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A SHELL MODEL WITH AN EQUIVALENT BOUNDARY FOR BURIED PIPELINES UNDER THE FAULT MOVEMENT

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SUMMARY

A new shell model with an equivalent boundary is presented for estimating the response of a buried pipeline under large fault movement. The length of affected pipeline under the fault movement is usually too long for a shell-mode calculation because of the limitation of memory and time of computers. In this study, only the pipeline segment near fault is modeled with plastic shell elements in order to consider the effect of local buckling and large section deformation. The material property of the pipeline segment far away from the fault is considered as elastic and nonlinear spring elements at the equivalent boundaries are obtained and applied at the ends of the shell model. At last, the failure performances of two water steel pipelines with large diameters at fault crossing in Kocaeli Earthquake and Ji-Ji Earthquake are studied with the proposed shell model considering the different local soil conditions on two sides of the fault.

INTRODUCTION

Several simplified design methods have been proposed to obtain the maximum stress or strain in pipelines crossing an earthquake active fault. A literature review is shown in Fig.1. Usually, the pipe is modeled as a cable (Newmark-Hall[1], Kennedy[2]) or a beam(Wang[3],Liu-Hu[4]) in these methods. The beam model considered the bending stiffness of the pipe which was neglected in the cable model. After a number of severe earthquakes in these years, for example, the 1995 Kobe Earthquake in Japan, the 1999 Ji-Ji Earthquake in Taiwan and the 1999 Kocaeli Earthquake in Turkey, it has been noticed that the huge deformation in the pipe section always creates the very large amount of strain in pipeline, and then causes cracking or fracture in the pipe body. Since it is difficult for the cable or beam model to analyze the large deformation in the pipe crossing section, the shell FEM model has been proposed in the analysis of a pipeline crossing the fault.

The theoretical method shows that the length of affected pipeline under the fault movement is usually larger than 200m, it is too long for a shell-FEM-model calculation because of the limitation of memory and time of computers. To reduce the calculation time, only the pipe segment (about 30*D) near the fault was modeled with shell elements in the beginning, the fixed boundary was adopted at two ends of the pipe. But this way would bring the error to the analysis result because of the forced boundary. Later, a beam-shell hybrid FEM was proposed to avoid adding this manmade boundary. In this study, the pipe

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segment near the fault is also modeled with plastic shell elements in order to consider the effect of local buckling and large section deformation. For the pipeline segment far away from the fault, the material property of the pipe is considered as elastic and nonlinear spring elements at the equivalent boundaries are obtained and can be easily applied to the ends of shell FEM model. Since only the pipe segment near fault is modeled with plastic shell elements, the needed memory and calculation time for this shell FEM model with equivalent boundary are reduced.

