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Paper No. 349. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

NUMERICAL STUDY ON THE EFFECTIVENESS OF STABILIZING TECHNIQUES OF OFFSHORE PIPELINES AGAINST LIQUEFACTION

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ABSTRACT

Designing an offshore pipeline for installation in an area subjected to earthquake activity requires an investigation of potential effects of seismic shocks. If the seabed or the filling material along a pipeline route consists of cohesionless soils likely to liquefy under the influence of seismic shocks, a pipeline buried in such soils may lose stability and float to the surface of the seabed. The present paper numerically studies the effectiveness of three types of stabilization techniques: 1) Anchoring the pipeline, 2) Increasing the weight of the pipeline, and 3) A new stabilization technique which is proposed by the authors. A brief explanation is also given of a pipe burying strategy in a project based on the results of the numerical method.

KEYWORDS

offshore, pipeline, liquefaction, stabilization, FEM, gravel, anchor, concrete-coating

INTRODUCTION

With the development of industries based on waterfronts, a number of offshore pipelines have been constructed in Japan to serve as efficient transportation means for oils, water and gas. It is usual that the pipelines are first installed in an excavated trench in the sea bottom, and then buried in sand at a depth of 2 to 3 meters to reduce the effects of anchor loading from ships and wave loadings (see Fig.1). It is likely that the sand used to bury the pipelines (hereafter, to be referred to as surrounding ground) liquefies under the influence of seismic shocks, since both the effective overburden pressure and the relative density are low. Then, two engineering problems arise: one is to evaluate the effects of the liquefaction on the offshore pipelines; and the other is to implement effective and economical countermeasures.

A literature survey suggests that the following are the potential factors affecting the safety of offshore pipelines:

(1) Irregular ground motions under incomplete liquefaction where the excess pore water pressure is increasing (Kitaura and Miyajima, 1983; Oishi and Sekiguchi, 1983; Sekiguchi and Oishi, 1987, 1992);
(2) Buoyancy due to completely liquefied soils (JSCE, 1969; Sasaki *et al.*, 1981);
(3) Ground settlements due to the dissipation of pore water pressure (Kitaura and Miyajima, 1983; Oishi and Sekiguchi, 1983; Sekiguchi and Oishi, 1987, 1992);

(4) Liquefaction-induced lateral ground movements (Morgenstern, 1976; Swanson and Jones, 1982; Hamada *et al.*, 1986a, b).

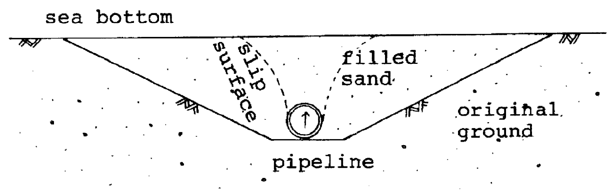


Fig.1. The Cross-section of offshore pipeline.

Among the various factors mentioned above, buoyancy may be the most important factor for offshore pipelines since the structure is simple and the strength is relatively high. To evaluate the effect of buoyancy on offshore pipelines, Minami *et al.*(1983) proposed a numerical model, and performed extensive numerical studies (Kiyomiya and Yokota, 1984; Kiyomiya and Minami, 1988). One of the authors experimentally studied the effectiveness of two stabilization methods against buoyancy during the liquefaction: anchoring and/or weighting the pipelines (Oishi and Sekiguchi, 1983; Sekiguchi and Oishi, 1987, 1992).

This paper numerically studies the effectiveness of these traditional stabilization methods, and a new stabilization method proposed by the authors (Oishi and Sekiguchi, 1985), using a numerical model proposed by Minami *et al.*(1983). A pipe burying strategy undertaken in the Kushikino Project, one of the national underground crude oil storage projects, is summarized, whereby the numerical method played an important role. Part of this paper was published in Japanese (Oishi and Sekiguchi, 1985; Sekiguchi and Oishi, 1987).

