An In-situ Experimental Study on Buried Pipelines with Internal Pressure Subject to a Simulated Reverse-slip Fault Movement

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SUMMARY:
This paper presents an in-situ experiment on full-scale high-density polyethylene (HDPE) pipelines with a butt fusion welding connector and water pressure inside subject to the action of an artificial reverse fault. In order to simulate the movement of the reverse fault and the earthquake-induced permanent ground deformations, a facility consisting of a reinforced concrete reaction floor and three pieces of reaction wall is built on the field lying the Nanjing Jubaoshan Park, and a set of loading device is developed to create the soil displacements simultaneously in the vertical and longitudinal directions, which are the results that the reverse fault have moved. Total 8 standard HDPE pipelines served as water supply function in China are assembled into 4 groups of test condition and measured when they are buried in the undisturbed clay sites and forced by the artificial ground displacements. Based on the test results, behaviour of the pipelines due to the large permanent ground deformation caused from the reverse fault is researched, and parametric effects of the buried pipelines are also presented.

Keywords: Buried pipelines; reverse fault; in-situ experiment; full scale test; permanent ground deformation

1. INTRODUCTION

Buried pipelines are vital lifeline systems that provide essential services for human needs in modern society. Some buried oil, gas, water and sewer pipelines have been damaged heavily during destructive earthquakes. One of the major reasons why the buried pipelines are destroyed is that large abrupt differential ground movements due to rupture of an active fault will present severe affects on a buried pipeline. For example, surficial displacement of more than 4 m was observed along the fault during the great Wenchuan, China earthquake of May 12, 2008. Thus, it is necessary to investigate behaviour of the pipelines across the fault zones, so that the pipelines could be designed safely to accommodate large ground deformations without failures.

Newmark and Hall (1975) were one of the first to develop simplified analysis methods to estimate performance of the buried pipeline subject to the fault movement. Then there have been a number of approaches to the fault crossing problem over the years, for example, Kennedy et al. (1977) extended the Newmark and Hall's procedure, Wang and Yeh (1985) modified the analytical model of Kennedy's, Takada et al. (1998) proposed a shell model for the fault response analysis of the pipe. It is noted that two tendencies existed on present studies for investigations of the buried pipeline crossing an active fault, they are: (1) available simplified analytical and semi-empirical methods for the analysis of earthquake effects on the buried pipeline were only applicable to strike-slip and normal faults, and cannot be used for the case of reverse fault; (2) Seldom had experimental researches done for the problem because of difficulties of implementation, especially for full-scale pipeline tests. In general, a buried pipeline will be tensile due to the strike-slip fault compared to be compressive due to the reverse fault. In published experimental studies, Trautmann et al. (1985) performed an experiment to study uplift and lateral force-displacement response of steel pipe buried in sand, Karimian (2006) investigated soil-pipe interaction of relatively large diameter steel pipelines by a new full-scale physical modelling facility. All these two experiments are model tests without considerations of fault types, in which the pipe imposed by forces moves in the soil packed in a storage bin. Feng et al. (2000), Zhang et al. (2011) and Sim et al. (2012) performed individually shaking table tests modelling the pipes subjected to the fault motion, and Yoshizuka et al. (2003) investigated the affects of fault-induced permanent ground deformation to the buried steel pipelines with elbows by large scale experiments.

As mentioned above, presently most experiments are either small-scale tests or conducted in the laboratory, and suitable mainly for the strike-slip type fault. In this paper, an in-situ experimental study on full-scale buried pipelines under the movements of a simulated artificially reverse fault is introduced. The objective is to investigate the performance of the buried pipelines crossing the reverse fault area, and reduce the influences of similarity law that caused from the model tests in the laboratory as well, meanwhile to provide a discriminant for reliability of finite element modelling.

