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Effect of Circular Cavity on Maximum Equivalent Stress and Stress Intensity Factor at a Crack in Buried Pipeline

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The effects of cavities on maximum equivalent stresses of buried pipelines are investigated in terms of two factors such as size and location of the underground cavities by using a finite element code. It has been found that the cavities affect maximum equivalent stresses of buried pipeline significantly in case that the diameters of cavities are larger than that of the pipeline. The variation of the stress intensity factors for a crack existing on the buried pipeline nearby cavities is also studied. The mode II stress intensity factor, K_{II}, for a tilt crack located at the top portion of a buried pipeline is found to be influenced significantly regardless of the location of the underground cavities.

Key Words: Buried Pipeline, Cavity, Stress Intensity Factor, Maximum Equivalent Stress

1. Introduction

The possibility of leakage for the buried pipeline transporting gas and/or oil is high during its life time because of various defects and material degradation caused by manufacturing and environmental conditions (Lee, 1997). Furthermore the loading conditions such as the internal pressure and the external applied load with deterioration behaviors of the pipeline would influence its efficiency and life significantly (Burichau and Deconinck, 1994). The failure accidents on such pipelines especially initiated by leakage bring not only economic losses, but also serious disasters which usually take human lives. Therefore, it is urgently needed to develop the methodology to prevent and/or predict such accidents in advance to ensure the safety and reliability of the pipeline (Fu and Kirkwood, 1992, Mohammadi et al, 1985).

In cases of the pipeline installed on the ground, we are able to detect a leak to prevent disastrous accidents because of its easy accessibility. Futhermore it is relatively easy to perform periodic inspections for checking the reliability and integrity of the ground system. However, it seems to be difficult to locate defect area of the buried pipelines accurately even though many detection technologies have emerged. Furthermore, we also need to develop a methodology that estimates a survival life and safety margin of the buried pipeline under operation. The systematic investigation is, thus, required for the prediction and prevention against catastrophic disasters (Coates, 1995, Ellyin, 1985).

The technical researches on pipelines of oil refineries, chemical plants and nuclear energy have been carried out by many investigators (Lee, 1997). However, it is hardly to find technical results in domestic for the underground pipelines except the investigations by the Refs. (Lee and Choi, 1998a, 1998b, KOGAS, 1997a, 1997b, 1996a, 1996b). Moreover, the topics of researches are limited to simple design problem of pipeline structure and analysis of thermal stress.

We need, thus, to investigate the effects of mechanical and chemical interactions between buried structures in detail. Especially, in the case of buried pipelines under internal pressure loading conditions, the defects of pipelines may affect in deterioration of the pipelines significantly.

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Hence, the buried pipelines under internal pressure must be constructed after in-depth studies regarding the effects of cavities existing under the ground.

In this paper, the effects of cavities on maximum equivalent stresses of buried pipeline are investigated in terms of two factors such as size and location of cavities. The effects of cavities on the stress intensity factors for a crack existing in buried pipeline are also studied by using a finite element code.

2. Analysis Methods

The effects of cavities on buried pipeline with internal pressure are analyzed by using a finite element package, ANSYS 5.3. The finite element model for the analysis is shown in Figs. 1(a) and 1(b).

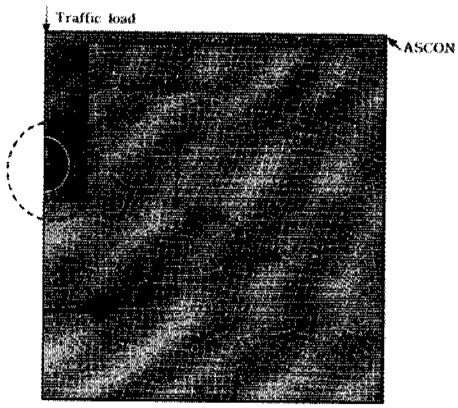


Fig. 1 (a) A finite element model for the analysis of cavity's effect on maximum equivalent stress of pipeline.