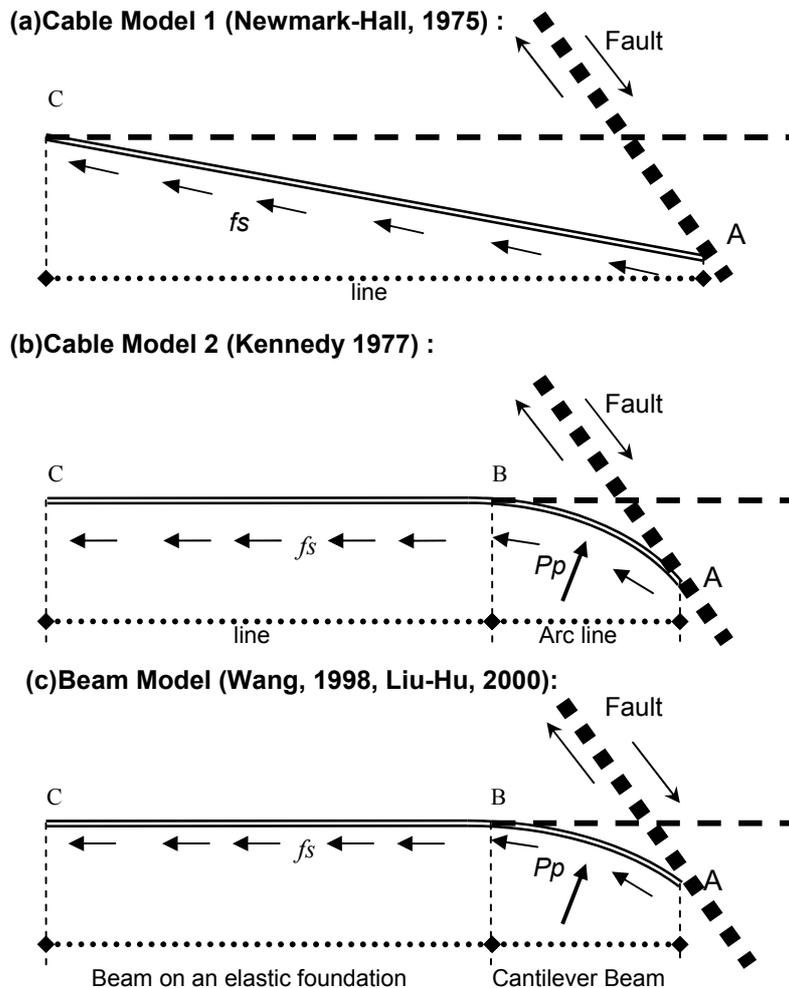
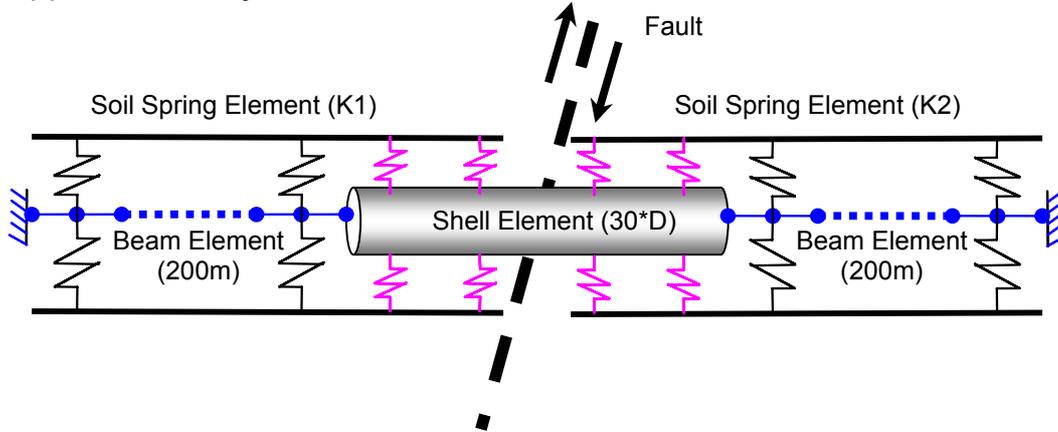


Fig.1 Literature review of the theoretical methods

In 1999, there were two catastrophic earthquakes, Ji-Ji Earthquake in Taiwan and Kocaeli Earthquake in Turkey. In both of these two earthquakes, the damages of water steel pipelines with large-diameter are reported (Table.1). Considering that the large-diameter pipeline usually takes a very important role in the water supply pipeline network, the failure performances of these two pipes are studied with the shell FEM proposed by this paper.

(a) Shell-Beam Hybrid FEM Model



(b) Shell FEM Model with Equivalent Boundary(This Study)