NUMERICAL MODELLING

To simulate the behavior of pipelines due to buoyancy during the liquefaction, numerical modelling proposed by Minami *et al.*(1983) is used; which is summarized as follows. Figure 2 shows the illustration of liquefied and non-liquefied zones along a buried offshore pipeline. It is assumed that: 1) in the non-liquefied zone, the surrounding ground support the pipeline such that it does not float to the sea bottom; and that 2) in the liquefied zone, an upward force (*i.e.* buoyancy) is applied to the pipeline due to the difference of the unit weight of the pipeline and the liquefied soil. To simulate the behavior of the pipeline, a beam on Winkler foundation model shown in Fig.3 is employed. In the figure, the displacement-force characteristics of "K_s *spring*" and "K_f *spring*" are also shown; and the explanation for them is given in the following paragraphs.

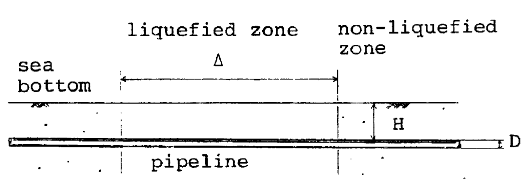


Fig.2. Illustration of non-liquefied and liquefied zones.

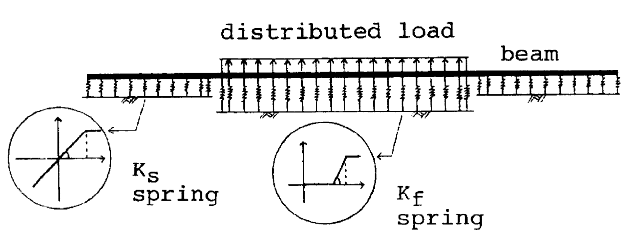


Fig.3. Finite element model for numerical simulation.

The "K_s *spring*" is employed in the non-liquefied zone, and represents the reaction characteristics of the surrounding ground. The maximum reaction may be estimated by the following equations (Vesic, 1971): $P = q_o D_o + W$; $q_o = CF_c + \gamma' HF_q$,where q_o = ultimate breakout pressure; D_o = outer diameter of pipeline; W, γ' = submerged unit weight of pipeline and surrounding ground, H = buried depth of pipeline; C, ϕ = cohesion and frictional angle of the surrounding ground; F_c, F_q = breakout coefficient.

The "K_f *spring*" is employed in the liquefied zone, and is introduced to take into account the effect of the difference of the buoyancy acting on the pipeline under and above the seabed. The upward force acting on the pipeline can be calculated by the following equation when the pipeline is located at the liquefied ground/sea water boundary: $Q = A_l(\gamma_s - \gamma_u) + A_w(\gamma_w - \gamma_u)$, where γ_w = unit weight of sea water; γ_s = unit weight of liquefied surrounding ground; γ_u = unit weight of pipeline; A_l, A_w = cross sectional area of pipeline below/above the sea bottom level; A = total cross sectional area of pipeline ($A = A_l + A_w$). Thus, the displacement-force characteristics of the "K_f *spring*" should be represented by the dotted line in FIg.4; however, linear approximation shown by the solid line is used in the analysis.

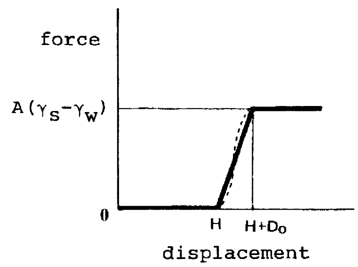


Fig.4. The characteristics of K_f *spring*.

To solve the problem described, a computer program FLOAT/3D was developed which uses the incremental solution scheme for the non-linear analysis, and the wave-front method for solving equations.

