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Ground Dislocation Input-Model for Anti-seismic Design of Fault Crossing Facilities

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ABSTRACT

In many design methods of input fault dislocation, only one side dislocation is generally taken. However, it is necessary to consider the dislocation inputs on both sides of the fault line. We have developed a test device that can verify the viewpoint above points. In this research, verification experiments and numerical calculation have been conducted for the purpose of the optimization of the input model using the above device.

1. Forewords

Recently infrastructures are forced to be constructed crossing active faults due to narrow land usage areas. In the case of the recent Kumamoto 2016 earthquake in Japan, roads, bridges, buried pipelines, etc. have suffered enormous damage. Also, in the past big earthquakes, significant damages were caused by ground fault displacement like as at the time of the 1999Taiwan Ji-Ji earthquake, 2008 China Sichuan earthquake and 1999 Turkey Kocaeli earthquake. Various measures in hardware and software field have been taken for fault crossing facilities. However, it is difficult to establish proper design methods to fault crossing facilities. Particularly, we should think about the input design model of ground dislocation as future research topics.

2. Damage of fault crossing pipelines during 2016 Kumamoto earthquake

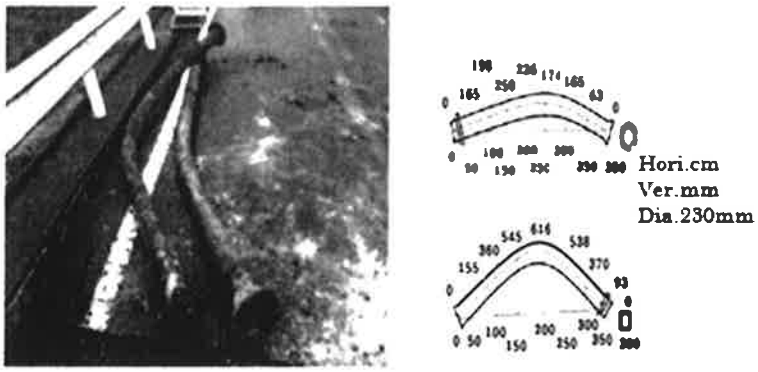


Fig. 2. 1 Deformed DCIP due to fault movement

Fig.2.1 shows damaged water ductile iron pipe segments with φ100mm and 4m length with K-joint type found in Mashiki-Town during the 2016 Kumamoto earthquake. The maximum deformation amounts are 616 mm and 236mm in each segment. The two pipe segments had been connected before the earthquake. The connection position was just same as at the intersection with the fault line. The locations of pipelines and faults are shown in Fig.2.2. Intersection angles between the fault and pile line was approximately 45 degrees. Fig.2.3 shows the fault dislocation in the vicinity of the location of Fig.2.2. The discrepancy was about 1.2 m. There have not been such cases in ductile cast iron pipelines showing deformed pipe body during past big earthquakes as shown in Fig.2.1. In order to clarify the mechanism, authors conducted simple surface wave exploration and experiments[1),2),3)].

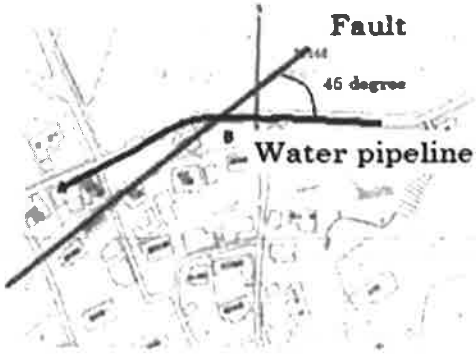


Fig. 2. 2 Cross angle of pipeline and fault line

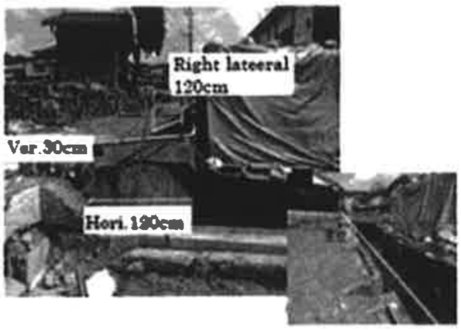


Fig. 2. 3 Dislocation on surface ground

3. Estimation of damage mechanism

Surface wave test was conducted at damaged pipeline sites to know the condition of the ground below the surface where the pipeline is buried. The surface survey test measures the time histories of surface wave excited by the impulse source using a large number of geophones on the sounding line, and calculates the phase velocity curve (dispersion curve) from the large number of wave test histories, and measures the one-dimensional measurement line give a method of obtaining a two- dimensional S wave velocity structure by performing continuously.

