A SEISMIC RESPONSE ANALYSIS OF UNDERGROUND PIPELINE FOR EMERGENCY CORE COOLING SYSTEM IN NUCLEAR POWER PLANT

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SUMMARY

The aseismic design of the Emergency Core Cooling System which is essential to the prevention of hypothetical accidents should be required to ensure the safety of nuclear power plant under severe earthquakes. Few reports have been found as to the analysis of underground pipeline stresses due to soil cracks during earthquakes. This paper, however, deals with the significant aseismic design problem, and the above mentioned stresses are estimated using a mathematical model subjected to soil cracks.

In nuclear power plants, a critical piping system, such as a component of ECCS, is often placed underground. This paper presents a result of stress analysis of such an underground pipeline based on certain assumptions related to its behaviours during an earthquake.

The earthquake damage to underground pipings is in a wide variety such as tension and shear ruptures, bucklings or joint failures. Damage patterns are influenced by seismic ground motions, soil conditions, piping material and its rigidity and ductility. It is observed that earthquake damage to pipings is particularly serious at locations where alluvial soil layers are deeply deposited or its formation is complicated.

It can be observed from the results of vibration tests with underground piping models and submerged tunnel models that interaction of underground facilities and surrounding soils plays an important role. Furthermore, from records and photographs of damage in the past earthquakes it is observed that soil deposits are cracked down to a considerable depth, causing local, serious damage to pipings.

From this point of view, stress analysis of underground pipelines are carried out in this paper using a mathematical model subjected to soil cracks. Both tension-type and slip-type cracks of the soil are considered in establishing the equation of equilibrium in which the effects of interaction are incorporated. The solution to the equation and the evaluation of stresses in the pipeline are shown, which may be useful for the aseismic design of a nuclear power plant.

1. Introduction

Some vibration characteristics of underground pipelines have been revealed through seismic observations (Sakurai, et al. (1)) and vibration experiments (Nasu (2)). According to the foregoing reports it is observed that the underground pipelines would be under restraint by surrounding soil without showing their coherent vibration and the stress of a pipeline appears to relate closely with the strain of the soil. As the observed earthquakes are of comparatively small scale the reported strain values would be smaller than those expected in possible severe earthquakes. The estimated shear strain of soil in these severe earthquakes is roughly from 10^{-3} to 10^{-2}, and at times soil cracks are observed. The stress of a pipeline will be influenced by the relative displacement of its surrounding soil. The local stress caused by a soil cracking will be very high as the relative soil displacement is extremely large.

In another report (Kobayashi (3)), depending on the mode of seismic soil cracks, they are classified as follows:

Tension type cracks	(Fig. 1-a)
Slip type cracks	(Fig. 1-b), etc.

Their generation and stress conditions are also being discussed in the report. Tension type cracks are reported to have been observed very frequently, while slip type cracks took place comparatively less often.

Analysis of quantitative relationship of seismic scales and soil crack widths has been a hard problem, to which the description of the M.S.K. Intensities of Earthquake will contribute to some extent. (Comparison of the Intensities and accelarations not shown, the Intensities are quantitatively corelated to soil crack widths: Intensity VIII for a few centimeters of crack width: Intensity IX for 10 centimeter width.)

With scare data available of underground pipeline stresses subjected to soil cracks, a stress analysis is carried out in this paper by use of a mathematical model (Figs.2, 3).

2. Fundamental equations

The equation of motion of an underground pipeline subjected to inertia force is expressed as follows;

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{O\} \tag{1}$$

where $[M]$: mass matrix $[C]$: damping matrix

$[K]$: stiffness matrix $\{U\}$: displacement vector

The stresses of underground pipelines are most influenced by soil displacements (Ref. (1)), thus the third term in eq. (1) has to be taken into consideration.

