Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VII)

11-2-8

EVALUATION OF STRESSES ON SUBMARINE PIPELINES IN LIQUEFIED SEABED

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SUMMARY

This paper shows a new calculation procedure by finite element method to estimate pipe stresses occurred by liquefaction of the ambient ground during earthquakes and the counterplans to decrease large pipe stresses exceeding the yield stress. It is predicted that factors such as burial depths of submarine pipelines, the range of liquefaction, pipe diameter and so on play important roles in pipe stresses. Calculations are carried out to know the influences of above the factors on pipe stresses. Driving of piles or backfill with gravel at some locations along the submarine pipelines are available to decrease large pipe stresses.

INTRODUCTION

In Japan where navigation is congested, submarine pipelines are buried in the seabed to protect them from damage by anchorage from ships. Pipes are laid in the trench and backfilled with clay or sand. Compaction of backfill material is not usually done and backfill material is left in the state of loose. Therefore liquefaction of backfill material may occur during earthquakes. The behavior of the submarine pipelines in liquefied seabed can be classified into (1)floating or subsidence of the submarine pipelines due to difference in unit weight between the liquefied seabed and pipe,and (2)horizontal movement due to sliding of the seabed.

This paper mentions only the former behavior of the submarine pipelines. Estimation of the pipe stresses during liquefaction of the seabed is very important to prevent ocean contamination and to confirm the safety of the submarine pipelines whether oil leaks from the pipe or not during earthquakes. New calculation procedure is proposed to estimate the pipe stresses. Some calculations are carried out for the submarine pipelines.

CALCULATION MODEL

Fig.1 shows the calculation model[2]. This model shows the case in which the submarine pipeline at the left side is in the non-liquefied seabed and that at the right side is in the liquefied seabed. The submarine pipeline floats to the surface of the seabed at the right side. The pipe stresses can be calculated by supposing that the pipe is under the following conditions.

Applied Force In the liquefied section, D-E in the figure, a buoyancy by liquefaction acts on the pipe as shown in Fig.2. The buoyancy can be

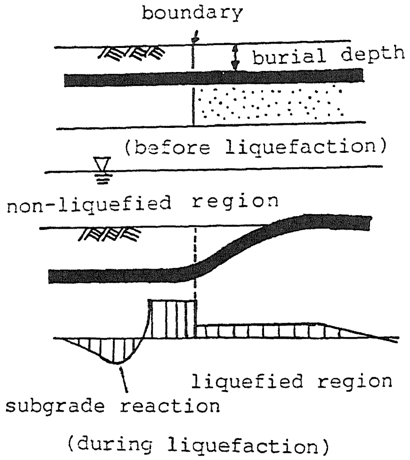

Fig.1 Calculation Model

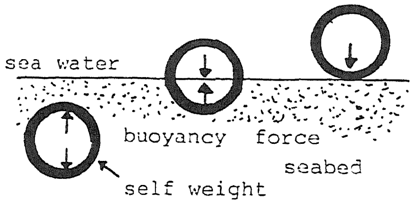

Fig.2 Forces Apply to Pipe

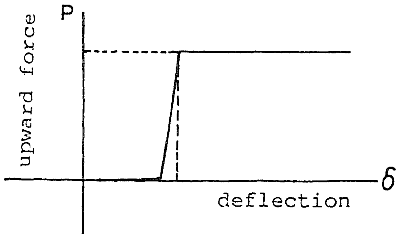

Fig.3 Load-deflection Relationdship

obtained by supposing that the pipe is in a fluid having the same unit weight as the saturated sand. When the apparent unit weight of the pipe is smaller than that of liquefied seabed, the pipe receives an upwards force. The pipe reaches the surface of the seabed due to the buoyancy and then the buoyancy acting on the pipe decreases. When the pipe is on the surface of the seabed, the downward force due to self weight of the pipe acts on the pipe. The loads on the pipe can be replaced with a load-deflection relationship in the calculation model as shown in Fig.3.

Subgrade Reaction In the non-liquefied seabed, there is a limit to the subgrade reaction against the upward movement of the pipe. The maximum force is the sum of the earth's weight and shear resistance of the ground. The maximum force[3] (Q) is obtained by the equation below.

$$Q = C F_c + r'H F_q \qquad (1)$$

where C :Cohesive strength of the backfill material
F_c ,F_q :Coefficients
H :Burial depth
r' :Unit weight of backfill material

In the territory between the liquefied seabed and non-liquefied seabed, the subgrade reaction is supposed to decrease linearly.