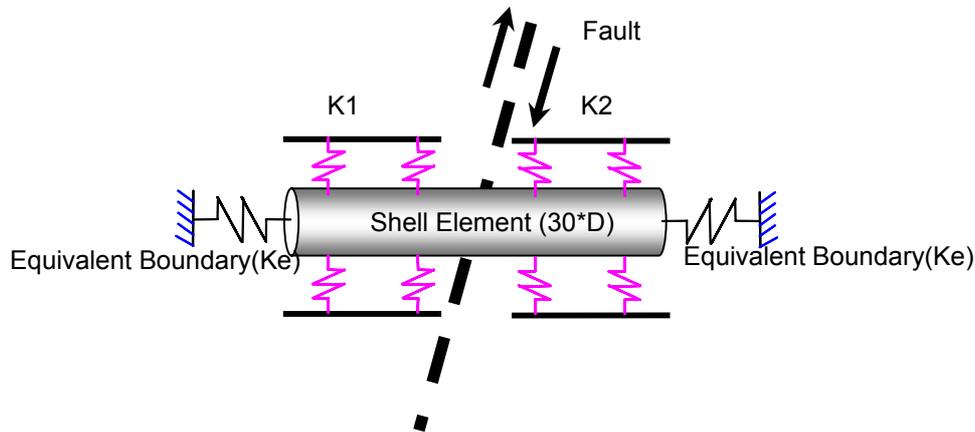


Fig. 2 Shell FEM models for an pipe crossing the fault

Table 1 Damage cases of two water supply pipes with large-diameter

Case	Earthquake	Fault Type	Fault displacement	Pipe	Soil conditions on the two sides of fault
1	Kocaeli Earthquake	Nearly strike-slip	Lateral offset: 1.70m Axial shorten: 2.47m Vertical: 0.0m	$\Phi=2.2\text{m}$ $t=18\text{mm}$	Soil on one side of the fault is much softer than that on the other side.
2	Ji-Ji Earthquake	Reverse slip	Lateral offset: 6.87 m Axial shorten: 1.51m Vertical lifted: 3m	$\Phi=2.0\text{ m}$ $t=20\text{mm}$	Same soil conditions on both sides.

EQUIVALENT BOUNDARY FOR THE SHELL FEM MODEL

Based on the settlement experiment of buried pipeline, the relative displacement of soil and pipe in lateral direction becomes very small when the pipe is far enough to the fault line, and there is only the soil friction along the axial direction. The pipe keeps in a straight line and moves along with the local soil.

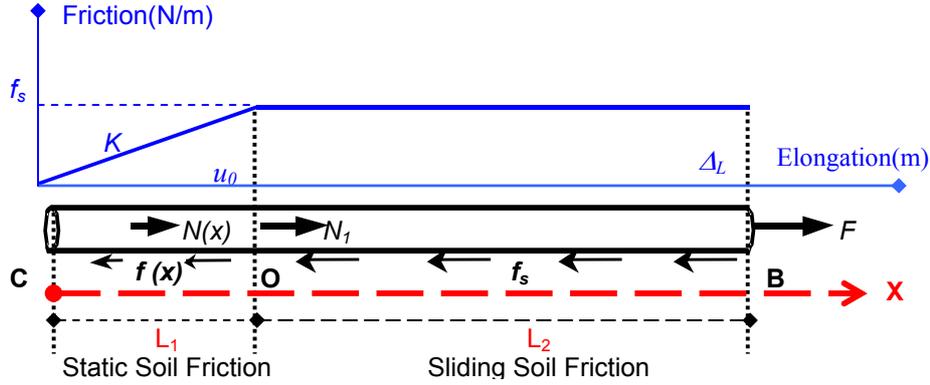


Fig. 3 Equivalent boundary for a buried pipeline

As shown in Fig.3, when the buried pipe segment is far enough to the fault line, the axial strains of points C and B (ε_C and ε_B) caused by F in the axial direction would be:

$$\varepsilon_C = 0, \varepsilon_B = F / AE \quad (1)$$

Where A is the area of pipe section and E is the elastic stiffness of the pipe material.

It is noticed that the length of this pipeline segment BC is not fixed and dependent on the value of F . The pipe segment CB can be divided into two parts: CO and OB. For the pipe segment CO, there is no slide happened between the soil and the pipe, the static soil friction $f(x)$ along CO is assumed increasing with the distance to Point C (x):

$$f(x) = f_s x / L_1 \quad 0 \leq x \leq L_1 \quad (2)$$

$$f_s = 0.75\pi DZ\gamma\mu = Ku_0 \quad (3)$$

where, f_s : the soil friction per unite length along pipeline, D : the diameter of pipe, Z : the buried depth, γ : the density of surrounding soil; μ : the frictional coefficient, u_0 : the yield displacement for the pipe to start to slide in the soil, K : the stiffness of axial soil spring.

