension which is proportional to a difference in the inclinations between the rope and pipeline end, the third terms represent the drag forces, and the fourth terms represent the inertia forces including the added mass. The coefficients $1/2$, $1/4$ and $1/3$ at the first, third and fourth terms, respectively, are adopted replacing the distributed forces of the ropes by the forces at the pipeline ends on the assumption of a straight rope.

From the assumption (8), the initial conditions are

$$z(x, 0) = 0 \quad (4)$$

$$\frac{\partial z(x, t)}{\partial t} \Big|_{t=0} = 0 \quad (5)$$

and, using the boundary conditions of the beam with free ends, the boundary conditions are represented as follows:

$$\frac{\partial^2 z(x, t)}{\partial x^2} \Big|_{x=0, L} = 0 \quad (6)$$

$$\frac{\partial^3 z(x, t)}{\partial x^3} \Big|_{x=0, L} = 0 \quad (7)$$

4. Analysis by the Equivalent Linearization Technique

Fig.1 Illustration of model

4.1 Linearized equation of motion

To simplify, the nonlinear drag force terms of Eqs. (1), (2) and (3) are linearized using the equivalent linearization coefficient α as follows:

$$\rho_p \frac{\partial^2 z(x, t)}{\partial t^2} + \frac{1}{2} \alpha C_D \rho_w D_p \frac{\partial z(x, t)}{\partial t} + EI \frac{\partial^4 z(x, t)}{\partial x^4} - T \frac{\partial^2 z(x, t)}{\partial x^2} - w_p - bH(x - vt) - V_1 \delta(x) - V_2 \delta(x - L) = 0 \quad (8)$$

$$V_1 = \frac{1}{2} w_r L_1 H(t) - T \left(\frac{z(x, t)}{L_1} - \frac{\partial z(x, t)}{\partial x} \right) \Big|_{x=0} - \frac{1}{6} \alpha C_D \rho_w D_r L_1 \frac{\partial z(0, t)}{\partial t} - \frac{1}{3} \rho_r L_1 \frac{\partial^2 z(0, t)}{\partial t^2} \quad (9)$$

$$V_2 = \frac{1}{2} w_r L_2 H(vt - L) - T \left(\frac{z(x, t)}{L_2} + \frac{\partial z(x, t)}{\partial x} \right) \Big|_{x=L} - \frac{1}{6} \alpha C_D \rho_w D_r L_2 \frac{\partial z(L, t)}{\partial t} - \frac{1}{3} \rho_r L_2 \frac{\partial^2 z(L, t)}{\partial t^2} \quad (10)$$

4.2 Equivalent linearization coefficient α

To minimize the mean square error between the nonlinear drag force and the linearized drag force, the equivalent linearization coefficient is decided as follows:

$$\alpha = \int_0^{t_1} \left(\frac{\partial z(x, t)}{\partial t} \right)^3 dt / \int_0^{t_1} \left(\frac{\partial z(x, t)}{\partial t} \right)^2 dt \quad (11)$$

where t_1 = estimated time required for the pipeline to sink.

To simplify the computation, $z(x, t)$ in Eq. (11) is approximated by $z_e(t)$, which is a displacement of an equivalent mass point to the pipeline as shown in Fig. 2. The equation of $z_e(t)$ is reduced to

$$\left\{ \rho_p L + \frac{1}{3} \rho_r (L_1 + L_2) \right\} \frac{d^2 z_e(t)}{dt^2} + \frac{1}{2} \alpha C_D \rho_w \left\{ D_r L + \frac{1}{3} D_r (L_1 + L_2) \right\} \frac{dz_e(t)}{dt} + T \left(\frac{1}{L/2 + L_1} + \frac{1}{L/2 + L_2} \right) z_e(t) = w_p \{ L - (L - vt) H(L - vt) \} + \frac{1}{2} w_r (L_1 + L_2) \quad (12)$$

and the initial conditions are

$$z_e(0) = 0 \quad (13)$$

$$\frac{dz_e(t)}{dt} \Big|_{t=0} = 0 \quad (14)$$

Fig. 2 Model of approximation to a single-mass-point system

Eq. (12) is able to be solved by distinguishing the external force at $t \leq L/v$ from that at $L/v < t$ and by using a particular solution $z_e(t) = \beta_{e1}t + \beta_{e2}$ (β_{e1} and β_{e2} are arbitrary constants). Substituting $z_e(t)$, which is a function of α , into Eq. (11), a transcendental equation of α is obtained. And α is calculated by Newton's method.