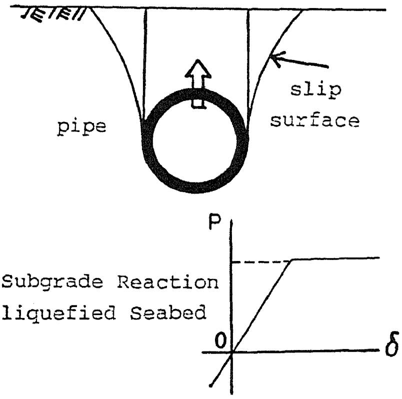

Fig.4 Subgrade Reaction in Non-liquefied Seabed

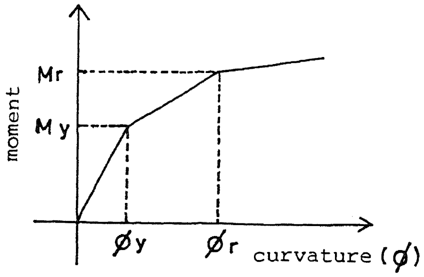

Fig.5 Bending Moment and Curvature Relationship of pipe

Moment-curvature Relationship of Pipe The submarine pipeline is replaced by a beam. The load given to the pipe and resistance of the seabed are described above. The stresses and displacements in the pipe are calculated by a discrete model:finite element method. The bending moment and curvature in the pipe are supposed to have a non-linearity as shown in Fig.5. A geometrical non-linearity is not considered here. The maximum elastic bending moment(M_y) and the plastic moment(M_r) are obtained by the following equations.

$$M_y = \pi(D^4 - d^4)\sigma_y/32 \qquad (2)$$

$$M_r = (D^3 - d^3)\sigma_y/6 \qquad (3)$$

where D :Outer diameter of the pipe
d :Inner diameter of the pipe
σ_y :Yield point stress of steel

The curvature(ϕ) of the pipe is obtained by ϕ=M/EI, where EI is bending rigidity of the pipe. When conducting non-linear analysis by the above-mentioned model,the problem is not solved by the Newton method due to the characteristic of load-displacement relationship of spring shown in Fig.2 The quasi-Newton method[4] is valid for this calculation model to obtain the required convergence.

AN EXAMPLE OF CALCULATION

The calculation model mentioned above can be applied to a few cases as follows.

(1) The seabed along the submarine pipeline is partially liquefied.
(2) The submarine pipeline is fixed at the bottom of a single-point mooring buoy or at the riser of a platform.
(3) The submarine pipeline passes under structures such as a breakwater and so on.

A case when the seabed is partially liquefied is discussed here. When liquefaction does not occur along total length of the submarine pipeline but occurs at some locations, the pipe stresses are large. The stress is small when the liquefaction occurs only in small region or along the total length. The range of the liquefaction along the submarine pipeline plays an important role in the estimation of pipe stresses.