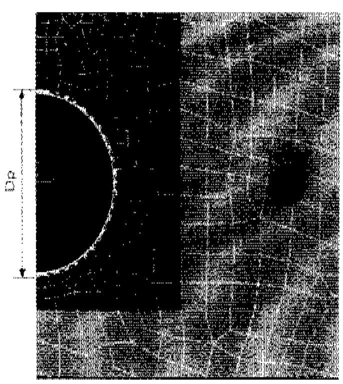


Fig. 1 (b) The detailed configuration of finite mesh configuration at A.

The buried pipeline has a diameter of 406.4mm, a wall thickness of 10mm and an internal pressure of 7.84MPa. The center of pipeline is at a depth 1.016m from the free surface. The external load, e.g. a vehicle load of 294.2kN is assumed to be vertically applied to the pipeline as shown in Fig. 1(a). As a simple example to appreciate the effect of cavities on the buried pipelines, two cavities are assumed to be located at equal distance and depth from the pipeline.

The maximum equivalent stress of buried pipeline is estimated for various locations of cavities. D_c/D_p of 0.5, 1.0 and 2.0 are taken for the analysis, where D_c is the cavity diameter and D_p the pipeline diameter. The backfill material as well as the subgrade around it are assumed to behave elastically since the available data are limited. Those properties are shown in Table 1.

2.1 Maximum equivalent stress evaluation

The principal stresses (σ_1, σ_2, σ_3) at the finited elements in the buried pipeline are obtained by solving the cubic Eq. (1).

$$\begin{vmatrix} \sigma_x-\sigma_o & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_y-\sigma_o & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z-\sigma_o \end{vmatrix}=0 \tag{1}$$

where, σ_o=principal stress (3 values)

The von Mises or equivalent stress σ_{eqv}, which may be an applicable design parameter for the buried pipelines, is evaluated for each finite element as

Table 1 Properties of materials (refer to Fig. 1) (KOGAS. 1997a)

Materials / Property	Pipeline	ASCON	Sand -backfill	Subgrade
Elastic Modulus, E(MPa)	207000	10000	100	86
Poisson's ratio, ν	0.36	0.35	0.35	0.35
Mass density, ρ(kg/m^3)	7860	2400	2080	1800
Yield stress(MPa)	448	-		-

$$\sigma_{eqv}=\sqrt{\frac{1}{2}\{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\}} \quad (2)$$

The maximum σ_{eqv} for all finite elemenents are used to make comparison between the boundary conditions such as the location of cavities.

2.2 Stress intensity factor evaluation

The displacement field near a crack under the mixed loading conditions for linear elastic materials are represented as.

$$u=\frac{K_I}{4G}\sqrt{\frac{r}{2\pi}}\left((2\chi-1)\cos\frac{\theta}{2}-\cos\frac{3\theta}{2}\right) -\frac{K_{II}}{4G}\sqrt{\frac{r}{2\pi}}\left((2\chi+3)\sin\frac{\theta}{2}+\sin\frac{3\theta}{2}\right)+O(r) \quad (3)$$

$$v=\frac{K_I}{4G}\sqrt{\frac{r}{2\pi}}\left((2\chi-1)\sin\frac{\theta}{2}-\sin\frac{3\theta}{2}\right) -\frac{K_{II}}{4G}\sqrt{\frac{r}{2\pi}}\left((2\chi+3)\cos\frac{\theta}{2}+\cos\frac{3\theta}{2}\right)+O(r) \quad (4)$$

where,

u, v=displacements in a local Cartesian coordinate system shown in Fig. 2(a).

$r\theta$=coordinates in a local polar coordinate system shown in Fig. 2(a).

G=shear modulus, $E/(2(1+\nu))$.

E=longitudinal elastic modulus.

K_I, K_{II}=stress intensity factors relating to deformation shapes shown in Fig. 2(b).

$\chi=3-4\nu$, (plain strain).