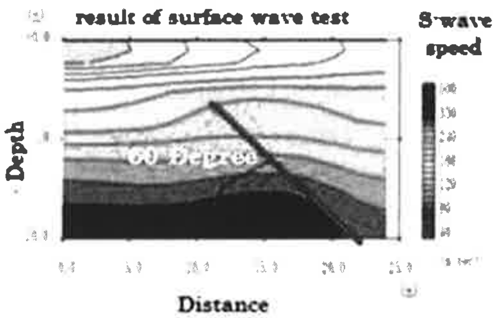


Fig. 3-1 2D S-wave velocity structures

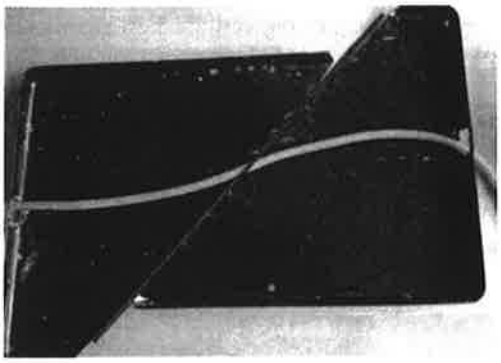


Fig. 3-2 Simple experiment device

By setting a line of 50 m and putting seismographs in an interval of 2 m, the S-wave velocity structure can be determined. It is possible to estimate the ground depth structure up to about half the survey line length. Fig. 3.1. S-wave velocity in pipe-buried ground layer is about 150 meters / sec showing inclined rock layer with about 500 meters / sec S-wave in the vicinity of the underground 10 m depth. The rock formation angle is about 60 degrees. It corresponds to the inclination angle assumed in the tomographic analysis model. These velocity values can also be used when calculating the ground reaction force when examining the response of the pipeline. Further, in order to study the mechanism of failure mode of the pipeline, as shown in Fig. 3.2, a ground model box movable to 45 ° direction was made and a model pipeline was embedded in the ground model box to dislocation equivalent to fault movement in the cross angle direction. The material of the ground box is the paper clay.

Fig. 3. 3 Behavior of model pipeline

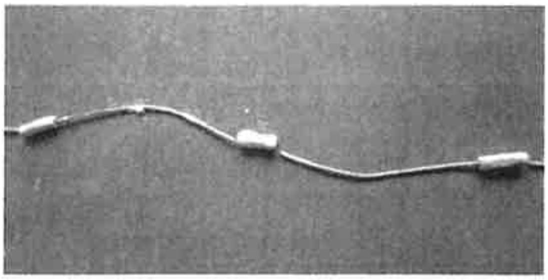


Fig. 3. 4 Deformed jointed pipeline by model test

In order to simulate the damage performance of the actual ductile pipe segments, a metal wire covered by rubber tube was used as a model of ductile pipe with K-type joints. The joint was placed at just a position crossing the fault line. Results is shown in Fig.3.4. The process of the pipe behavior is considered as shown in Fig.3.5. At the beginning of the pipe behavior under dislocation may deformed like as a straight pipe because of the fixed point at the position of cross point between fault and pipeline under the help of rotation of the joint up to the joint limit angle. Then, the second step, the pipe segments are continued to receive compression forces by soil stiffness and deformed like as arch configuration making separation gap between the pipe and surrounding ground. At the final stage of ground dislocation, every joint is separated like as ④stage shown in Fig.3.5. Fig.3.6 shows the estimated damage deformation based on the experimental results. The deformed configuration is very similar to the actual damaged ductile iron pipelines. When the fault displacement increases, the K-type joint rotates to a certain extent, but beyond that, rotation does not proceed, and it is presumed that the ground pushing force acts in opposite directions on both sides of the fault line to cause the actual deformation.

From the experiment, the damage mechanism of DCIP with K-type joint that received a right lateral slip 200cm fault amount crossing the fault at 45 degrees is considered as above Fig.3.5. The pipeline before the earthquake was straight, and receive the pushing action force and moment of the rotary-expansion at the joint under fault displacement, and deformed up to a possible angle in step ②. In ③ stage, the pipeline behind the faulting direction without reaction force acts on for the release of soil force. Then soil pressure from the opposite direction is generated and tube deformed by acting forces. It is considered that the joint completely disjoined by further fault displacement at ④stages. Fig.3.5 is the image of sketch of actual DCIP pipelines behavior after the stop of fault dislocation. The existence of a joint at the intersection of the pipeline and the fault line is presumed to be one of the factors that led to the arch deformation of two DCIP segments.