EFFECT OF BUOYANCY TO OFFSHORE PIPELINES

To study the effect of buoyancy on offshore pipelines, a series of parameter studies has been performed employing the numerical model explained in the previous section. Table 1 summarizes the dimensions and sectional properties of pipelines studied; pipe types "10B", "20B" and "40B" are for oil transportation, and "20B*" is for gas transportation.

Table 1. Dimensions and sectional properties of offshore pipelines used for calculation

Pipe Type		10B	20B	40B	20B*
Diameter	D (cm)	26.74	50.8	101.6	50.8
Wall thickness	t (cm)	0.93	1.27	1.6	1.8
Coating thickness	t_c (cm)	1.73	3.33	7.57	4.26
Outer diameter	D_o (cm)	30.2	57.5	116.7	59.3
Sectional area	(cm^2)	75.4	197.6	502.7	277.1
Total sectional area	A (cm^2)	716.3	2592.2	10701.8	2762.8
Moment of inertia	I (cm^2)	6290	606×10^2	628×10^3	833×10^2
Section modulus	Z (cm^3)	470	2390	124×10^2	3280
Weight per length	(gf/cm)	592	1550	3950	2175
Unit weight	γ_u (gf/cm^3)	1.9	1.7	1.7	1.4

For the space limitation, attention is paid to the effect of the liquefied zone lengths, Δ. Figure 5 shows the calculated displacement and bending moment of the "40B" pipeline for various lengths of liquefied zones. The spring constant for the *"K_s spring"* was determined assuming that the unit reaction coefficient is 1.0 kgf/cm^3 (9.81 MN/m^3). It was also assumed that the buried depth was 3 m, and that the unit weight of the liquefied soil was 2.0 gf/cm^3 (19.6 kN/m^3). From figures, it may be found that: 1) maximum displacement is observed at the center of the liquefied zones; and that 2) the maximum bending moment is observed near the boundary between the liquefied and non-liquefied zones.

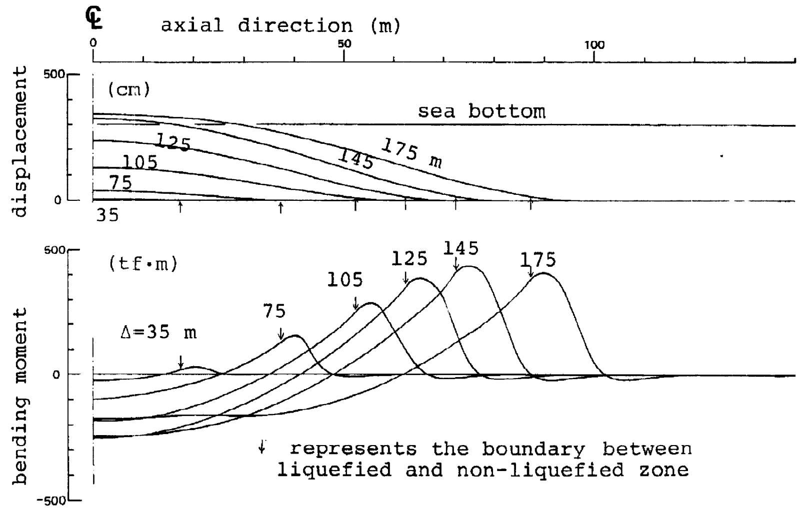


Fig.5. Displacement and bending moment calculated for various lengths of liquefied zone (40B, H=3m, γ_s=2.0 gf/cm^3, γ_u=1.7 gf/cm^3).

Figure 6(a) and (b) show the relationships between the liquefied zone lengths, maximum displacements and maximum bending stress for four types of pipelines. From these figures the following important observations can be made: 1) the maximum displacements increase rapidly with the increase in the liquefied zone lengths up to a limiting liquefied zone length, whereby part of the pipeline appears above the sea bottom; 2) the peak values in the maximum bending stresses are found at these limiting liquefied zone lengths.

