Response Analysis of a Buried Pipeline Considering the Process of Fault Movement

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SUMMARY:
For the seismic design of a pipeline crossing the fault, the fault displacement is usually estimated with the empirical relationship between Magnitude and Fault displacement. It should be noticed this fault displacement may under-estimate the fault displacement imposed on the buried pipeline. Based on those strong ground motion records near the causative faults, the maximum displacement of fault movement (MFD) is larger than permanent fault displacement (PFD). With the baseline correction, fault displacement time histories were obtained from those recordings near fault during Chi-Chi earthquake and Wenchuan earthquake, and the relationship between MFD and PFD is developed. As an example, the response of an oil pipeline crossing the Xiaojiang fault was analysed. The axial strain of static analysis under PFD is less than the Max. strain but a little larger than the last residual strain in the pipeline of dynamic analysis considering the process of fault movement.

Keywords: *Buried pipeline, Fault movement, Shell model*

1. GENERAL INSTRUCTIONS

Oil and gas pipelines are important lifeline facilities, spread over a large area, and generally encounter a range of seismic hazards and soil conditions. Many buried pipelines run through areas of high seismic activity and are therefore exposed to considerable seismic risk. The seismic hazards to oil & gas pipelines include the transient ground movement and the permanent ground displacement (PGD). Transient ground movement describes the shaking hazard by seismic waves and the amplifications due to surface and near-surface ground conditions and topography, including peak ground acceleration (PGA), peak ground velocity (PGV), response spectrum (Sa) and ground motion history, a(t). Permanent ground displacement (PGD) describes the ground failures resulting from surface fault rupture, slope movements and landslides, liquefaction-induced lateral spreading and flow failure, and differential settlement.

The performance of oil pipeline systems was relatively better than those buildings. However, catastrophic failures did occur in many cases, particularly with large permanent ground displacement due to fault movement. Based on the investigation of pipeline damage in the 1995 Kobe Earthquake, the 1999 Ji-Ji Earthquake and the 1999 Kocaeli Earthquake, PGD poses the greatest hazard to a buried pipeline. Therefore, assessment of permanent ground displacement is important for the design of oil/gas pipelines that cross faults, which is usually estimated with the empirical relationship between Magnitude and Fault displacement. But the fault displacement imposed on the buried pipeline may be under-estimated. Based on those strong ground motion records near the causative faults, the maximum displacement of fault movement (MFD) is usually larger than permanent fault displacement (PFD). This paper is aimed to discuss its effect on the response of pipeline.

2. SEISMIC HAZARD ASSESSMENT OF OIL & GAS PIPELINE SYSTEM

Davis (2005) presented an initial version of the uniform confidence methodology for the design of water pipeline systems that is used by the American Lifelines Alliance (ALA, 2005). The uniform confidence hazard evaluation provides a methodology to assess earthquake hazards so that all pipes in a pipeline system are designed to be consistent with their intended function, with a uniform confidence that design forces are greater than or equal to the actual forces a pipe may experience during an earthquake. For the oil/gas pipeline, seismic hazard level applied during design depends on the importance of pipe, adopting the probability of exceedance in 50 years, as shown in Table 2.1.

Table 2.1 Design levels of Oil & Gas Pipelines seismic hazard in China

Pipe class	Probability of exceedance in 50 years	Return period (Years)
I	2%	2475
II	5%	975
III	10%	475

In general, an oil/gas pipeline system includes pump stations, buried pipe, above-ground pipe and pipe bridges when crossing rivers. Table 2.2 summarizes the transient and permanent ground movement hazards considered during the design of pipelines.