$\chi=\frac{3-\nu}{1+\nu}$, (plane stress).

ν=Poisson's ratio

$O(r)$= higher order terms of r.

Evaluating Eqs. (3) and (4) at $\theta=\pm180°$ and dropping the higher order terms, we get

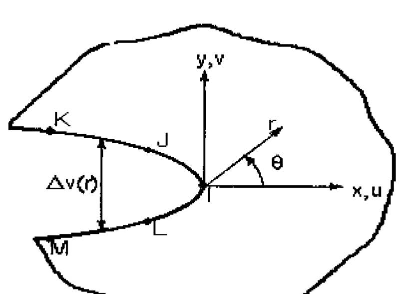


Fig. 2 Nodes used for the determining crack-tip displacements.

$$u=\frac{K_{II}}{2G}\sqrt{\frac{r}{2\pi}}(1+\chi) \quad (5)$$

$$v=\frac{K_I}{2G}\sqrt{\frac{r}{2\pi}}(1+\chi) \quad (6)$$

At a nodal point of a finite element near the crack tip location, we can obtain the stress intensity factors, K_I and K_{II} by calculating the displacements, $\triangle u$ and $\triangle v$ shown in Fig. 2 (1992, Lee and Cho) as follows,

$$K_I=\sqrt{2\pi}\frac{G}{1+\chi}\frac{|\triangle v|}{\sqrt{r}} \quad (7)$$

$$K_{II}=\sqrt{2\pi}\frac{G}{1+\chi}\frac{|\triangle u|}{\sqrt{r}} \quad (8)$$

3. Results and Discussions

3.1 Cavity located below pipeline

The effects of cavities on maximum equivalent stresses of buried pipeline are shown in Figs. 3~8 for various locations of cavities.

Figures 3~5 show the effects of cavity size. When the diameter of cavity is 1/2 times of that of

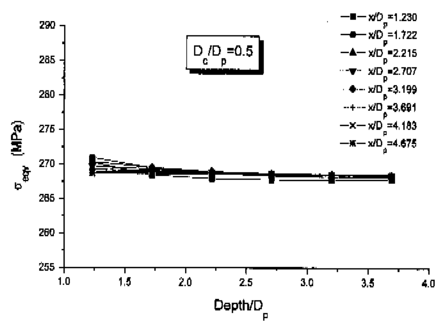


Fig. 3 Effect of cavity's size on maximum equivalent stress, σ_{eqv}.($D_c/D_p=0.5$, D_c:diameter of cavity, D_p:diameter of pipeline)

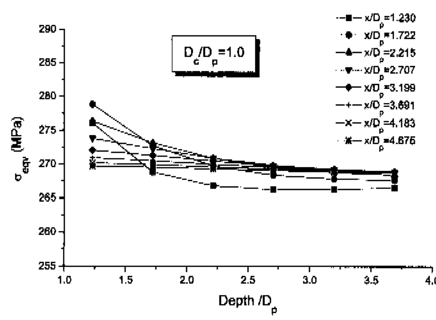


Fig. 4 Effect of cavity's size on σ_{eqv}. ($D_c/D_p=1.0$)

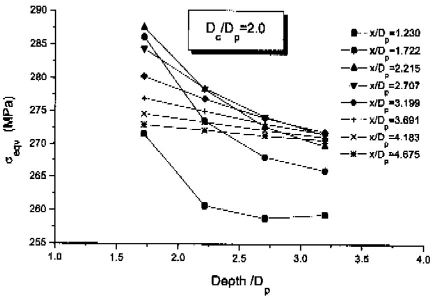


Fig. 5 Effect of cavity's size on σ_{eqv}. ($D_c/D_p=2.0$)