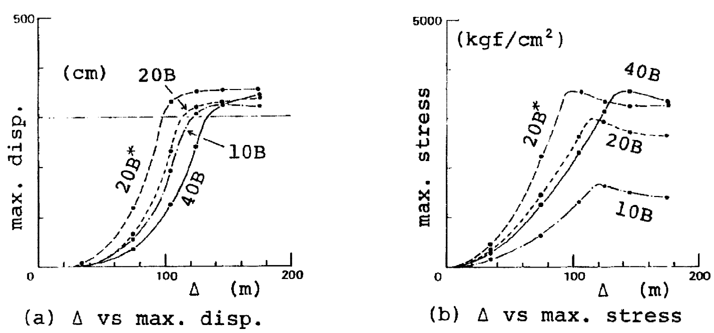
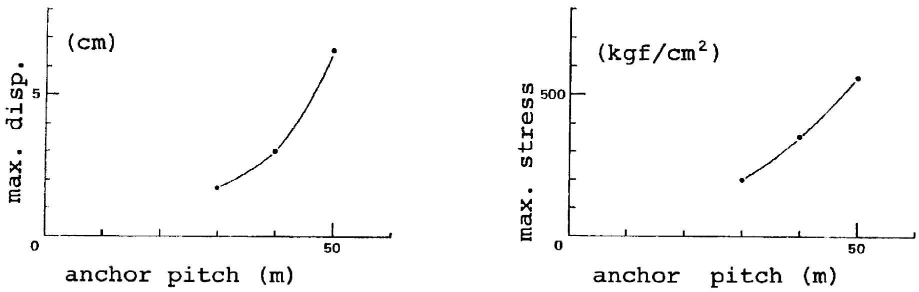


Fig.6. The relationships between the liquefied zone length, maximum displacement and maximum bending stress (H=3m, γ_s=2.0 gf/cm^3).

EVALUATION OF TRADITIONAL STABILIZATION TECHNIQUES

To study the effectiveness of *"Anchoring the Pipeline"*, a series of parameter studies was performed on the "40B" pipeline, assuming that the liquefied zone length was 175 m, and that the unit weight of the liquefied soil was 2.0 gf/cm^3. The effect of anchoring was modelled by introducing elastic springs at the anchor points. Fig. 7(a) and (b) show the relationships between the anchor pitches, maximum displacement and maximum bending stress. From these figures, it is recognized that anchoring can reduce the maximum displacements and bending stresses to very low levels compared with those without countermeasures (Fig.6). The cost effectiveness of the method usually greatly depends on the geologic conditions of the site.

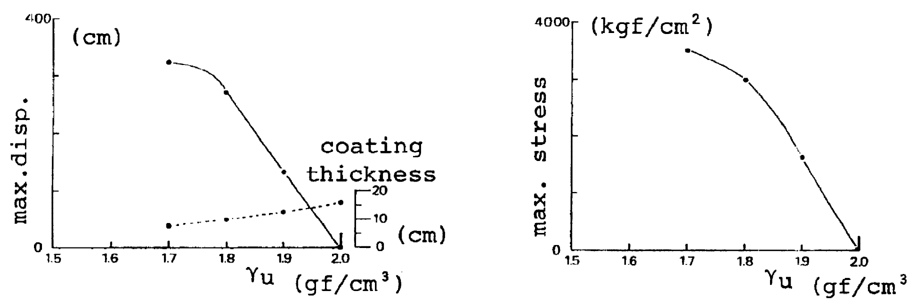


(a) anchor pitch vs max. disp.

(b) anchor pitch vs max. stress

Fig.7. The relationships between the anchor pitches, maximum displacement and maximum bending stress (40B, H=3m, γ_s=2.0 gf/cm^3, γ_u=1.7 gf/cm^3, Δ=175 m).