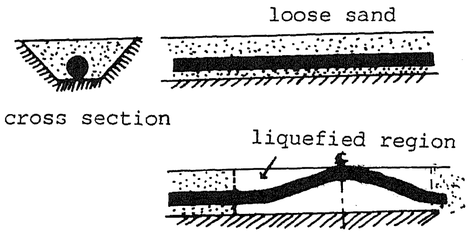

Fig.6 Calculation Conditions

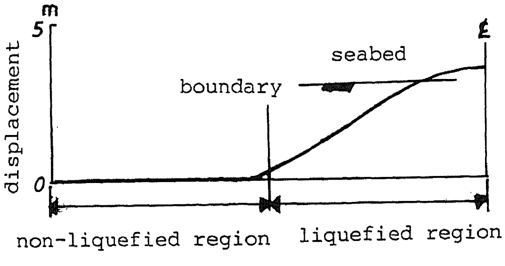

Fig.7 Displacement of Pipeline

Range of Liquefaction Fig.6 shows the calculation conditions. A pipe,40B(outer diameter:1016mmm,thickness:16mm),is embedded at a level 3m below the seabed surface. The soil properties of the backfill material are as follows. Internal friction angle is 25 degree and cohesion is 0. The coefficient of soil reaction is 1.0kgf/cm^2. Fig.7 shows the distribution of displacements along the submarine pipeline. This figure shows only the left side of the distribution because of symmetry of the calculation model. In the liquefied section, the pipe floats upwards to the seabed surface and is partly exposed above the surface at a location approximately 40m apart from the boundary shown in Fig.7. In the non-liquefied section, displacement of the pipe is very small. The stresses calculated at the bottom edge of the submarine pipeline are shown in Fig.8. The maximum bending stress is obtained in the seabed adjacent to the boundary and its value is $3600\mathrm{kgf/cm^2}$. The stresses in the non-liquefied section is very small at the location approximately 10m apart from the boundary. Where the pipe is exposed above the seabed surface, the stress is about $2000\mathrm{kgf/cm^2}$.

Fig.9 shows the relationship between the length of liquefied section along the submarine pipeline and the maximum bending stress. The stress of the pipe becomes maximum when the length of the liquefied section is 130m or so. When its length is longer than 130m, the stresses decrease to reach a constant value in the region longer than 180m. While its length is shorter than 120m, the pipe stays under seabed surface. The pipe is exposed above the seabed surface when the length of liquefied section is over 150m.

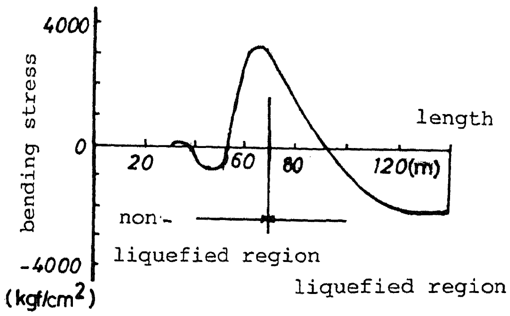

Fig.8 Distribution of Bending Stresses

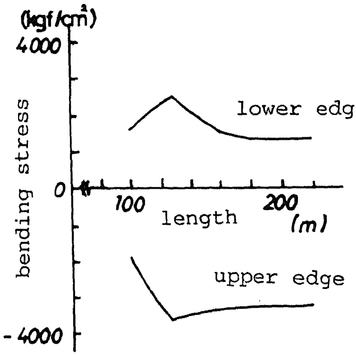

Fig.9 Bending Stress and Length of Liquefied Region

<u>Burial Depth</u> Fig.10 shows the relationship between the bending stresses and the burial depths of the pipes. The pipe is embedded in the seabed at a burial depth ranging 2 to 4m. As shown in the figure, the value of pipe stresses increases as the burial depth becomes deeper. In addition, with larger burial depths, the length of the liquefied section which gives the maximum stress becomes longer. However, for lengths of liquefied sections within 110m, the burial depths have little effect on the value of stresses. When the burial depth is 4m, the pipe stress exceeds $4000\mathrm{kgf/cm^2}$.

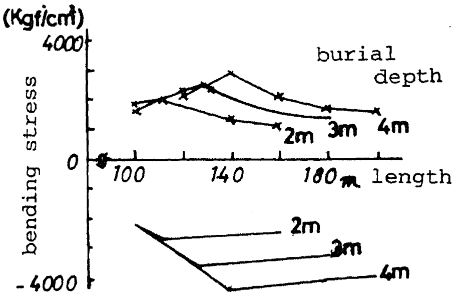

Fig.10 Burial Depth and Bending Stress

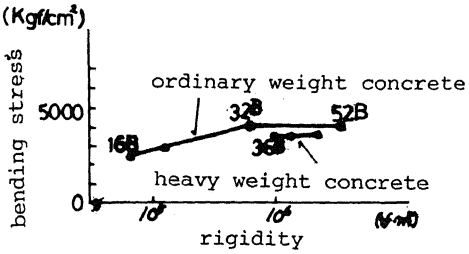

Fig.11 Rigidity of Pipe and Bending Stress

Rigidity of Pipes Fig.11 shows the relationship between the bending stress and the rigidity of the pipes buried 3m below the seabed. Rigidity of the pipe depends on the pipe diameter and its thickness. The pipes with a larger diameter gives a larger bending stress rather than the pipes with a smaller diameter. Concrete with unit weight of 2.3 tf/m^3 is usually used for the pipes with small diameters. On the other hand, heavy weight concrete with unit weight of 3.0tf/m^3 is sometimes used for the pipes with large diameters. The bending stresses decrease about 10% when the heavy weight concrete is used in place of ordinary weight concrete for the coverage.