2. EXPERIMENTAL SETUP

2.1. Apparatus

The test apparatus consisted of four parts, including the reaction facility, the fault loading device, instrumentation, and data acquisition system. The reaction facility, as shown in Figure 1, was constructed on the test field lying the Nanjing Jubaoshan Park and consisting of a floor, a wall reaction force and two piece of side wall, all of which fabricated from reinforced concrete. The reaction floor was a rectangular RC bedplate of 5.15 m long, 4.10 m wide, and 500 mm thick, and four foundation beams with the section of 300×800 mm were set perpendicular to the side walls at the bottom of the floor to prevent the reaction facility slide. Both the reaction wall and the side walls were anchored to the floor and all the heights of them were 3 m. The thickness of the reaction wall varied gradually from 500 mm on the top to 1000 mm on the bottom compared to the side walls with the constant thickness of 300 mm. The two side walls of 3.75 m wide were used for containing the soil covered the loading flat and support to raise artificial fault device.

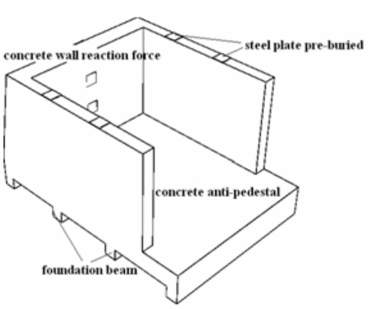


Figure 1. Concrete facility reaction force

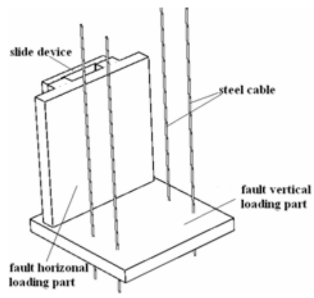


Figure 2. Loading device

The Loading device was used to create displacements for simulating the reverse fault movement, the structure of the device was shown in Figure 2. Total two 10mm thick plates stiffened by grid-beam structure fabricated from H section steel of 200×200×10 mm were prepared, one of them was laid on the concrete floor in the reaction facility, and another stood on it. The lying plate was 1.9 m wide and 1.95 m long, and drawn by four steel cables stiff enough to ensure very small tensile strain when forced. Another ends of the cables were connected to two big steel girders supported on the concrete side walls. See Figure 3. There were four mechanical jacks between the steel girders and the side walls to raise the girders up, so that the lying plate would produce vertical displacement because of traction by the cables, and anything on the lying plate, e.g. the soil covered together with part of the buried pipeline inside and the standing plate, would be hoisted. The standing plate of 1.62×2.0 m was pushed to move horizontally by other four mechanical jacks between the wall reaction force and the plate, and the soil and the pipeline could be squeezed together along the axial direction. Total ten rolled cylinders arranged in two columns were fixed on the standing plate in order that the plate could move relative to the jacks. See Figure 4.

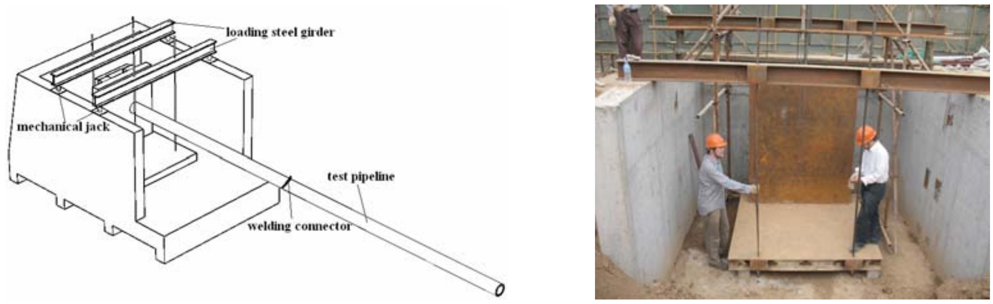


Figure 3. Apparatus used for the loading test

(a) Jacks for loading (b) The steel plate with cylinders (c) Displacement meters

Figure 4. The Loading device used for the test

As Figure 3 has shown, the facility reaction force is developed like a big box without the cap. After the loading device, including the lying and standing plates, steel girders, cables and jacks, is installed and the test pipeline has been took place, soil will be filled in the facility and the gully that the pipeline buried inside. When the lying plate is lift up and the standing plate is pushed forward simultaneously, the soil together with the pipe close to the loading plates will slide upward along a slope with respect to the other portion of ground, which remains stationary during the slip. Thus the artificial movements simulating the reverse-slip fault are made in the field, and the behaviours of the pipelines may be investigated.