To study the effectiveness of *"Weighting the Pipeline"*, for example by concrete-coating, the "40B" pipeline was analyzed assuming that the liquefied zone length was 145 m, and that the unit weight of the liquefied soil was 2.0 gf/cm^3. The relationships between the unit weight of the pipeline, maximum displacement and maximum bending stress are shown in Fig.8(a) and (b). It may be seen from these figures that weighting can reduce the effects of buoyancy; however, it should be noted that the concrete-coating has to be thickened to an impractical level in some cases.



(a) γ_u vs max. disp.

(b) γ_u vs max. stress

Fig.8. The relationships between the unit weight of offshore pipeline, maximum displacement and maximum bending stress (40B, H=3m, γ_s=2.0 gf/cm^3, Δ=145 m).

A NEW STABILIZATION TECHNIQUE

One of the most efficient methods for stabilizing offshore pipelines against liquefaction may be burying the pipeline with geologic materials which are not likely to liquefy (for example, gravel). However, the cost of such material is usually much higher than that of sand. Figure 9 illustrates a new stabilization method proposed by the authors. As shown in the figure, non-liquefied zones are located at a certain pitch along the pipeline, and are to be constructed using geologic materials which are not likely to liquefy.

The length of the liquefied zone can be determined from acceptable maximum displacement and/or stresses of the pipeline by using the results of numerical calculation such as those shown in Fig.6(a) and (b). The minimum required length of the non-liquefied zone, Δ_g, can be determined by equating the total buoyancy acting in a liquefied zone and the total soil reaction in a non-liquefied zone (*i.e.*, $\Delta_g = A(\gamma_s-\gamma_u)\Delta/P$). However, the calculated length by this equation is usually small, and other factors such as construction accuracy and stability of the zone under seismic shocks should be taken into account.

The effectiveness of the proposed method will be explained based on the parameter study on the "40B" pipeline. Assuming that the acceptable bending stress of the pipe is 1500 kgf/cm^2 (147 MPa), then the liquefied zone length may be determined as 78 m from Fig.6 (b). Figure 10 shows the distribution of bending moment for various non-liquefied zone lengths; this figure suggests that any non-liquefaction zone lengths analyzed are acceptable from the view point of pipe stresses.

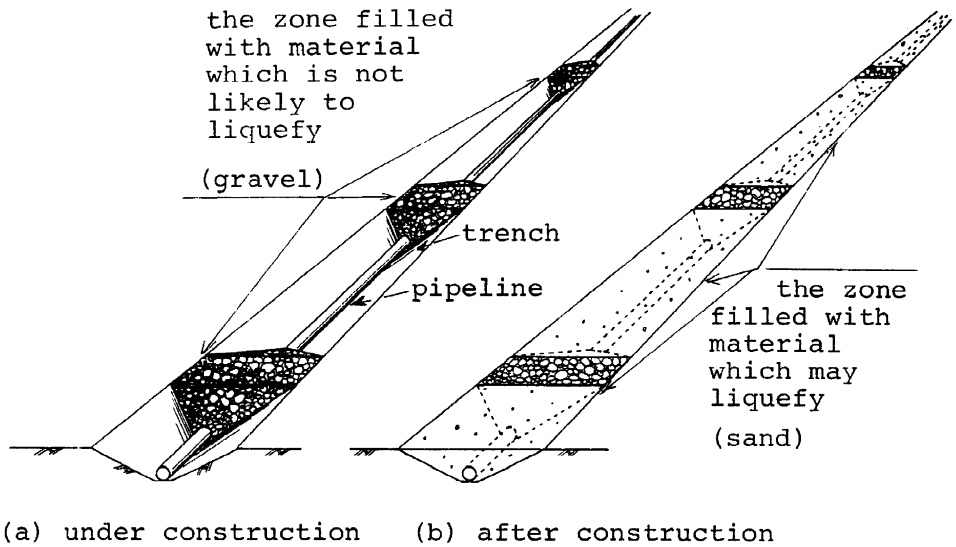


Fig.9. A new stabilization technique of offshore pipeline against liquefaction.