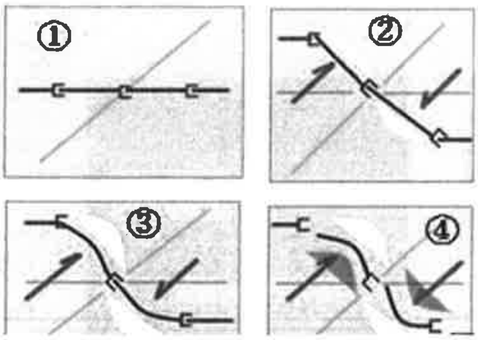


Fig. 3. 5 Estimated behavior of fault crossing pipeline

Fig. 3. 6 Estimated behavior of actual pipeline

Currently in many design codes, it is usually assumed that the pipeline position at the intersection of the pipeline and the fault line is in fixed boundary condition. In the design guideline of ALA (American Lifeline Alliance) is giving one side of the fault displacement without giving the ground motion at the opposite side. It is considered to be appropriate to give on side vertical displacement for ground sinking, of course. However, It is important to make clear which one is better to give one side or both side input for strike slip fault movement.in order to verify the validity of the deformation process of the pipelines, several experiments were carried out by developing a new experimental devices that can be observe the more accurate behavior.

4. Verification experiments

4.1 Experiment device

Fig.4.1 and Fig.4.2 show experiment devices to verify the optimum input model for fault crossing facilities. Fig. 4.1 is for horizontal strike-slip fault dislocation and Fig. 4.2 is for vertical fault dislocation. Two soil boxes (200x200x50mm) could move simultaneously or just one box is movable and the other is fixed. For the latter case, ground subsidence performance could be experimented.

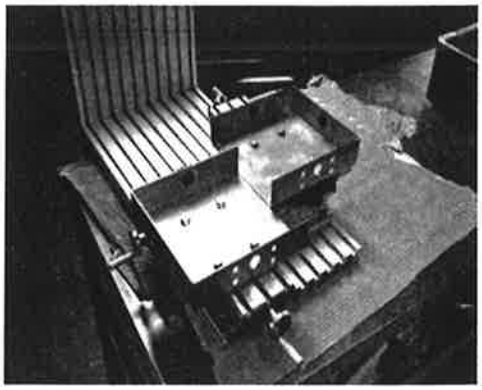


Fig.4.1 Horizontal dislocation device

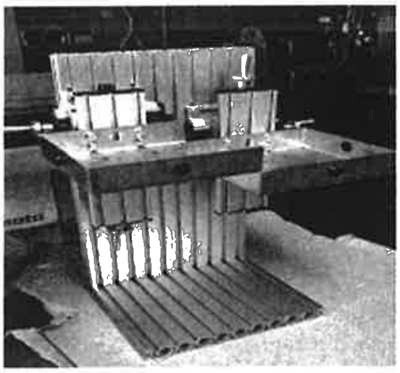


Fig.4.2 Vertical dislocation device

In order to observe the behavior of the buried pipeline that receives fault displacement, two cases of the tests were done. The part of both ends of the pipeline can be moved following surround ground in the soil boxes. In addition, agar (transparent gelatin) material was used so that the buried pipeline behavior could be seen visually (Fig. 4.3). The devices shown in Fig.4.1 and Fig.4.2 are jointly developed by author and Tsukahara Manufacturing Co. Ltd[4].

4.2 Test for horizontal fault dislocation

First, horizontal fault dislocation tests will be explained. Fig. 4.3 shows a photograph of the new device. The soil boxes are set on plates with rails. Displacement of fault dislocation 0 to 200 mm can be given at contacting line at two boxes in horizontal directions. The displacement is given by changing screw rotation to horizontal movements.