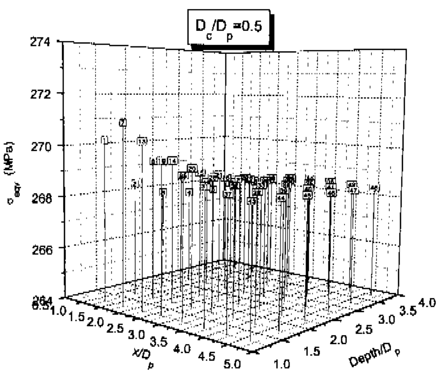


Fig. 6 Effect of cavity's location on σ_{eqv}. ($D_c/D_p=0.5$)

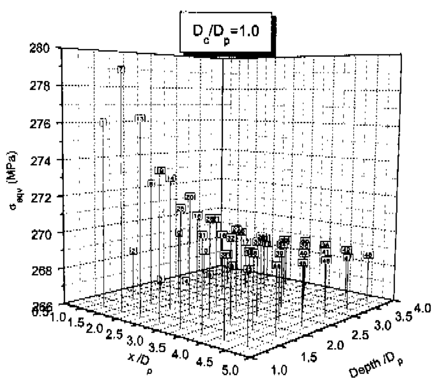


Fig. 7 Effect of cavity's location on σ_{eqv}. ($D_c/D_p=1.0$)

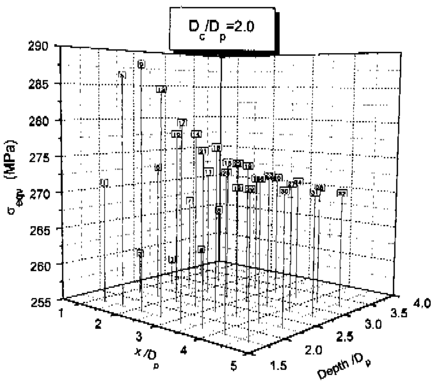


Fig. 8 Effect of cavity's location on σ_{eqv}. ($D_c/D_p=2.0$)

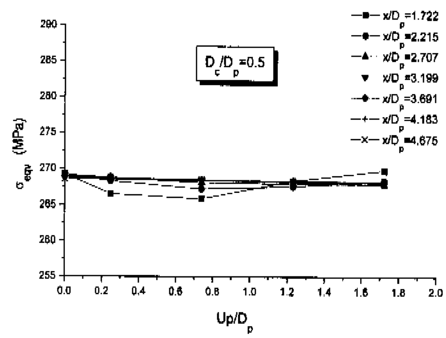


Fig. 9 Effect of cavity's size on σ_{eqv}. ($D_c/D_p=0.5$)

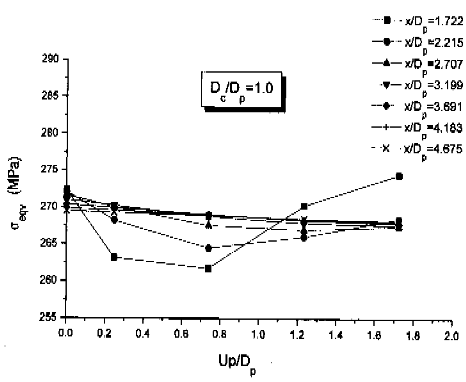


Fig. 10 Effect of cavity's size on σ_{eqv}. ($D_c/D_p=1.0$)

the pipeline, the effect of cavity location is negligible as shown in Fig. 3. But, in cases of D_c/D_p of 1.0 and 2.0, the effects are found to be large as noted in Figs. 4 and 5 where D_c and D_p are the diameters of cavity and pipeline, respectively.

The effects of cavity locations are shown in Figs. 6～8. The effects of horizontal distances between cavities and pipeline are found to be larger than those caused from vertical depths. The influential ranges of cavity locations are about 3 times of D_p in horizontal distance and 2 times of that in vertical depth, for D_c is larger than D_p.

3.2 Cavity located above pipeline

In case of cavity located above the pipeline, the effects of cavities are shown in Figs. 9~12. Figures 9 and 10 also show the effects of cavity size on maximum equivalent stresses in buried pipeline for various locations of cavities.