2-1. Pipeline stress caused by a tension type crack

Where a soil crack takes place, a soil displacement W does not coincide with a pipeline dusplacement U, causing slippage S=W-U, by which a friction force f will be induced between the two (Fig. 3-a). The equilibrium of the force $P_p(x)$ which acts upon a pipeline at an infinitesimal length dx is expressed as follows;

$$\frac{d P_R(x)}{dx} = \varphi \cdot f(x) \qquad (2)$$

where φ : circumferential length of pipe

The compatibility of strains of soil and pipe, $\varepsilon_G(x)$ and $\varepsilon_p(x)$, is expressed as follows;

$$\frac{d S(x)}{dx} = \varepsilon_G(x) - \varepsilon_p(x) \qquad (3)$$

$\varepsilon_G(x)$ and $\varepsilon_p(x)$ in eq. (3) are expressed as

$$\varepsilon_G(x) = \frac{1}{E_G \cdot A_G} \int_0^x \varphi \cdot f(x) \cdot dx \qquad (4)$$

$$\varepsilon_p(x) = \frac{1}{E_p \cdot A_p} \left\{ \int_0^x \varphi \cdot f(x) dx - P_p(0) \right\} \qquad (5)$$

where E_G, A_G : modulus of elasticity and section of soil

E_p , A_p : modulus of elasticity and section of pipe

From eqs. (2), (3) and (4),

$$\frac{d^2 S(x)}{dx^2} = K_s \cdot f(x) \qquad (6)$$

where Ks : function of friction force and slippage

A relation of friction and slippage between soil and pipeline is expressed in an exponential function, on the basis of some experimental results on bond stresses in reinforced concrete (Morita, et al. (4)) and negative friction of steel piles (J.S.S.M.F.E. (5)), as follows (Fig. 4)

$$f_1(x) = e\,\frac{\log\{(e-k)\ S_1(x) + k\}}{(e-k)\ S_1(x) + k} = e\,\frac{\log t_1(x)}{t_1(x)} \qquad (7)$$

$$f_1(x) = \frac{f(x)}{f\ max}\ , \quad S_1(x) = \frac{S(x)}{S_{f\,=\,f\ max}}\ ,$$

$$t_1(x) = (e-k) \cdot S_1(x) + k$$

In eq. (7), $f_1(x)$ takes the maximum value, $f_1(x) = 1$, when $S_1(x) = 1$.

2-2. Pipeline stress caused by a slip type soil crack

Where a pipeline deforms flexurally, an equilibrium of forces is calculated on the assumption that the reaction force of the surrounding soil is proportional to the relative displacement of soil and pipe when it is small, and that the soil reaction becomes constant after the relative displacement has reached a certain value (Fig. 3-b).

Where $0 \leqq x \leqq X_m$,

$$E_p\, I_p \frac{d^4 U_1}{d x^4} - \alpha_o = 0 \qquad (\alpha_o = \alpha \cdot Z_o = K_p \cdot \gamma \cdot D) \qquad (8)$$

$E_p I_p$: rigidity of pipe

K_p : passive earth pressure coefficient

γ : unit weight of soil

D : diameter of pipe

Z_o : depth from ground surface

The solution to eq. (8) is

$$E_p I_p \cdot U_1 = \frac{1}{24} \alpha Z_o \cdot X^4 + \frac{1}{6} C_1 \cdot X^3 + \frac{1}{2} C_2 \cdot X^2 + C_3 \cdot X + C_4 \qquad (9)$$

C_1 , C_2 , C_3 , C_4 : integral constants

Where $X_m \leqq X \leqq l$,

$$E_p \cdot I_p \frac{d^4 U_2}{d x^4} + K_h \cdot D \cdot U_2 = K_h \cdot D \cdot W \qquad (10)$$

K_h : subgrade reaction coefficient

The solution to eq. (10) is

$$U = e^{-\beta x}(\cos\beta x \cdot A_1 + \sin\beta x \cdot A_2) + e^{\beta x}(\cos\beta x \cdot A_3 + \sin\beta x \cdot A_4) + E_1$$

A_1 , A_2 , A_3 , A_4 : integral constants (11)

E_1 : a variant with soil displacement

$$\beta = \sqrt[4]{\frac{Kh \cdot D}{4 \cdot E_p I_p}}$$

Unknown quantities are nine in total, which consist of eight integral constants, C_1, C_2, C_3, C_4, A_1, A_2, A_3 and A_4; and a plastic length X_m. These unknown quantities can be determined from nine conditional equations, four of which can be determined from boundary conditions at the both ends ($x = o$, $x = l$), five of which can also be determined from continuities, as displacements, rotations, bending moments, shear forces and soil reactions at the point where $X = X_m$ are equal respectively.

3. Numerical example

3-1. Basic data

In order to present the differences in characteristics of the stresses caused by a soil crack, calculations were performed using the various values of soil properties and crack widths.

The numerical values used in the mathematical models are summarized in Table I. The soil modulus data are assumed to be

$$G = 1200\, N^{0.8} \quad (t/m^2)$$

where N : N value in standard penetration test

The above formula has been suggested by Ohsaki and Iwasaki.