2.2. Test field and pipe specimen

A flat ground against a small hill in the Nanjing Jubaoshan Park is selected for the fault crossing tests, in which a portion of soil has been took out and a flight of step formed. The concrete facility reaction force was built under the step in order to keep roughly the same elevation with the ground. The soil in the test site is well graded natural undisturbed silt clay and its properties are listed in Table 1.

Table 1. Properties of Soil

Soil density (g/cm^3)	Moisture content (%)	Cohesive force (kPa)	Friction angle (deg)	Compression modulus (MPa)	Poisson's ratio
2.00	21.20	64.00	21.40	16.44	0.30

Total 8 pipes were tested during the simulated fault experiment. All the test pipes, as shown in Figure 5(a), were standard HDPE pipelines with the length of 6 m, which served as water supply function in compliance with China GB/T 13663-2000 standards. These standard HDPE pipes were connected for every two pipes so that the test pipes were assembled into 4 groups, in which any group of pipe was 12 m long and contained a joint. The butt fusion welding method was utilized for the pipes according to GB/T 13663-2000 standards, as shown in Figure 5(b). The heat butt fusion welding method is installed easily and connected reliably, however, some initial stress would be produced near the connectors after welding. Both ends of each group of pipes for test were sealed with steel flanges, as shown in Figure 5(c). The group of pipe was full of water before test and kept a standard atmospheric pressure inside during test.

(a) HDPE pipe (b) Butt joint of pipes (c) Sealing flange (d) Pipe before buried

Figure 5. Pipes used in the test

In order to investigate performances of the buried HDPE pipe under the large permanent ground deformation caused from the reverse-slip fault, total 4 groups of pipe were tested. Table 2 summarizes the parameters for each test. Note that the planes of the artificial fault are perpendicular to axial direction of the pipeline for the first and second group, and skewed in the intersection angle of 60 degree for the third and fourth group.

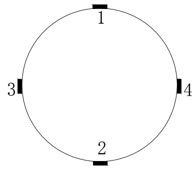
Table 2. Summary of the test modes

Mode number	Initial angle of pipe crossing fault	Outer diameter of pipe (mm)	Wall thickness of pipe (mm)	Ratio of diameter to wall thickness	Burial depth of pipe (mm)	Ratio of burial depth to outer diameter	Fault offset vertically (mm)	Fault offset horizontally (mm)	Fault angle
1	90°	200	18.2	11	990	4.95	200	30	81.5°
2	90°	315	28.6	11	880	2.93	200	45	77.3°
3	60°	200	18.2	11	810	4.05	200	55	74.6°
4	60°	110	10.0	11	820	8.20	200	71	70.5°

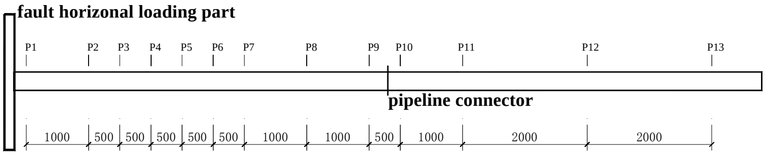
2.3. Measurement system

The four HDPE pipes were tested successively, and the pipe's responses including strains and vertical displacements were measured in pace with the ground deformation increasing step by step. The axial and flexural strains were measured around some selected section at different positions spaced longitudinally to the pipe. At each instrumented section, there are four metal strain gauges epoxy bond to the surface of the pipe uniformly along the ring, in which two strain gauges mounted to the top and bottom surface (Location 1 and Location 2) are used for measurement of axial strain while an additional two strain gauges on the two side of the surfaces (Location 3 and Location 4) measurement for flexural strain. Considering that the peak strain and the maximum displacement probably appear close to the fault zone, the spacing for the measured sections are selected densely near the fault fractural area and location of the butt fusion connector of the pipe, and scattered far away from the connector and the fault zone. The instrumentation scheme for the strains is shown in Figure 6. All the strain gauges and sensors were wrapped tightly by a few layers of cellophane for protection before the tested pipe was buried.