When D_c is 1/2 that of D_p, the effects of cavity location are negligible as indicated in Fig. 9. However, the effects of cavity location are found to be significant as noted in Fig. 10, when D_c is the same as D_p. Especially, when the horizontal distances between cavities and pipeline are smaller than 3 times the magnitude of D_p, the fluctuation of maximum equivalent stresses is big.

In Figs. 11 and 12, when the cavities are located at the same depth as the pipeline elevation, the effects of cavities on maximum equivalent stresses are negligible. In case of cavities located above pipeline, the influential ranges of cavity location are about 3 times of D_p in horizontal distance, but negligible in vertical depth.

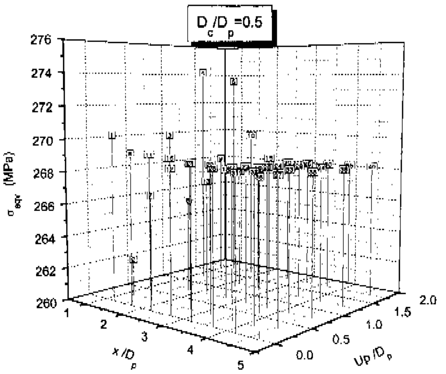


Fig. 11 Effect of cavity's location on σ_{eqv}. ($D_c/D_p=0.5$)

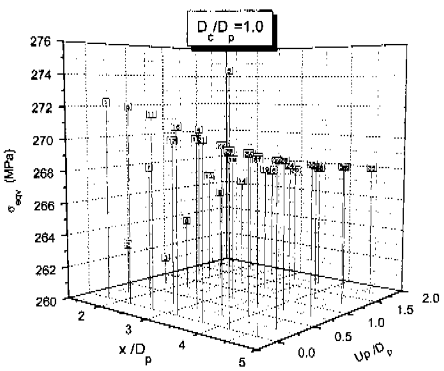
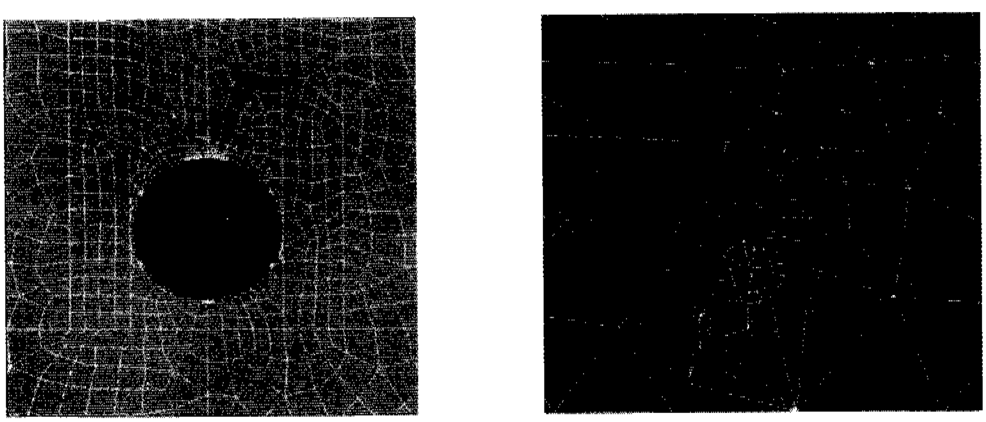


Fig. 12 Effect of cavity's location on σ_{eqv}. ($D_c/D_p=1.0$)

3.3 Tilt crack locating at the top inner surface on a buried pipeline

Figs. 14 and 15 show the effects of cavity depth on the stress intensity factors, K_I and K_{II} for a part-through tilt crack as shown in Fig. 13.