To calculate the pipe stresses caused by a tension crack, the effective soil area A_G is assumed to equal the cylindrical area: having thickness of 3 × D from the pipe surface. Then, in the case of a slip crack, the following assumptions are considered; the soil displacement W is equal to $a \cos(\frac{\pi}{2l} x)$ and the pipe displacement U and bending moment M are equal to zero at the both ends.

3-2. Result of calculation

Figs. 5 to 8 show the pipeline stresses caused by a tension type soil crack. The pipe stresses are influenced by the pipe size, the soil modulus and the crack width.

Figs. 9 to 12 show the pipeline stresses caused by a slip type soil crack. In these cases, not only the three factors above mentioned but the plastic length X_m also affects the pipe stresses.

4. Conclusion

Since there is only limited reference materials available on the local stresses caused by a soil cracking, the stresses have been examined by using a mathematical model, which would make some contributions to solving problem of the stresses in underground pipelines.

5. Acknowledgement

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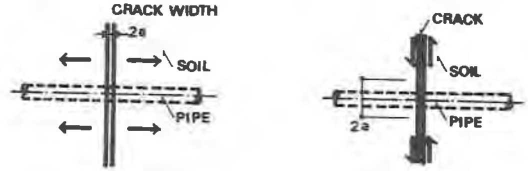
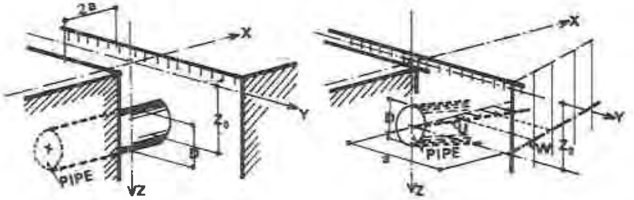


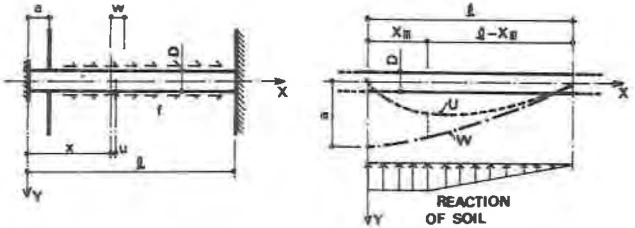
1-a TENSION TYPE 1-b SLIP TYPE

FIG.1 SOIL CRACK TYPES



2-a TENSION TYPE 2-b SLIP TYPE

FIG.2 SOIL CRACK AND PIPE ARRANGEMENT



3-a TENSION TYPE 3-b SLIP TYPE

FIG.3 ANALYTICAL MODEL

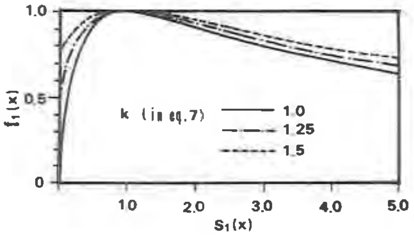


FIG.4 FRICTION FORCE AND SLIPPAGE

PIPE

	D (cm)	t (mm)	E_p (kg/cm²)
1	31.85	6.4	2.1×10^6
2	60.96	9.0	2.1×10^6

SOIL

TENSION CRACK

	E_G (kg/cm²)	f_{max} (kg/cm²)		E_G (kg/cm²)	f_{max} (kg/cm²)
1	1200	1.0	4	650	1.0
2	2300	1.5	5	1150	1.5
3	3150	2.0	6	1575	2.0