The relationship between the axial force ($N(x)$) and the elongation ($\Delta_L(x)$) of the pipe for any point at the pipe segment CO could be obtained by:

$$N(x) = \sqrt{3AEf_s / 2u_0}^{-1/6} \Delta_L(x)^{2/3} \quad (4)$$

At Point O, Equation (4) becomes:

$$N_1 = \sqrt{3AEf_s / 2u_0}^{-1/6} u_0^{2/3} = \sqrt{3AEf_s u_0} / 2 \quad (5)$$

At the point O, the pipe begins to slide in the surrounding soil, the sliding soil friction (f_s) does not change along the pipe segment OB. The length of OB (L_2) can be calculated by:

$$L_2 = (F - N_1) / f_s \quad (6)$$

Then, the relationship between the axial force (N_2) and the elongation (Δ_L) of point B could be obtained by the following equations:

$$\Delta_L = \int_0^{L_1} \frac{N(x)}{AE} dx + \int_{L_1}^{L_1+L_2} \varepsilon_x dx = u_0 + \left(\frac{F^2}{2AEf_s} - \frac{3}{4}u_0 \right) \quad (7)$$

Noticed that the material property of the pipe segment BC should be elastic, the elongation (Δ_L) is conditioned by:

$$\Delta_L \leq \frac{\sigma_1^2 A}{2Ef_s} + \frac{1}{4}u_0 \quad (8)$$

where σ_1 is the yield stress of the pipe material.

Combing Equations (4) and (7), the relationship of the force (F) and the elongation (Δ_L) could be expressed as:

$$F(\Delta_L) = \begin{cases} \sqrt{\frac{3AEf_s}{2}} u_0^{-1/6} \Delta_L^{2/3} & 0 \leq \Delta_L \leq u_0 \\ \sqrt{2f_s AE \left(\Delta_L - \frac{1}{4} u_0 \right)} & u_0 < \Delta_L \leq \frac{\sigma_1^2 A}{2Ef_s} + \frac{1}{4} u_0 \end{cases} \quad (9)$$

When the fault displacement is large enough, $u_0/4 \ll \Delta_L$, Equation (9) can be simplified as:

$$F(\Delta_L) = \sqrt{(2f_s AE)\Delta_L} \quad (10)$$

Equation (10) can also be obtained when the static soil friction is ignored and only the sliding soil friction is considered. In fact, this assumption is also taken in Kennedy method.

Equation (10) is easy to be thought as an expression for the force-displacement curve of a nonlinear spring, it can be the equivalent boundary of the shell FEM model for a buried pipeline under the fault movement.

PERFORMANCE OF THAMES WATER PIPELINE IN KOCAELI EARTHQUAKE

Kocaeli Earthquake (M_w 7.4) occurred on the North Anatolian fault in the northwestern Turkey on August 17, 1999. The Thames Water 2200 mm diameter butt-welded steel pipeline is a raw water pipeline from Yuvacik Dam to Kullar water treatment plant, covering a distance of 5.5 km. The water pipeline crosses the Sapanca Segment of the North Anatolian fault and was damaged at the fault crossing (Eidinger[5]). Within a few days after the earthquake, this Φ 2.2m pipe was exposed in the area of the fault to allow a better understanding of the nature and extent of damage to the pipe. A manhole was cut into the pipeline at the excavation to allow for access and emptying of the pipeline. Damage was observed at three locations: Point A, Point B and Point C. As shown in Fig.4, a small surface leak was observed in the pipe at point A near the fault crossing; a significant leak occurred at point B and the minor leak happened at the bend of pipe (point C).

It should be noticed that the locations of three main wrinkles are not symmetrically spaced around the fault. The wrinkle at point A is very near the fault offset and others at points B and C on the other side are more distant from the fault offset. This strongly suggests that the soil on the side with wrinkles B and C is much softer than the soil on the other side with wrinkle A. To account for the asymmetric pattern of soil properties along the length of the pipeline, 50% of the transverse soil spring on the rigid soil side is adopted for that on the soft soil side.