4.3 Analytical method

Simultaneous ordinary nonhomogeneous equations are derived by the mode expansion of Eq. (8) using the eigenfunctions of a parallel motion and a rotational motion

$$1 \quad (15)$$

$$(x/L) - 0.5 \quad (16)$$

and the eigenfunctions of a simple beam with free ends,

$$\begin{aligned} & \sin(\lambda_j \frac{x}{L}) + A_j \cos(\lambda_j \frac{x}{L}) \\ & + \sinh(\lambda_j \frac{x}{L}) + A_j \cosh(\lambda_j \frac{x}{L}) \\ & (j=1, 2, \dots) \end{aligned} \quad (17)$$

For a simple pipeline shape, the eigenfunctions over the 4th elastic mode are neglected. Then, an eigenvalue problem of the simultaneous equations, which are constituted of five equations of two rigid modes and three elastic modes ($j \leq 3$), is solved. And a particular solution is obtained by determining the unknown constant α_{jk} , β_{jk} , γ_{jk} of the following equation:

$$\begin{aligned} & \alpha_{j1} + \alpha_{j2} \frac{v}{L} + \alpha_{j3} \left(t \frac{v}{L} \right)^2 \\ & + \beta_{j1} \sin \left(\lambda_1 t \frac{v}{L} \right) + \beta_{j4} \cos \left(\lambda_1 t \frac{v}{L} \right) \\ & + \gamma_{j1} \sinh \left(\lambda_1 t \frac{v}{L} \right) + \gamma_{j4} \cosh \left(\lambda_1 t \frac{v}{L} \right) \\ & + \beta_{j2} \sin \left(\lambda_2 t \frac{v}{L} \right) + \beta_{j5} \cos \left(\lambda_2 t \frac{v}{L} \right) \\ & + \gamma_{j2} \sinh \left(\lambda_2 t \frac{v}{L} \right) + \gamma_{j5} \cosh \left(\lambda_2 t \frac{v}{L} \right) \\ & + \beta_{j3} \sin \left(\lambda_3 t \frac{v}{L} \right) + \beta_{j6} \cos \left(\lambda_3 t \frac{v}{L} \right) \\ & + \gamma_{j3} \sinh \left(\lambda_3 t \frac{v}{L} \right) + \gamma_{j6} \cosh \left(\lambda_3 t \frac{v}{L} \right) \end{aligned} \quad (18)$$

To solve the above equation, the external force for $t \leq L/v$ should be distinguished from that for $L/v < t$, where L/v expresses the time required to remove all buoys. So a general solution is obtained by using the initial conditions, and an analytical solution of the equivalently linearized equations (8), (9) and (10) is found by the inverse mode expansion.

4.4 Analytical solution

As a numerical example, the following data of the Tokunoshima ocean thermal energy conversion test plant are used:

Length of the pipeline $L = 1500$ m
 Outer diameter of the pipeline $D_p = 0.55$ m
 Gravitational force per unit length of the pipeline including the buoyancy $w_p = 147$ N/m
 Mass per unit length of the pipeline including the added mass $\rho_p = 503$ kg/m
 Bending stiffness of the pipeline $EI = 1.40 \times 10^6$ Nm²
 Horizontal tension $T = 1.96 \times 10^5$ N
 Removing rate of the buoys $v = 5.0$ m/s
 Length of the shore-side rope $L_1 = 150$ m
 Length of the offshore-side rope $L_2 = 800$ m
 Diameter of the rope $D_r = 0.03$ m
 Gravitational force per unit length of the rope including the buoyancy $w_r = 39.2$ N/m
 Mass per unit length of the rope including the added mass $\rho_r = 5.45$ kg/m
 Density of the sea water $\rho_w = 1030$ kg/m³
 Fluid drag force coefficient $C_D = 1.1$