(a) Strain gauges on the pipe



(b) Arrangement of strain gauges at section

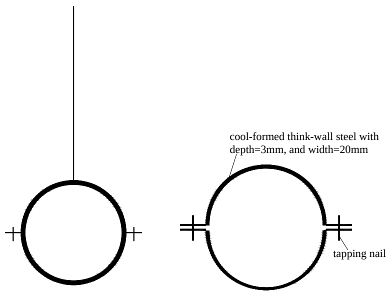


(c) Positions of the measured section for strains

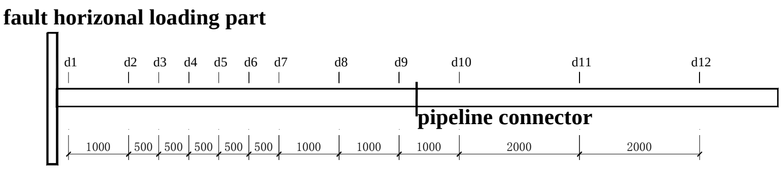
Figure 6. Instrumentation scheme for pipe strains

It is difficulty to measure the displacements of the pipe because they have been covered by the soil during the test. A kind of metal surveyor's pole with a hoop in one tip is developed for this purpose, see Figure 7(a) and 7(b). All the poles were connected to the pipe by the hoops which grip the surface of the pipe without sliding relatively and stood perpendicularly so that another tip could be revealed outside from the soil. The 1.2-m-high poles are used for measurement of the displacement of the pipe and high enough to ensure the top tips are above the ground at least 200 mm. A 1-m-high shaft with 100 mm diameter, which is created by PVC pipe and isolated from the soil, is constructed at each location that the pole stands, so that the poles could be stretched from every shaft and move freely with the buried pipe. There are total 12 poles located in the positions near the strain gauges mounted on the pipe, and the elevation of the top tip of every pole is surveyed after each load level. Thus, it is easy to infer the burial depth of the pipe and the vertical displacements at the selected positions during every test stage.

(a) Surveyor's poles for displacements



(b) Hoops connected to the poles



(c) Positions of the measured section for displacement

Figure 7. Instrumentation scheme for vertical displacements of the pipe

The ground deformation close to the fault area was also observed during the test. Many small wooden stakes nailed partly in the ground were placed in cross rows with spacing 500×500 mm or 1000×1000 mm each other, and joined together by the cotton thread, as shown in Figure 8. The elevations of these stakes were surveyed and recorded after each load level, and the ground deformation was also observed by changes of the squares gathered round with the cotton spread.

Figure 8. Small wooden stakes used for observation of the ground

Two soil pressure cells were installed up and down the pipe respectively at the end of the pipe and kept close to the standing plate of the loading device. Meanwhile, four displacement meters were used, two of them were placed to the upper surface of the lying plate for collections of vertically displacements of the fault, and others to the outer surface of the standing plate for horizontally displacements. All the data, including forces, strains and displacements, were collected by the data acquisition system during the test.

3. EXPERIMENTAL PROGRAM

The artificial reverse fault movement was created when the lying plate rose up and the standing plate went forward simultaneously. As described above, any plate was driven by four mechanical jacks with a travel of 200 mm. Therefore, the displacement that the artificial fault could reach must be less than 200 mm based on the capacity of the loading device. The loading process was divided into 8 levels mainly in accordance with implementation of the maximum displacement vertically, see Table 3. It was impossible to reach the displacement more than 65 mm in horizontal direction during all the tests accomplished because the jacks cannot be operated when the soil had been squeezed heavily. All the values listed in Table 3 were collected by the displacement meters.