SLIP CRACK

	K_h (kg/cm³)	P_k	Z_a (m)	γ (t/m³)
1	1.5	2.0	1.5	1.6
2	2.0	3.0	2.5	

TABLE I TABULATION OF DATA USED

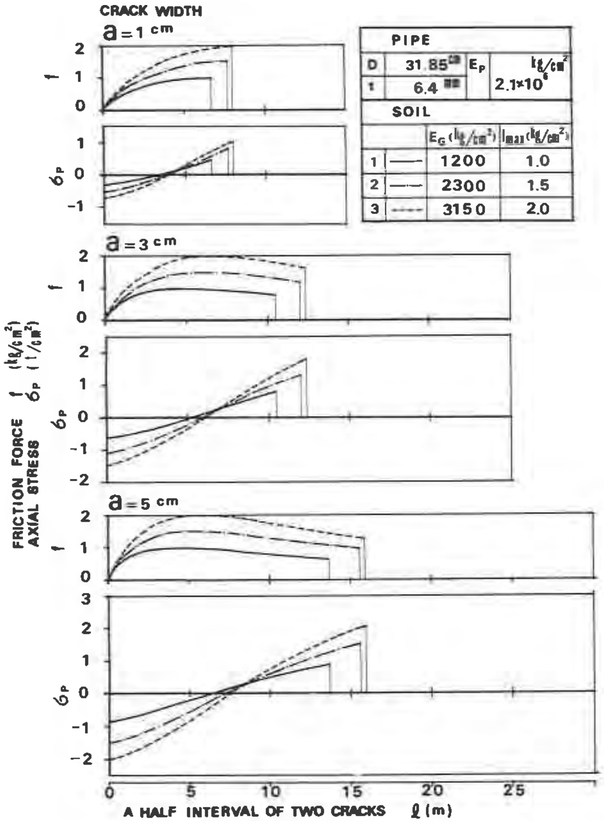


FIG. 5 PIPE STRESSES CAUSED BY TENSION CRACK

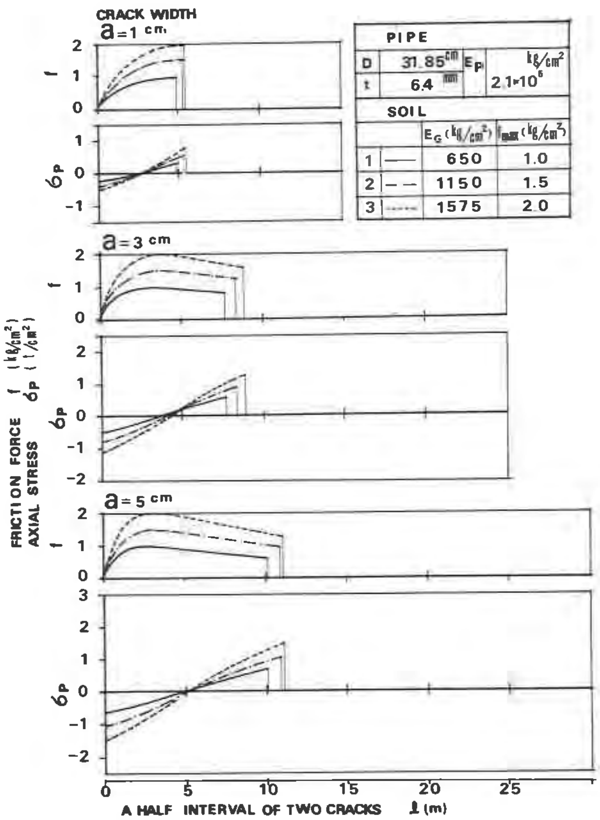


FIG. 6 PIPE STRESSES CAUSED BY TENSION CRACK