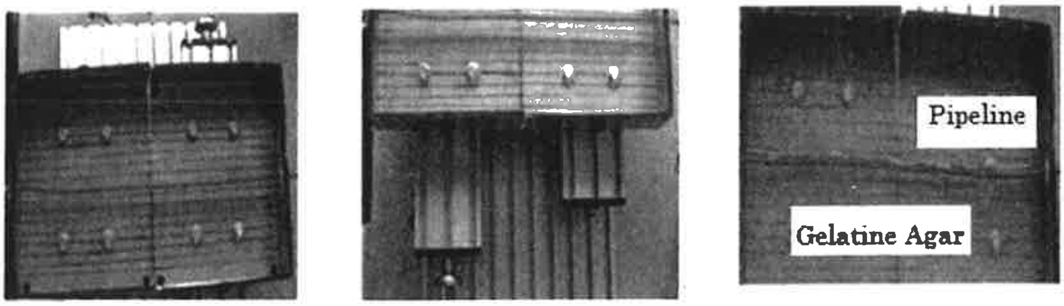


Fig.4.3 Experiment device for fault dislocation in horizontal movement

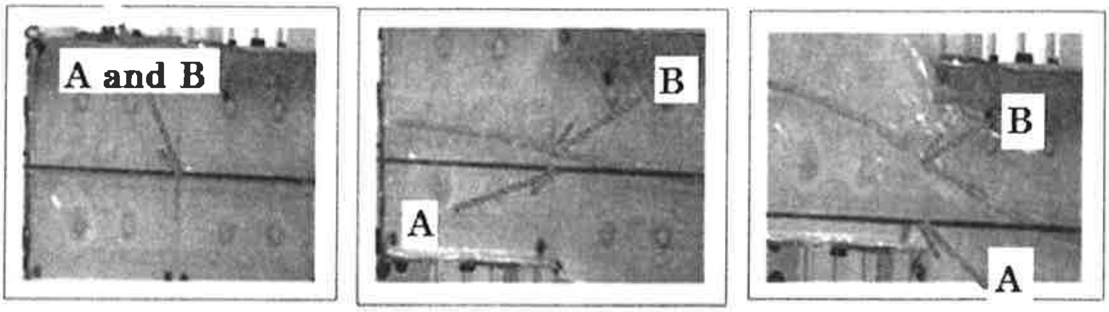


Fig. 4. 4 Behavior of buried continuous pipeline under one direction

In Fig.4.4, point A is a position in absolute coordinate of the soil movement at the exact cross position between soil and buried pipeline, and point B is a position of the pipeline in relative coordinate of pipe movement at the position between soil and buried pipeline. In one side fault movement, point A and point B is going to sepate under increasing the fault movement and pipe movement is also occurring in opposit sides by fault movement. When the soil stiffness in the fixed box is so large (hard ground), the point B will behave like as a fixed point in the pipeline. The pipeline behavior will be much affected by the stiffness in the non- movable opposite side box.

4. 3 Fault dislocation test under both direction movements

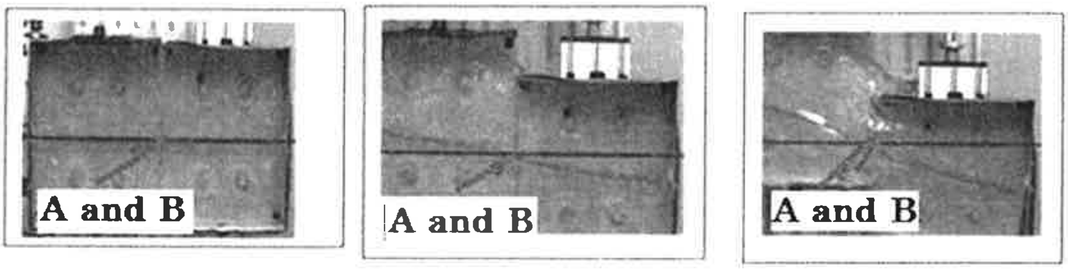


Fig. 4. 5 Behavior of buried continuous pipeline under two opposite direction movements