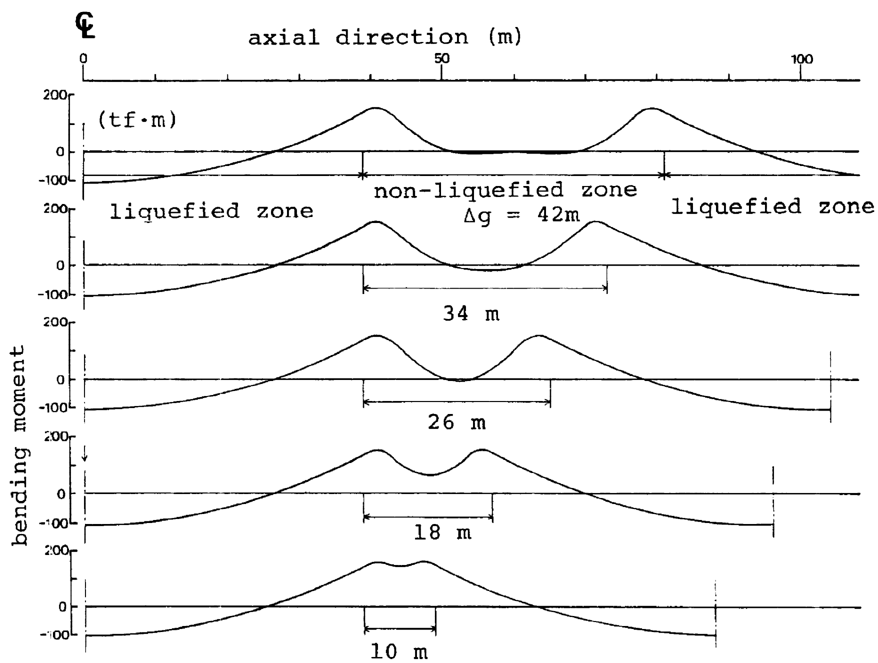


Fig.10. Bending moment calculated for various lengths of non-liquefied zone (40B, H=3m, γ_s=2.0 gf/cm^3, γ_u=1.7 gf/cm^3, Δ=78 m).

A PIPE BURYING STRATEGY IN THE KUSHIKINO PROJECT

Kushikino Station is one of the national crude oil underground storage stations in Japan, located in Kagoshima Prefecture, Kyushu (Tokimasa and Makita, 1993). This station has 1.75 million *kl* storage capacity employing 3 units of underground openings excavated in an andesite formation. As a transportation facility of crude oil from the tanker to the underground openings, an offshore pipeline with a 762 mm diameter, 9.7 mm thickness, and 2300 m length was constructed as shown in Fig.11. The concrete coating thickness of the pipeline was 87.5 mm, resulting in the unit weight of pipe being 1.577 gf/cm^3. Since the pipeline route was covered with sandy soil which is likely to liquefy, the following burying method was adopted, taking both the future extension plan of the Kushikino-New-Port and the effects of anchoring from ships into account (see Fig.11):

(1) Inside the Port, the pipeline was buried in gravel and crushed stones, a by-product of the underground excavation work. It was expected that this would eliminate the effect of liquefaction.
(2) Outside the Port except the PLEM (pipeline end manifold) part, the pipeline was buried with *in-situ* sand, allowing it to liquefy. The effect of buoyancy to the pipeline was assessed using numerical method described in the present paper, and it was confirmed that the stresses are smaller than the allowable stresses for the pipe material specified as API-5L-X52.