Post Yielding of Steel The standard for steel members used in offshore pipelines states that API 5LX-X52, for example, has 3660kgf/cm^2 of yield stress and 4640kgf/cm^2 of ultimate stress respectively. The pipe stresses exceed the yield stress and are within the ultimate stress in some calculation cases in Fig.10. According to experiments on pipe's ultimate strength done by Miyajima and his group members[5], the phenomena such as breaking or cracking of the pipe is not observed even when the pipe stress exceeds the yield stress but the pipe strain is within 0.3%. The pipe strain calculated is 0.28% at the maximum bending stress in the calculation cases in Fig.10. Namely, in view of the strain, there is little possibility for the pipe to have breaking or cracking. The worst situation:crude oil leaks from the pipe, can be avoided even though the pipe has been flattened or partially buckled due to the large stresses.

How to cope with Movement of the Pipeline The residual deformation of the pipe due to the large stresses may not be disappeared even after the liquefaction is finished. Repair will be required for the floated submarine pipeline and pipes with excessive residual deformation. It is very difficult to repair the submarine pipelines because the repair will need a considerable performance period and cost. If the field repair is considered inapplicable at the plan/design stage, any other suitable counterplans should be chosen in advance. Fig.12 shows examples of the counterplans. Kinds of the counterplans are as follows.

(1) driving of piles:simple portal frame
(2) anchors for preventing the pipe from float
(3) backfill with gravel at some locations
(4) increase of concrete coverage thickness
(5) use of heavy weight concrete for coverage
and so on

Fig.13 shows the effect of the driving of piles. Two piles and a horizontal beam form a simple portal frame. The pipe is allowed to move upwards up to the horizontal frame and can not move upwards any more when the pipe contacts with the frame. The piles are driven to non-liquefied ground to obtain enough pull-out force. It is assumed in the calculation that the piles are driven at the location 20m away from the boundary and 1m upwards movement of the pipe is allowed. The curvature of the submarine pipeline in the liquefied section is smaller than when no counterplan is taken. The pipe stresses are also small and are within the yield stress. Anchors method is the same idea as the driving of piles. In the metod of backfilling gravel at some locations, an interval of about 100m along the submarine pipelines can be placed according to Fig.10.

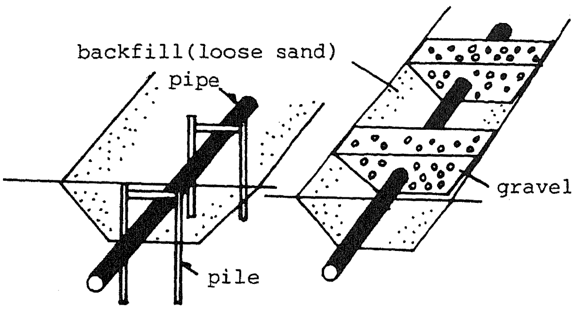

Fig.12 Examples of Counterplans

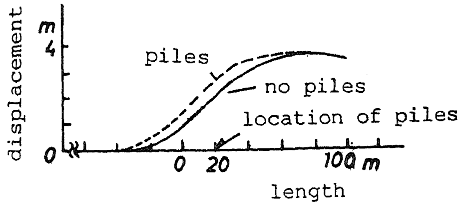

Fig.13 Displacement of Pipelines

CONCLUSIONS

(1) When liquefaction occurs in the seabed during earthquakes, pipe stresses become large due to upwards movement of the pipe. The pipe stresses in the liquefied seabed depend on the liquefied range along the submarine pipelines, burial depth, rigidity of the pipes and so on.

(2) Maximum pipe stress is calculated when the liquefied range is about 130m long along the submarine pipelines. The pipe stresses increase according to the burial depth of the pipes and rigidity of the pipes.

(3) The pipe stresses decrease about 10% when the heavy weight concrete,in place of ordinary weight concrete,is used for coverage of the pipes.

(4) The stresses on the 40B pipe buried 4m deep in the seabed are over the yield stress in the calculation. However, pipe strains are within 0.3% in this calculation. Therefore breaking or cracking that results in oil leakage can not occur in the pipes.

(5) A repair is needed when the submarine pipelines are exposed above the seabed or large residual deformation remains in the pipes. Counterplans such as driving piles, backfill with gravel at some locations along the submarine pipelines and so on are available for prevention of the pipe upward movement and decrease of the pipe stresses.

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