In cases of cavities located at the same depth as pipeline, the effects of cavities on K_I are found to be small due to the small interactive force between cavities and pipeline as shown in Fig. 14. Fig. 15 shows the ratio of K_I/K_{II} of the pipeline with a tilt crack corresponding to various depths of cavities. In this case, the values of K_{II} are found to be considerably larger than those of K_I. The ratio of K_I/K_{II} is found to be the smallest, when



(a) The configuration near tilt crack. (b) The detailed configuration of tilt crack tip at A.

Fig. 13 Configuration of a part-through tilt crack located at the top inner surface of pipeline.

the cavities are located at the same depth as for the pipeline. These results are also shown in Fig. 14.

3.4 Side crack inside of a buried pipeline

In case of the pipeline with a part-through side

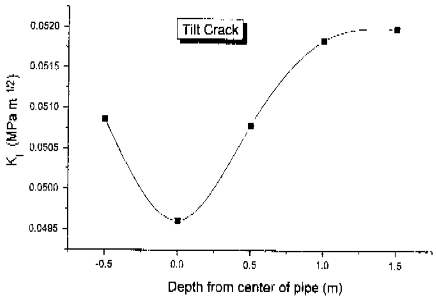


Fig. 14 Effect of cavity's location on stress intensity factor, K_I of pipeline with a tilt crack. ($D_c/D_p=1.0$, $x/D_p=2.215$).

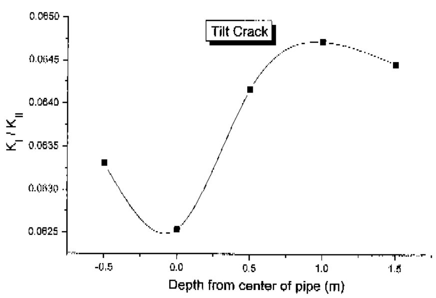


Fig. 15 Ratio of stress intensity factors of pipeline with a tilt crack corresponding to varying location of cavity. ($D_c/D_p=1.0$, $x/D_p=2.215$)

crack such as Fig. 16, the effects of cavity depth on K_I and K_{II} are shown in Figs. 17~20.

In case of cavities located in the same depth as the pipeline, the effects of cavities on stress intensity factor, K_I are found to be the smallest as shown in Fig. 17. These results are similar to

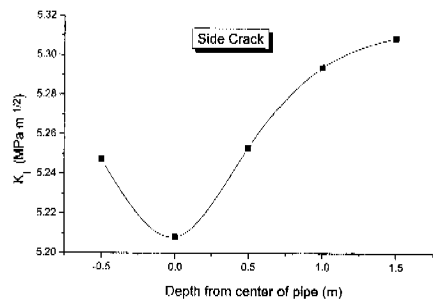


Fig. 17 Effect of cavity's depth on K_I of pipeline with a side crack. ($D_c/D_p=1.0$, $x/D_p=2.215$)

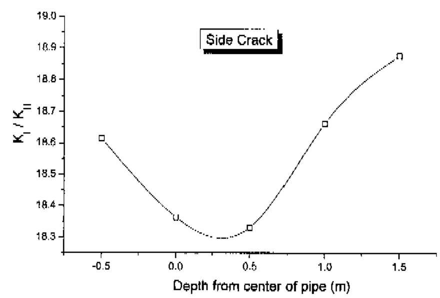
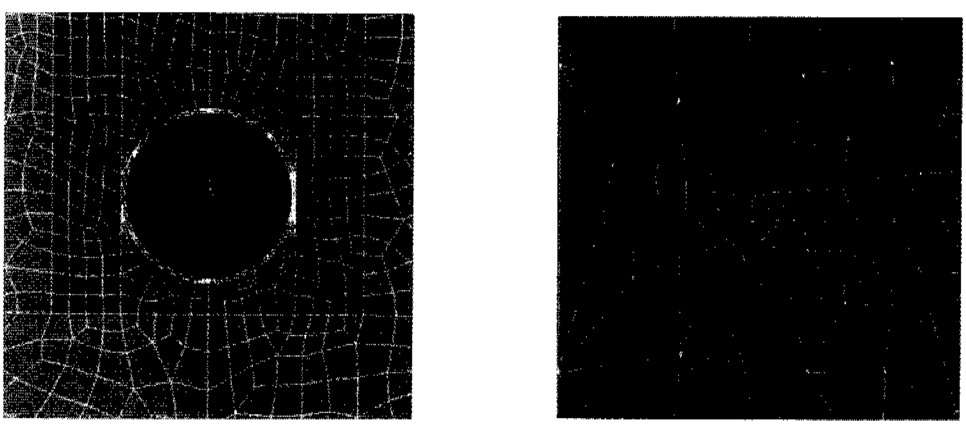