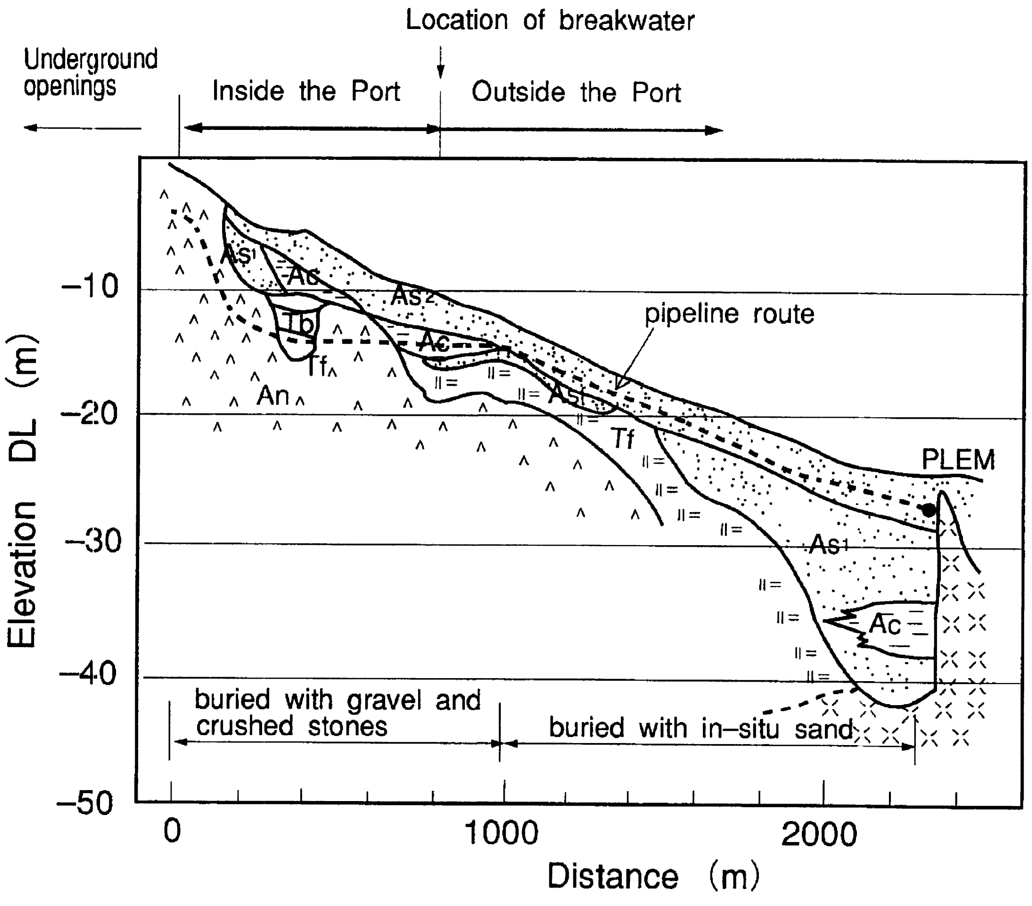


Fig.11. Sectional view of geologic condition and pipeline route for the Kusikino Project (As1, As2 = Alluvial Sand; Ac = Alluvial Clay; Tf = Tuff; Tb = Tuff Breccia; An = Andesite).

CONCLUDING REMARKS

From the present study the following conclusions may be drawn:

(1) Without stabilization techniques, maximum upward displacements and bending stresses of the pipeline tend to increase with the increase in the lengths of the liquefied zone.

(2) Both of the traditional stabilization techniques, ie. anchoring and/or weighting the pipelines, can reduce the amount of maximum upward displacement and bending stresses.

(3) A new stabilization technique, where non-liquefied zones are located at a certain pitch along the pipeline route, is able to reduce the level of maximum upward displacement and bending stresses to acceptable levels.

(4) In the Kushikino Project, the numerical method played an important role in making a pipe burying strategy.

The authors would like to thank Dr. O. Kiyomiya, Port Harbour Research Institute, for his valuable comments on the present study, and the managements of Japan National Oil Corporation and Japan Underground Oil Storage Co., Ltd. for allowing us to refer to the Kushikino Project.

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