It is clear that the amount of fault offset imposed on the pipeline was large enough to initiate the wrinkles of the pipeline. The locations of two closest observed wrinkles (Point A and Point B) are what would be expected due to high bending moments in the pipeline. The question is why the third wrinkle occurred. Based on Eidinger's report, this damage case is numerical simulated using the shell FEM model with the equivalent boundary. Considering the effect of pipe-water interaction, the thickness of the pipe adopted in the analytical model is 0.028m. The result is shown in Fig.5.

As shown in Fig.5, the response of the whole pipeline is agreed with the real damage performance of Thames water pipeline. It is very clear that three buckling points occurring in the pipeline. Buckling point A is very near the fault crossing on the rigid soil side. The others (Points B and C) are located on the soft soil side. The compression strain of Point B is the largest of three buckling points, agreeing with the significant leak observed at Point B. Although the compression strain of Point C is the smallest, about 4.3%, it is also larger than the theoretical strain (0.0098) to reach the onset of wrinkle, this is why the minor leak at Point C was observed.

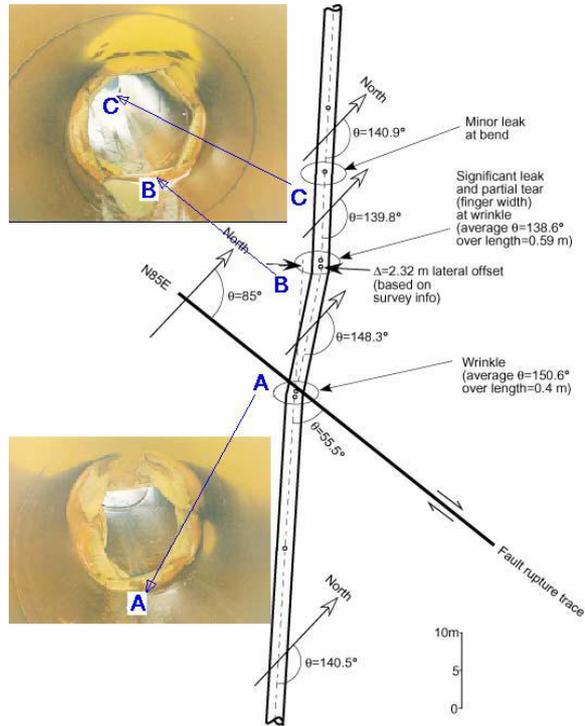


Fig.4 Performance of Thames Water Pipeline at the fault crossing

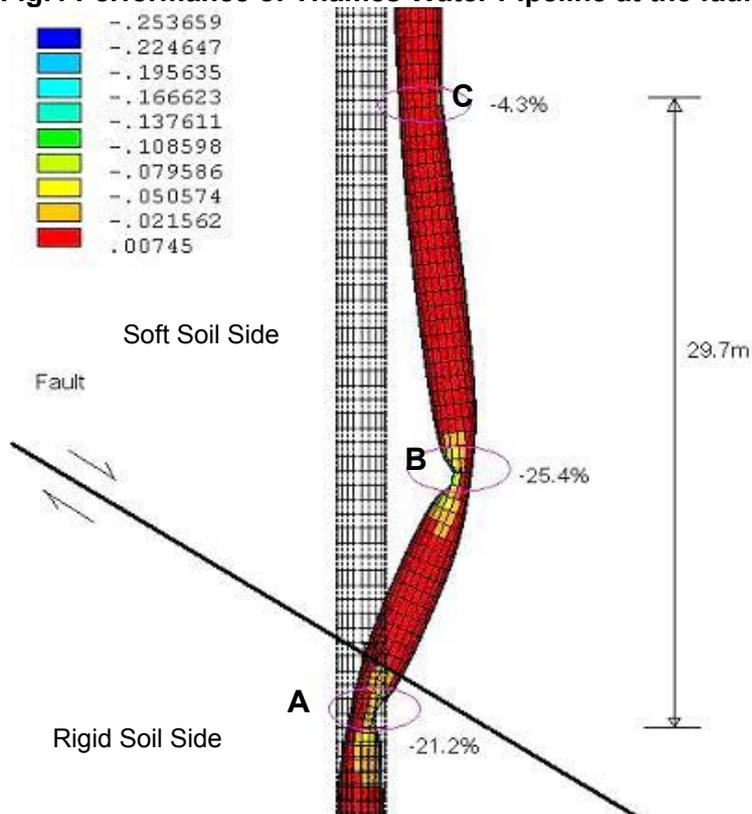


Fig.5 Numerical Simulation for Thames Water Pipeline

Fig.6 shows why and how the third buckling point occurred. Buckling points A and B occur at the beginning of fault movement. They can be thought as two hinges in the pipeline. The pipe segment between these two hinges behaviors like a rigid beam. With the increase of fault displacement, this pipe segment would rotate around the hinges (Points A and B) under the compression loading. Because the different soil conditions on two sides of the fault, the lateral displacement of point B on the soft soil side becomes larger than the lateral fault movement, therefore the third buckling point occurs.