Fig. 18 Ratio of stress intensity factors of pipeline with a side crack corresponding to various locations of cavity. ($=1.0$, $x/D_p=2.215$)



(a) The configuration near side crack. (b) The detailed configuration of side crack tip at B.

Fig. 16 Configuration of a part-through side crack located at the side inner surface of pipeline.

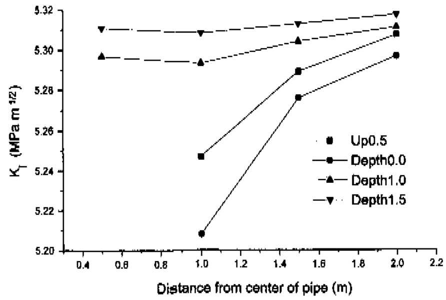


Fig. 19 Effect of cavity's location on K_I of pipeline with a side crack. ($D_c/D_p=1.0$)

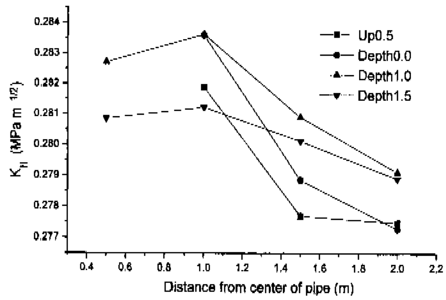


Fig. 20 Effect of cavity's location on K_{II} of pipeline with a side crack. ($D_c/D_p=1.0$)

those for the case of a tilt crack. But, in other locations of cavities, the effects of cavities on stress intensity factor are found to be large. Fig. 18 shows the ratio of K_I/K_{II} of pipeline with a side crack corresponding to various depths of cavities. In this case, the values of K_{II} are considerably smaller than those of K_I. The ratio of K_I/K_{II} is found to be the smallest, when the cavities are located at the same elevation as pipeline. In Fig. 19, the variation of K_I is small, when the cavities are far away from the pipeline, while it is large as the cavities are located nearby to the pipeline. That is because opening mode is largely affected by the cavities. Figure 20 shows that the effects of cavity location on K_{II} are large, when the cavities are located within about 3 times of D_p in horizontal distance. On the contrary, the effects of cavity location on K_{II} are decreased, when the cavity are far away from the pipeline. This is because the effects of interactive forces between the cavities and the pipeline are reduced.

4. Conclusions

The conclusions drawn from the finite element analyses for the effects of circular cavities on maximum equivalent stresses and stress intensity factor of buried pipeline are as follows:

(1) The size effects of cavities on maximum equivalent stresses of buried pipeline are found to be small, when D_c is smaller than D_p. In case of the larger cavities than pipeline diameter, the effects of cavities located below the pipeline are found to be larger than those of located above the pipeline.

(2) The location effects of cavities at the same depth as the pipeline on maximum equivalent stresses are negligible. In case of the cavities below pipeline, the influential ranges of cavity location are about 3 times of D_p in horizontal distance and 2 times of that in vertical depth.

(3) When the cavities are located at the same depth as the pipeline, the effects of cavities on stress intensity factor are found to be the smallest.

(4) The effects of cavities on K_{II} for a tilt crack are found to be large. But, in case of a side crack, the effects of cavities on K_I are shown to be large.

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