Table 3. Loading levels during the test

Test Number	Displacement (mm)	Loading levels							
		1	2	3	4	5	6	7	8
1	Vertical	20	40	70	100	140	170	200	-
	Horizontal	10	20	30	30	30	30	30	-
2	Vertical	20	40	70	100	130	160	180	200
	Horizontal	13.5	18	20	30	33	40	45	45
3	Vertical	20	40	70	100	130	160	180	200
	Horizontal	15	26	28	37	40	50	55	55
4	Vertical	20	40	70	100	130	160	180	200
	Horizontal	19	30	45	50	60	65	65	65

4. TEST RESULTS

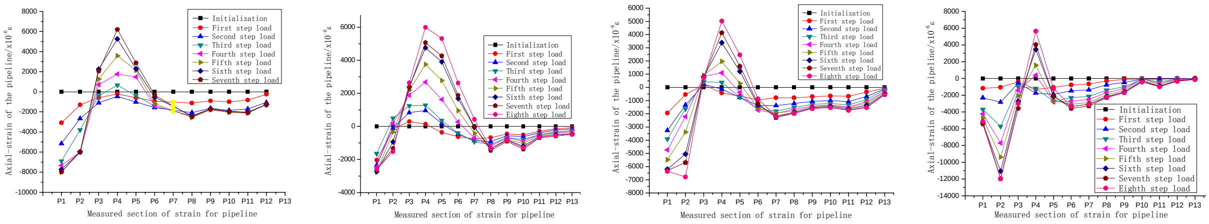
4.1. Surface rupture close to the fault

The process of the ground deformation and rupture was observed and measured by the wooden stakes. The surface cracks mainly concentrated on the places near the edges of the lying plate, which could be considered as the fault-rupture zone of the hanging wall. Both the number and width of the cracks would decrease gradually with the distance far from the loading plate. Figure 9 shows the final condition of the ground rupture in the vicinity of the fault during the test for second group of pipe.

Figure 9. View of the ground rupture

4.2. Axial strains of the pipe

Both axial strains at Location 1 (top surface) and Location 2 (bottom surface) on the measured section of the pipe were collected successfully except strains on the sections of P7 and P13 during the test for the first group of pipe because of no work of the strain gauges there. Figure 10 shows the collected strain results at Location 2 for the four tests, in which the strain on the P7 section of the first group of pipe is a forecasting value expressed in a yellow dot.

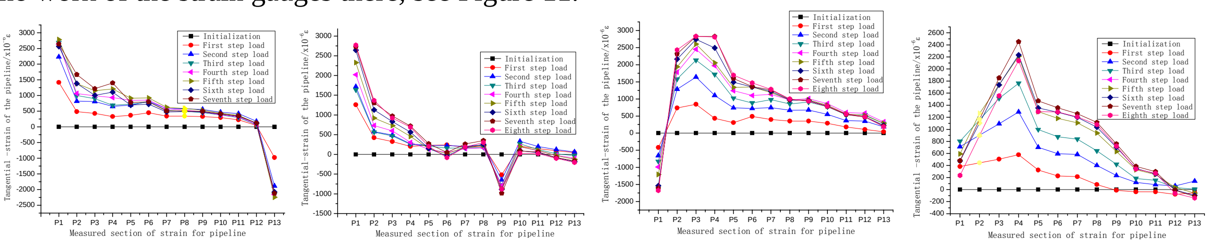


(a) Test for the 1st group (b) Test for the 2nd group (c) Test for the 3rd group (d) Test for the 4th group

Figure 10. Distribution of axial strain of the pipe (Location 2)

4.3. Tangential strains of the pipe

Both axial strains and tangential strains at Location 3 and Location 4 were measured and collected successfully except those on the P8 section for first group and P2 section for fourth group because of no work of the strain gauges there, see Figure 11.