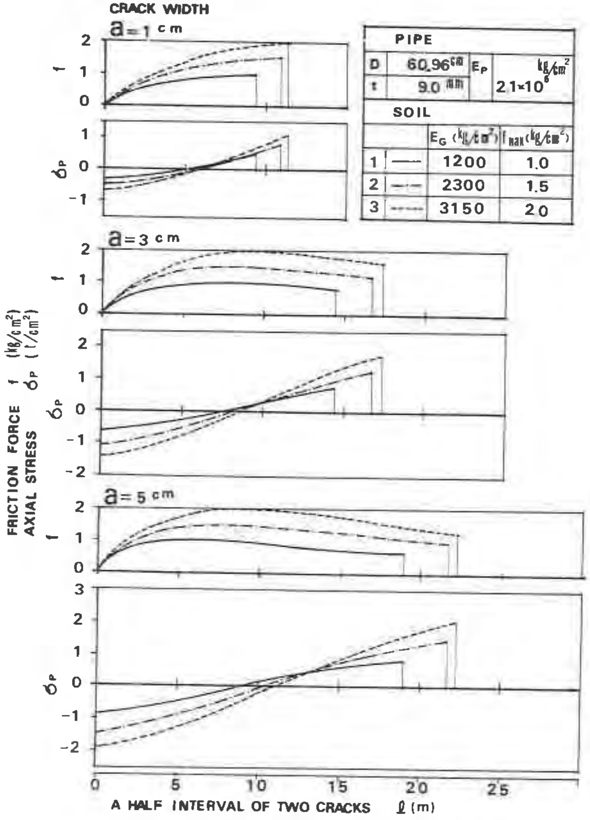


FIG. 7 PIPE STRESSES CAUSED BY TENSION CRACK

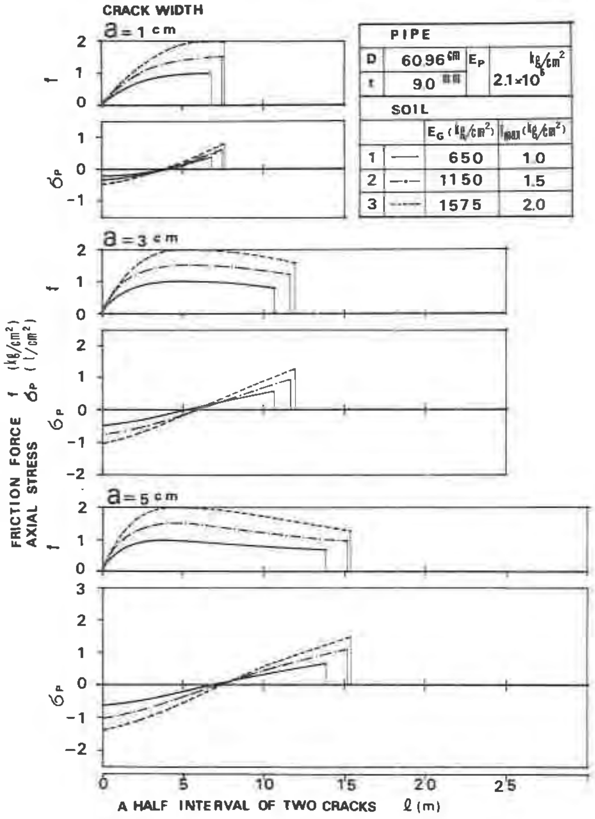


FIG. 8 PIPE STRESSES CAUSED BY TENSION CRACK

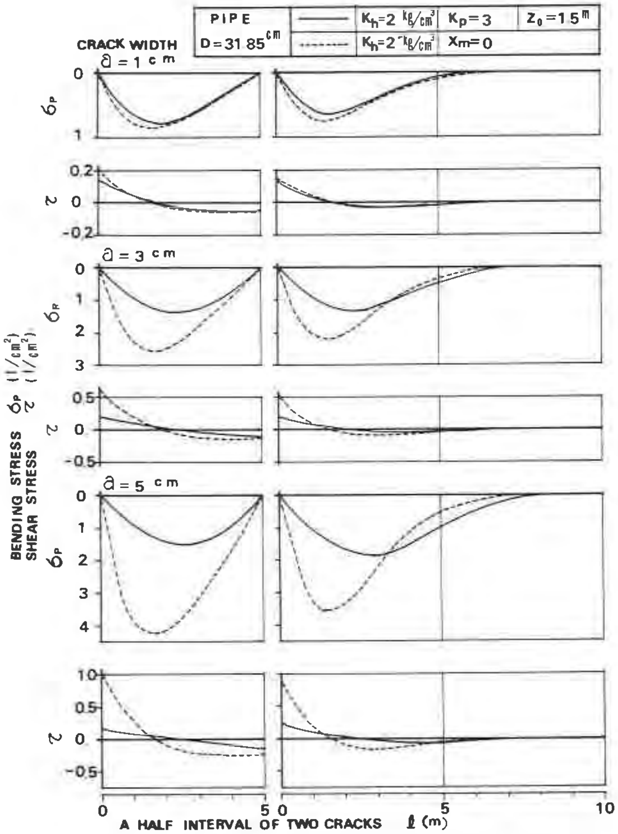


FIG.9 PIPE STRESSES CAUSED BY SLIP CRACK