Since the pipeline is sinking without vibration, the eigenvalues of the equation (12), which is used for finding the equivalent linearization coefficient α , should be negative real numbers. In the case of a large tension and a small mass of the pipeline (in this example, the cold water pipe is made of hard polyethylene), it is found that the smaller eigenvalue is small enough to be neglected to simplify the calculation of Eq.(11). So, assuming the estimated time required for the pipeline to sink t_1 is 450 sec, the equivalent linearization coefficient α is 0.124. And by using this value, the analytical solution is calculated and shown as a broken line in Fig.4.

4.5 The case where the buoys are removed from the offshore-side

Although the buoys are generally removed from the shallow shore-side of the pipeline to assure the pipeline installation location, the case where the buoys are removed from the offshore-side is also examined by the same method to

Fig.3 Pipeline end model in finite difference method

compare with the case where the buoys are removed from the shore-side.

Since the x axis in the latter case is inverse to that in the former case, an analytical solution is able to be obtained by exchanging the length of the shore-side rope and the length of the offshore-side rope with each other and by locating the origin of x axis at the offshore-side pipeline end. The result is shown as a broken line in Fig.5.

5. Finite Difference Solution

5.1 Approximation of the equation of motion

The equations of motion (1), (2) and (3) are nonlinear equations. To obtain the solution to these nonlinear equations, the finite difference method is applied. Since the cold water pipe in the previous example is made of hard polyethylene, it is assumed that the elastic term of the equation of motion (1) is negligibly small. To confirm this assumption, each term is compared assuming the reference values $z(x, t) = D_p$, $x = L$, $C_D = 1$, $\partial^2 z(x, t) / \partial t^2 = g$ (g = gravitational acceleration). Each term is given as follows:

$$\rho_p \frac{\partial^2 z(x, t)}{\partial t^2} = 4.9 \times 10^3 \text{ N/m} \quad (19)$$

$$\frac{1}{2} C_D \rho_w D_p \left(\frac{\partial z(x, t)}{\partial t} \right)^2 = 1.5 \times 10^3 \text{ N/m} \quad (20)$$

$$EI \frac{\partial^4 z(x, t)}{\partial x^4} = 1.5 \times 10^{-7} \text{ N/m} \quad (21)$$

$$T \frac{\partial^2 z(x, t)}{\partial x^2} = 4.8 \times 10^{-2} \text{ N/m} \quad (22)$$

where, Eqs.(19), (20) are differentiations on the time and Eqs.(21), (22) are differentiations on the space. Although they are unable to be compared with each other, Eqs.(19), (20) have the same order with each other, while Eqs.(21), (22) are fairly different from each other. So it is found that the effect of the tension is fairly larger than that of the elasticity. In the application of the finite difference method, the elasticity term of Eq.(1) is neglected for simplicity.

5.2 Finite difference method

To obtain the finite difference solution to the approximated equation of motion, the variable is changed as follows:

$$z(x, t) = u_{i,j} \quad (0 \leq i \leq n, 0 \leq j) \quad (23)$$

where, i is an integer corresponding to x , j is an integer corresponding to t , and Δx , Δt are finite difference intervals of space and time, respectively.