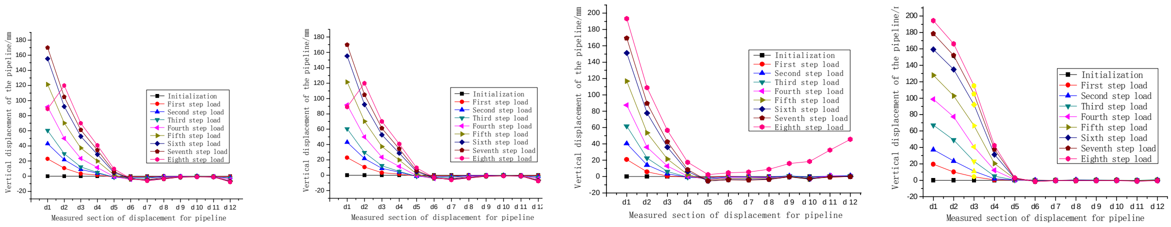


(a) Test for the 1st group (b) Test for the 2nd group (c) Test for the 3rd group (d) Test for the 4th group

Figure 11. Distribution of tangential strain of the pipe (Location 4)

4.4. Vertical displacements of the pipe

The test results of the vertical displacements along longitudinal direction of the pipe are shown in Figure 12. During the test for the fourth group of the pipe, the value collected at the position of d3 section is not correct because of surveying mistakes. The value marked by a yellow dot in Figure 11 is the result forecasted.

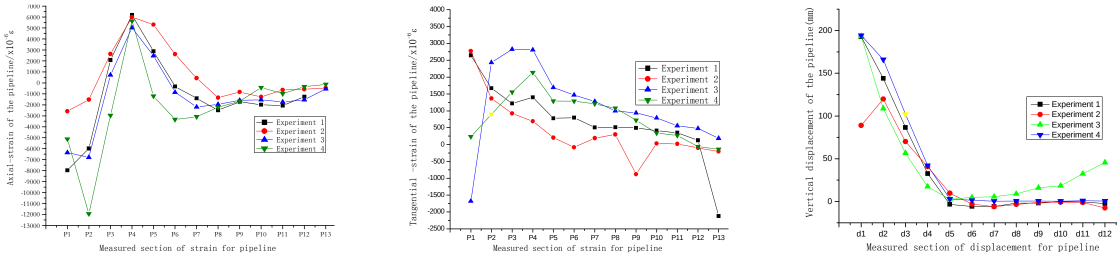


(a) Test for 1st group (b) Test for 2nd group (c) Test for 3rd group (d) Test for 4th group

Figure 12. Distribution of vertical displacement of the pipe

4.5. Maximum responses of the pipe

It is obvious that all the maximum axial strain, the maximum tangential strain and the maximum vertical displacement must arise after the last level loading (level 8). Figure 13 shows the results.



(a) Axial strains (Location 2) (b) Tangential strains (Location 4) (c) Vertical displacements

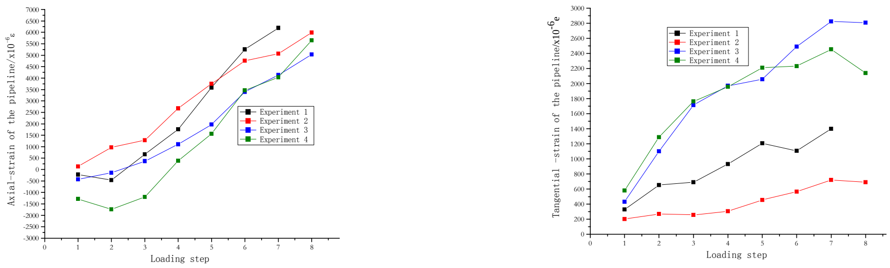
Figure 13. Maximum responses of the pipe

Observing Figure 13, the maxima of both axial strain and tangential strain appear generally at the position of P4 section, where is the nearest among the measured sections to the edge of the lying loading plate, and decrease gradually with increase of the distance to the lying plate and approach to zero at the end of the pipe. For distribution of the maximum vertical displacements, as shown in Figure 13(c), the value at the position of d1 section is larger obviously than the other section and reach to 200 mm, which is consistent with the biggest height the loading plate has been lifted during the test. The displacements decrease swiftly and tend to zero as the range of about 2.5 m to the loading plates has been exceeded. This means that the buried pipeline is obliged to move synchronously together with the surrounding soil in the vicinity of fault rupture zone and affected smaller and smaller with increasing distance to the fault because of the constraints of the soil. Note that neither the strains nor the displacements of the pipe near the connector vary greatly, so the connecting way of butt fusion welding for HDPE pipes could be safe if the connecting part lies out of a certain distance to the fault.