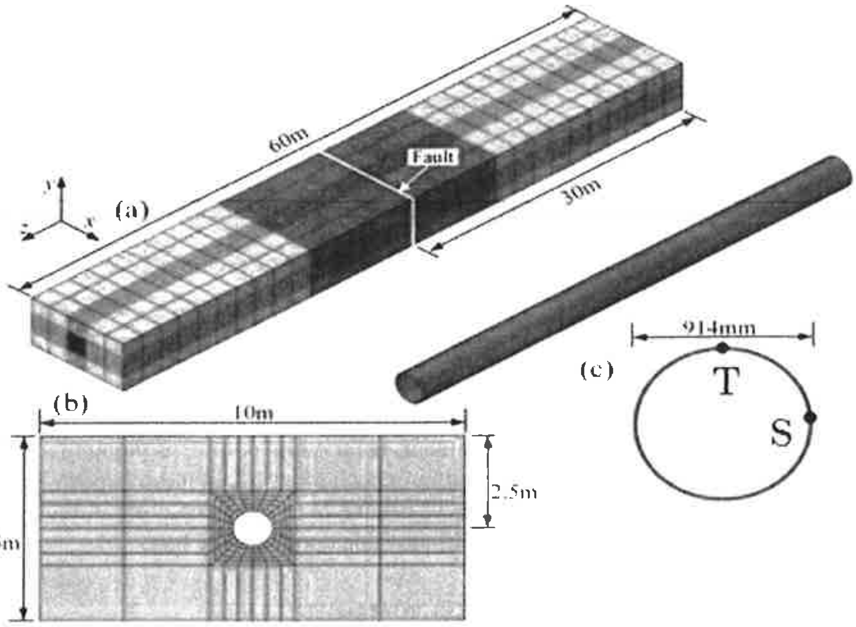
In the case of both side soil boxes are moving by fault dislocation, point B does not move and point B is matching point A due to no relative movement at point B. Then the pipeline behavior is much different compared with ones by one side soil box moving case by fault dislocation. The span length of pipe moving by both side movement becomes half span length compared with that one side movement case.

5. Analytical calculation

5. 1 Numerical analysis of continuous pipeline subjected to strike-slip fault movement

(1) 3D Finite Element Model

The general-purpose of finite element program ABAQUS was adopted in this study to investigate the structural response of steel pipelines subjected to strike-slip fault movement, by considering two different fault movement modes: one direction movement and opposite direction movements. Fig.5.1(a) presents the three-dimensional (3D) finite element (FE) model of a continuous steel pipeline embedded in an elongated soil prism along the z axis. The overall dimension of the soil-pipe interaction model is 60m in 10m(width) x 2.5 m(depth). The seismic fault plane divides the soil into two blocks of equal size. The steel pipeline has a diameter of 914 mm, wall-thickness of 8 mm and a burial depth of 2.5 m from the center of the cross-section to the ground surface. The mesh for the surrounding soil in the x-y plane and the mesh for pipeline are shown in Fig.5.1(a),(b) and (c). Finer meshes were adopted to the surrounding soil close to the strike-slip fault. Four-node reduced-integration shell elements (type S4R) are employed for modeling the cylindrical pipeline segment, and eight-node reduced-integration “brick” elements (C3D8R) are used to simulate the surrounding soil. For this preliminary study, it is simply assumed that the pipeline crosses the fault at an angle of 90 degrees.



(a) soil formation with tectonic fault; (b) soil cross-section; and (c) steel pipeline

Fig. 5.1 3D Finite element model

The API X80 steel material is commonly used for oil and gas pipelines. A large-strain von Mises plasticity model with isotropic hardening is adopted in this study for the steel pipe material of an elastic modulus of 210 GPa and yield stress of 596 MPa. The mechanical behavior of soil material is described through an elastic-perfectly plastic Mohr–Coulomb constitutive model, characterized by the cohesion, the friction angle, the elastic modulus, and Poisson's ratio as listed in Table 5.1. The interface between the outer surface of the steel pipeline and the surround soil is modeled using a contact algorithm, which allows separation and sliding between the pipeline and the soil. The friction coefficient, between the pipe and the soil is assumed to be 0.5.

Table 5.1. Physical parameters of the materials.

Material	Density($kg \cdot m^{-3}$)	Elastic modulus	Poisson's ratio	Friction angle (°)	Cohesion (MPa)	Yield stress (MPa)
Soil	1640	0.022	0.32	36	0.01	—
Pipeline	7800	210	0.3	—	—	596

5.2 Application of fault movements

Two different fault movement modes were adopted in this study, namely the one direction movement (Method 1) and the both direction movements (Method 2), as illustrate in Fig. 5.2(a). For Method 1, one block of the soil is fixed and a uniform horizontal displacement of 1.2m is applied to the other block. For Method 2, both blocks of soil are moved simultaneously in the opposite direction as shown in Fig. 5.2(b). Fault movement is imposed using a displacement-controlled scheme, which increases gradually from zero up to a relative fault dislocation of the maximum magnitude of 1.2 m.