$u_{-1,j}$, $u_{n+1,j}$ are assumed to be vertical displacements near the pipeline ends as shown in Fig.3, that is

$$u_{-1,j} = (1 - \Delta x / L_1) u_{0,j} \quad (24)$$

$$u_{n+1,j} = (1 - \Delta x / L_2) u_{n,j} \quad (25)$$

and they are applied to represent the tension terms with the boundary conditions

as follows:

$$T \frac{\partial^2 z(x, t)}{\partial x^2} \Big|_{x=0} - T \left(\frac{z(x, t)}{L_1} - \frac{\partial z(x, t)}{\partial x} \right) \delta(x) \Big|_{x=0} \\ = T \frac{u_{1,j} - (1 + \Delta t/L_1) u_{0,j}}{\Delta t^2} \dots \dots \dots (26)$$

$$T \frac{\partial^2 z(x, t)}{\partial x^2} \Big|_{x=L} \\ - T \left(\frac{z(x, t)}{L_2} + \frac{\partial z(x, t)}{\partial x} \right) \delta(x-L) \Big|_{x=L} \\ = T \frac{u_{n,j} - (1 + \Delta t/L_2) u_{n,j}}{\Delta t^2} \dots \dots \dots (27)$$

By substituting Eq.(23), the center finite difference formula, Eqs.(26) and (27) into the approximated equation of motion, and by rearranging these expressions, three kinds of quadratic equations of $u_{0,j+1}$, $u_{i,j+1}$ ($1 \leq i \leq n-1$), $u_{n,j+1}$ are obtained. The finite difference solution is solved by using the initial conditions $u_{i,0} = 0$, $u_{i,-1} = 0$.

5.3 Finite difference solution

Since the pipeline is sinking at the beginning of the removal of the buoys from the assumption (8), the positive one of two finite difference solutions in the initial stage is selected. This finite difference solution is shown as a solid line in Fig.4 for the comparison with the analytical solution. This solution is calculated for the division number of the pipeline $n = 100$ and $\Delta t/\Delta L = 1/4v$, which are determined by trial and error to stabilize the solution and to minimize the calculation time. In the case of twice the tension and half the removing rate of the buoys, the solution is calculated for $\Delta t/\Delta L = 1/8v$ to stabilize the solution.

When the center finite differences of the sinking velocity in the fluid drag force terms are replaced by the backward finite differences, the amount of calculation increases for the stability of solution.

5.4 The case where the buoys are removed from the offshore-side

Fig.4 Sinking behavior of the pipeline (buoys are removed from the shore-side)
- - - : analytical solution
— : finite difference solution

In the case where the buoys are removed from the offshore-side, the equation of motion is derived by replacing the step function in the buoyancy of buoy term of Eq.(1) by $H(L-x-vt)$, and by replacing the step functions in the gravitational force terms in Eqs.(2), (3) by $H(vt-L)$, $H(t)$ respectively for the opposite removing direction of the buoys. The finite difference solution of this case can be found by the same method and is shown as a solid line in Fig.5.

5.5 Finite difference solution for landing

The landing of the pipeline on the sea floor is examined on the following assumptions:

(1) An inclination of the sea floor is $1/5$.

(2) At the landing on the sea floor, the pipeline does not rebound and does not slide horizontally.

According to these assumptions, when the finite difference solution gives a vertical displacement under the sea floor, the solution $u_{i,j+1}$ is replaced by the depth of the sea floor. The solution for the landing on the sea floor in the case where the buoys are removed from the shore-side is shown in Fig.6, and the one in the case where the buoys are removed from the offshore-side is shown in Fig.7.

The solutions under twice the tension, half the tension, twice the removing rate of the buoys and half the removing rate of the buoys were calculated by the same method.

6. Considerations

From Figs.4 and 5, it is seen that the analytical solution is roughly in good agreement with the finite difference solution. Therefore, the solution for the landing, which is not obtained by the analytical method, can be obtained by the finite difference method.

In the analytical solution, during

Fig.5 Sinking behavior of the pipeline (buoys are removed from the offshore-side)
- - - : analytical solution
— : finite difference solution

the slow pipeline sinking, i.e., just after the beginning of the removal of the buoys, the equivalently linearized fluid drag force is over-estimated, but during the fast pipeline sinking, i.e., after the long elapsed time of the pipeline sinking, the equivalently linearized fluid drag force is under-estimated.

In the finite difference solution, since the elasticity of the pipeline is neglected, the curvature of the pipeline is larger and the inclinations of the pipeline ends are the same as those of the corresponding ropes after removing all buoys.