5. AFFECTS OF SOME PARAMETERS

Among the four groups of the pipe used in the test, total three specifications of the HDPE pipe with different diameters are selected, including two pipes of 200 mm diameter and one with 110 mm and 315 mm, respectively. Note that all the ratios of diameter to wall thickness for the tested pipes are 11, and during the preceding two tests (the first group and the second group), and the later two tests (the third group and the fourth group), the pipes are arranged in same intersection angle with the fault but the diameters different. It is known from Figure 13 that the responses of the pipes with small diameter are more severe that those with big diameter when they own the same ratio of diameter to wall thickness. The affects of diameter and wall thickness are mainly concentrated on the range close to the fault zone, and very small when the pipe far away from the fault zone.

The diameters of the pipes are same but the crossing angles with the fault are different in the tests for the first group and the third group. Observing Figure 13, it is known that the affects of the crossing angles are also mainly concentrated on the range close to the fault zone, and decrease gradually with increase of the distance from the fault area. The response of the pipeline with crossing angle of 60 degree, in which the pipe will be in the state of biaxial bending, is bigger than that of 90 degree. The tangential strains close to the welding connector are bigger when the crossing angle is equal to 60 degree than those perpendicularly.



(a) Axial strains (Location 2)　　(b) Tangential strains (Location 4)

Figure 14. Influence of loading levels to response of pipeline

The loading processes of vertical displacements are same by eight loading levels for total four tests except the first group and all the maximum levels are 200 mm. The relationship between the maximum strains of the pipe and the loading levels is given in Figure 14. Based on Figure 14, it is known that: (1) both axial and tangential strains on the pipe will grow with increase of the loading levels, and responses of the pipe with small diameter are bigger than that large diameter; (2) the pipes with small diameter section are easier to produce large deformation in the local range and probably fail under the fault movement; (3) the affects of the loading levels to the pipe are bigger near the fault area than positions far away from there.

5. CONCLUSIONS

This paper has described the behaviour of buried HDPE pipe with a butt welding joint under different levels of artificial reverse fault movement. The test are conducted on the silt clay site, and main conclusions as following:

(1) Basically the state of motion of the reverse-slip fault and induced ground deformation can be produced by the facility reaction force and the loading device described in this paper, but the scale of the simulated fault movement relies on the capacity of the loading jacks;

(2) The standard HDPE pipes appear good performance to resist the ground deformation, the severe responses generally locate in the vicinity of the fault zone, and decrease gradually with the position of pipe section far away from the fault area;

(3) Some parameters, such as the pipe diameter, the thickness of pipe wall, the angle of pipeline crossing fault, and loading levels, have important influences on the responses of the pipeline under the reverse fault movement;

(4) The buried pipes will be in the state of biaxial bending if they cross obliquely the fault, so it is the best to lay the pipelines perpendicularly to the fault;

(5) Generally the way of butt fusion welding to connect the HDPE pipes is reliable, only slight influences exist in a local range close to the joints;

(6) The stiffness the pipe has a significant influence on the strains, because the standard HDPE pipes possess same ratio of diameter to wall thickness, the pipes with large diameter will be more stiff and seismic performance better than those small diameter.

AKCNOWLEDGEMENT

This research was funded by the National Natural Science Foundation of China under Grant Number 50678084, and the writer wish to thank Mr. H. Chang and R. Luo assisted with design and construction of the apparatus, M. Chen, Z. Bian, X. Liao, H. Xing, W. Jiang, H. Zhang, J. Yin, P. Zhao, X. Zhang and Z. Yang assisted with the pipe loading tests, Mr. G. Zheng assisted with measurement, Drs. L. Zhao, P. Zhang, Z. Zhou and A. Liu assisted with experimental program.

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