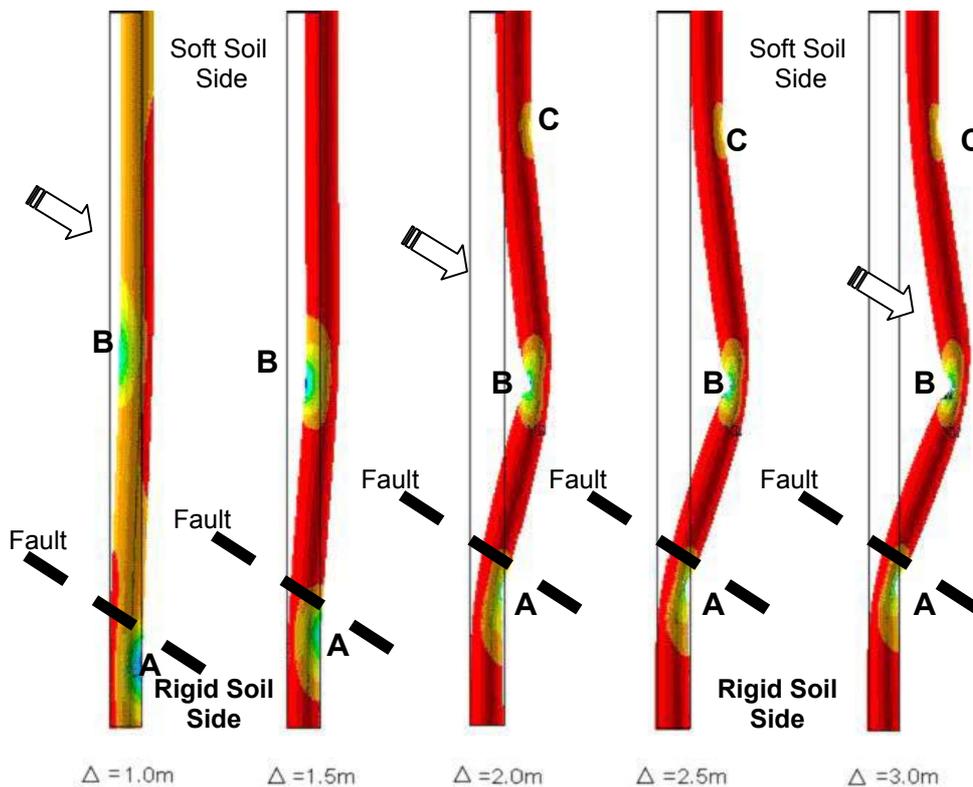


Fig.6 Response of Thames water pipeline with the increase of fault movement

PERFORMANCE OF SHIGANG WATER PIPELINE IN JI-JI EARTHQUAKE

Ji-Ji Earthquake (M_w 7.6) struck Taiwan on Sep. 21, 1999. Shigang water pipe is near Shigang dam, which was also damaged in Ji-Ji earthquake. The reverse-slip fault movement caused 3m vertical displacement, 6.5m horizontal displacement in North, and 2.7 m horizontal displacement in West. Based on the pipeline network map, the lateral displacement of Shigang pipeline is about 6.87 meters; the axial displacement is about -1.51 meters and the vertical uplifted displacement is 3m. The pipeline with 2.0 m for the diameter and 0.02 m for the thickness was buried about 3.4m. Different from the Thames Water pipeline, the soil condition on one side of the fault is same with the other. The result of shell FEM analysis for this damage case is shown in Fig. 7. It is shown that two buckles are symmetrically located on two sides of the fault and the maximum compression strain is about 14%.