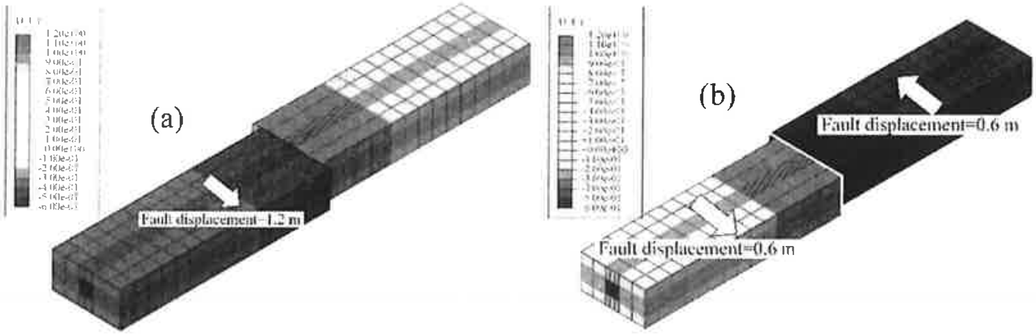


Fig.5. 2 Two methods of fault movement application
(a) Method 1 and (b) Method 2.

5.3 Numerical results

(1) Overall deformations of pipeline

Fig.5. 3 compares the overall deformations of the steel pipeline subjected to different magnitudes of relative fault movements using the affore mentioned two different methods. It can be seen that generally the overall structural response of the pipeline under two different fault movement methods are similar to each other. Method 1 of fault movement will lead to slightly larger structural response to the pipeline in term of Von-Mises stress. With the increase of the magnitude of relative fault movement, the ovarling of the center portion of the pipeline increases, which leads to the final buckling of the pipe wall in adjacent to the fault.

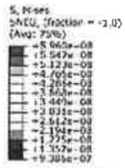
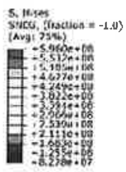
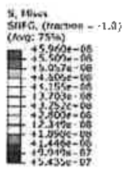
Relative fault movement	Fault movement methods	Overall pipeline deformations (length of the pipeline below is 20 m)	Magnitude of Von-Mises stress
0.8 m	Method 1		
	Method 2		
1.0 m	Method 1		
	Method 2		
1.2 m	Method 1		
	Method 2		

Fig. 5.3 Overling deformation of pipeline subjected to strike-slip fault movement

(2) Lateral displacement of pipeline

Figs.5.4 and Fig.5.5 present the lateral displacements of pipeline at pipe crown (Point T) and pipe waist (Point S) as indicated in Fig. 5.1(c) respectively. Slightly differences can be found for the pipeline lateral displacements under two different fault movement methods. When fault movement exceeds 1.0 m, buckling of the pipeline occurs. As shown in Fig.5.4 and Fig.5.5 are the response results in Method 1and Method 2. The pipeline position at the cross point of the pipeline and fault line is like as fixed point in Method2 and the pipe behavior is much different from the results by Method 1 both in the case of 0.1m and 0.4m strike slip fault displacement.

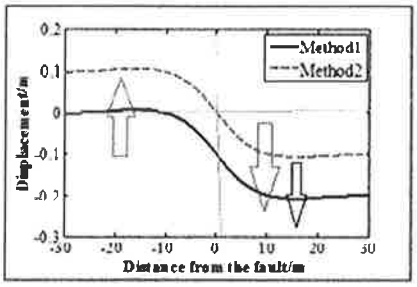


Fig.5.4 Pipe deformation for 0.1m soil dislocation

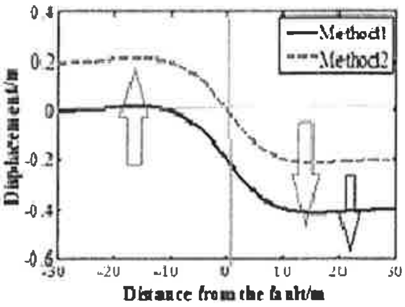


Fig.5.5 Pipe deformation for 0.4m soil dislocation

6. Summary

Followings are the contents obtained by present research results on strike slip fault crossing pipelines.

① Mechanism of arch -shaped large deformation of two segments of DCIP at Mashiki-Town during 2016 Kumamoto earthquake has been clarified due to surface fault movement with crossing 45 degree between a pipeline and a fault line.

② One of the reasons for severe damage was the location of the pipe joint just at the points of crossing location of the pipeline and the fault.

③ Difference of the performance under fault movement between one side or both sides strike slip fault movements has been compared by using simple test device. It turned out that the way of applied direction gives important effects to pipe deformation.

④ 3D-FEM analyses have been done to compare the results for different input directions.

⑤ Input fault dislocation should be applied at both sides of fault movements for the design of buried pipes crossing faults under consideration both for continuous and segmented pipelines.

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