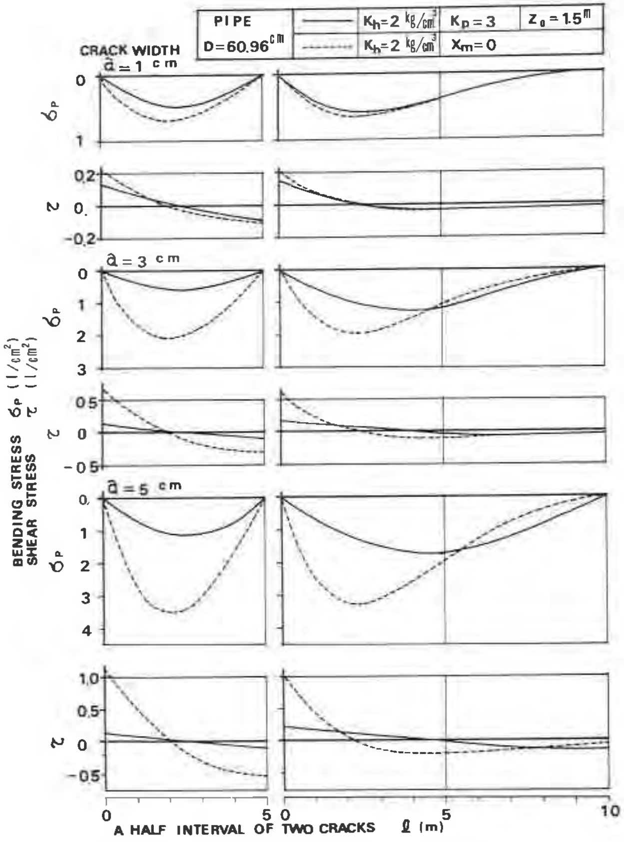


FIG.10 PIPE STRESSES CAUSED BY SLIP CRACK

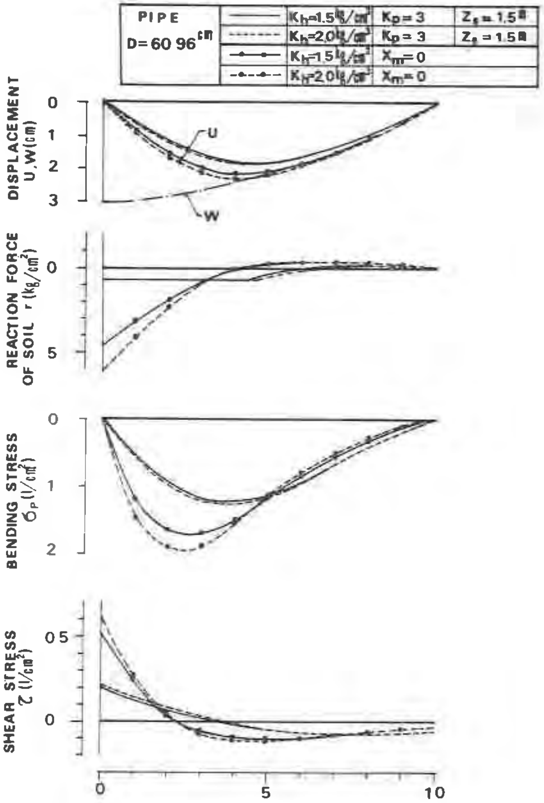


FIG.11 PIPE STRESSES CAUSED BY SLIP CRACK

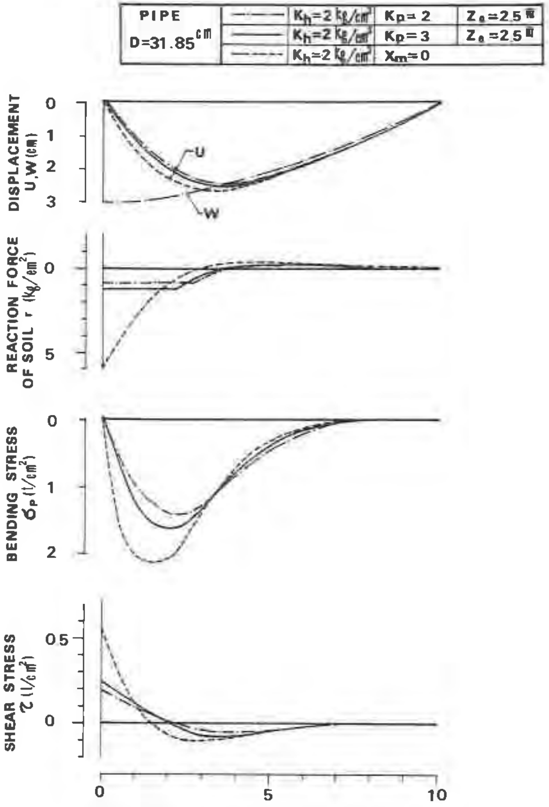


FIG.12 PIPE STRESSES CAUSED BY SLIP CRACK