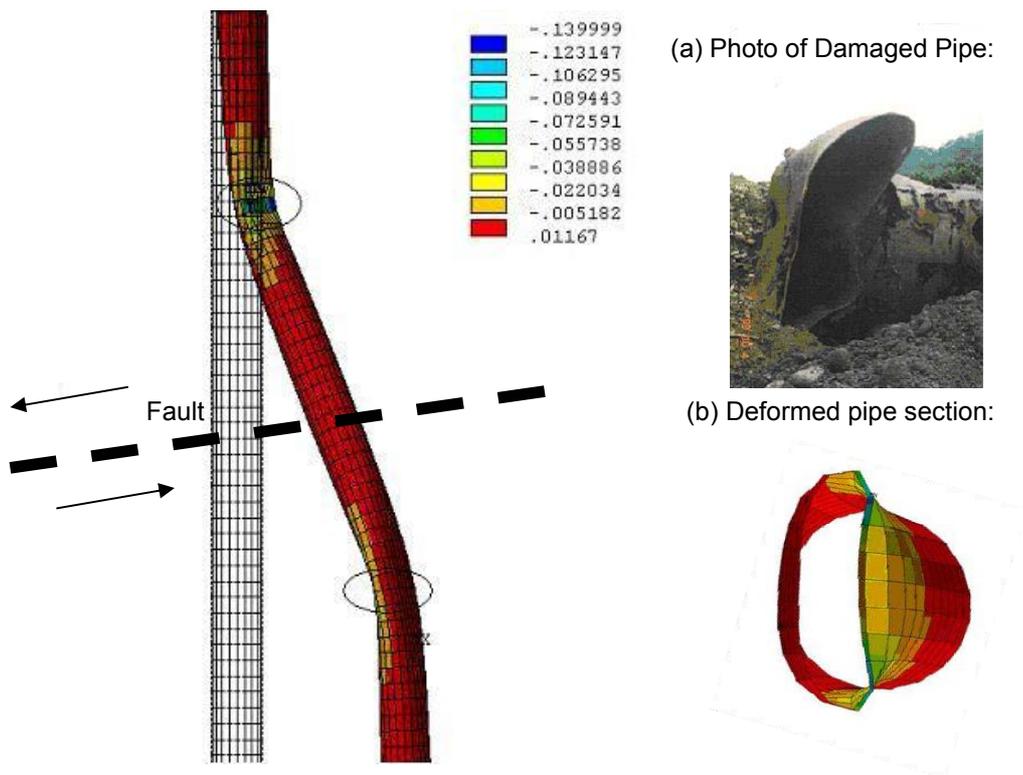


Fig. 7 Performance of the Shigang water pipeline

CONCLUSIONS

A shell FEM model with an equivalent boundary is proposed to estimate the response of a buried pipeline under large fault movements. With the equivalent boundary, only the pipeline segment near fault should be modeled with plastic shell elements in order to consider the effect of local buckling and large section deformation. The performance of Thames Water pipe in Kocaeli Earthquake is a typical damage case for different soil conditions on both sides of the fault. One of the main buckling point is very near the fault offset on the side with more rigid soil. If the fault displacement is large enough, the third buckling point may occur on the soft soil side further from the fault. The performance of Shigang Water pipe in the 1999 Ji-Ji Earthquake is another type of damage case with two main buckling points symmetrically located on two sides of fault.

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