In the case of a constant tension, the pipeline sinks till the vertical component of the gravitational force in the sea water is balanced with that of the tension. After arriving the balanced state, the pipeline begins free vibration. In the practical installation, the offshore-side rope is slowly pulled out from the barge to complete the landing. Since the landing velocity and the bending moment can be controlled by pulling out the rope, the maximum landing velocity and the maximum bending moment, which cause damage to the pipeline, appear before pulling out the rope. Therefore, this study focuses on the motion of the pipeline before pulling out the rope.

The landing of the pipeline starts from the shore-side pipeline end unless the buoys are removed from the offshore-side with a small removing rate. And the maximum landing velocity appears at the first landing point of the pipeline in all cases.

From Figs.6 and 7, it is seen that the first landing point of the pipeline is the same shore-side pipeline end in both cases where the buoys are removed from the shore-side and from the offshore-side. In the case where the buoys are removed from the offshore-side, the first landing comes

later and the last landing comes earlier than in the case where the buoys are removed from the shore-side, since the sinking shape of the pipeline is similar to the shape of the sea floor in the former case. The maximum landing velocity and the maximum bending moment in the former case are larger than those in the latter case, since the shore-side pipeline end lands at first after the buoy at the shore-side pipeline end is removed at last and the pipeline end is accelerated.

The maximum bending moment appears near the pipeline end just after the beginning of the removal of the buoys from the fact that the gravitational force of the rope acts near the buoyancy of the buoy, or appears near the first landing point just after the beginning of the pipeline landing due to a moment change by the landing. And the maximum bending moment appears at the offshore-side pipeline end just after removing the buoy at the offshore-side pipeline end in the case of a heavy rope.

When the maximum bending moment is occurs just after the beginning of the removal of the buoys, the landing velocity is relatively small, and the maximum bending moment in this case is smaller than in the other cases. Therefore, one of the effective methods to suppress the maximum bending moment is a suppression of the landing velocity.

In the cold water pipe of the numerical example, the maximum bending moment in the case where the buoys are removed from the shore-side (in the case of Fig.6) is 1940 Nm , and the modulus of section is $5.18 \times 10^{-3} \text{ m}^3$, therefore, the maximum bending stress is $3.75 \times 10^5 \text{ N/m}^2$. Since the yield stress of hard polyethylene is 280 kgf/cm^2 from JIS-K-6761, the pipeline is found strong enough. And the maximum landing velocity in this case is 0.147 m/s .

Fig.6 Sinking behavior of the pipeline including the landing (the finite difference solution) (buoys are removed from the shore-side)

Fig.7 Sinking behavior of the pipeline including the landing (the finite difference solution) (buoys are removed from the offshore-side)

The landing of the pipeline comes late and the deformation of the pipeline becomes larger as the removing rate of the buoys v decreases. And in the case where the buoys are removed from the offshore-side, the first landing point is not the shore-side pipeline end, but the mid-pipeline due to a faster sinking of the portion of the pipeline where the buoys are removed. And in this case, the maximum landing velocity is very large, since the first landing point of the pipeline is considerably accelerated by the long sinking distance.

Meanwhile, the landing becomes fast and the deformation of the pipeline becomes small as the removing rate of the buoys v increases, causing the maximum bending moment to decrease.

As the tension T decreases, the landing becomes fast, but the maximum bending moment increases for a large landing velocity.

Meanwhile, as the tension T increases, the maximum landing velocity and the maximum bending moment decrease, but the landing becomes late.

7. Conclusions

It has been made clear that the maximum landing velocity of the pipeline and the maximum bending moment produced in the pipeline can be made small by removing

the buoys from the shore-side to the offshore-side and by increasing the removing rate and the tension caused at both ends of the pipe.

But the removing rate of the buoys has an upper limit due to the fact that the barge is used to remove the buoys. Further, the pipeline is strongly affected by the sea wave and the ocean current because of a slow sinking of the pipeline caused under excessive tension. Therefore, it is necessary to work out a suitable tension.

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