Table 2.2 Seismic Hazards for Oil & Gas Pipelines

Hazard	Oil/gas pipeline system	Earthquake Parameters	Obtain from:
General Shaking	Buried pipe	PGA, PGV, Tg	PSHA
	Pipe bridge, Above-ground pipe, Pump stations	PGA, PGV, Tg, Sa, a(t)	
Faulting	Buried pipe, Above-ground pipe	expected amount of fault displacement, crossing angle	DSHA or Disaggregate PSHA
Liquefaction	Buried pipe, Above-ground pipe, Pipe bridge	PGA, Magnitude, L of pipeline exposed to PGD	Disaggregate PSHA
Differential settlement	Buried pipe, Above-ground pipe, Pipe bridge	PGA, Magnitude, L of pipeline exposed to PGD	Disaggregate PSHA

Disaggregate PSHA has been proposed to estimate the PGD induced by liquefaction and landslide. The PSHA for fault displacement is developed within the framework of probabilistic seismic hazard analysis (Youngs, 2003). The earthquake occurrences are also modelled as Poisonian sequences. In addition to earthquake occurrence rates, PSHA for fault displacement also requires the probability distribution function of displacement along the fault line and probabilities that a rupture will affect the site. The distribution of displacement along the fault line is strongly dependent on the source mechanism of the earthquake and the rupture of the site for pipelines crossing faults needs further research.

Because PSHA for fault displacement hazard analysis needs further research, the PGD induced by fault movement is still primarily determined by DSHA in China. Fault displacement can be estimated using historical evidence, paleoseismic evidence and/or slip rate calculations. Usually the maximum fault displacement (*Dmax*) is estimated by an empirical relationship with earthquake magnitude (*M*) as follows:

$$\log D_{\max} = \mathrm{A} \cdot M - \mathrm{B} \tag{2.1}$$

where *A* and *B* are the regression coefficients.

At present, the maximum fault displacement determined by DSHA in China is for a 100-year period. This period is much shorter than the design return period (2475 years) identified in Table 2.1. This would result in the design for a surface fault rupture corresponding to M less than the characteristic magnitude, thus the maximum fault displacement could be exceeded. To consider the uncertainty in the magnitude of the earthquake, as well as the uncertainty in the amount of displacement, given the occurrence of a particular magnitude earthquake, a more refined approach for DSHA is to define the design-basis fault displacements corresponding to the pipelines in Table 2.3. In another words, the design-basis fault displacement of pipe class I is larger than that of pipe class III.

Table 2.3 Design-basis fault displacement for oil & gas pipelines.

Pipe class	Probability of exceedance in 50 years	Design-basis fault displacement
I	2%	$\log D_{\max} = \mathrm{A}\cdot M - \mathrm{B} + \sigma$
II	5%	$\log D_{\max} = \mathrm{A}\cdot M - \mathrm{B} + \sigma/2$
III	10%	$\log D_{\max} = \mathrm{A}\cdot M - \mathrm{B}$

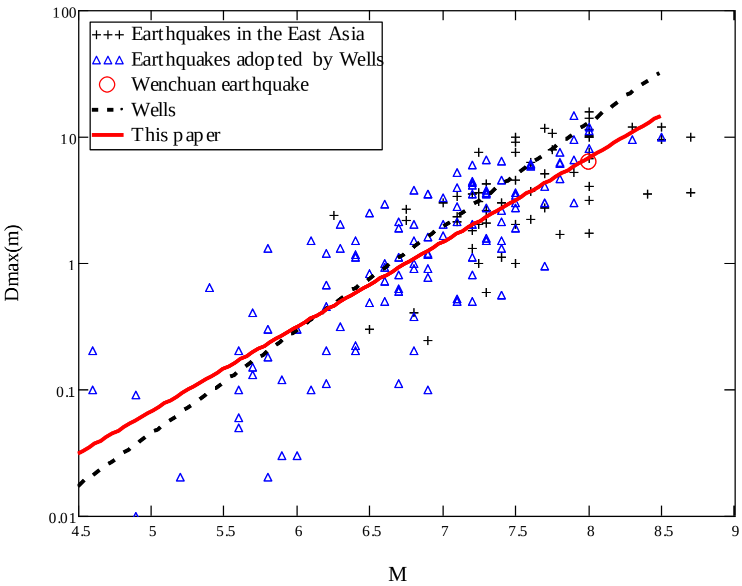

Figure 2.1. Maximum displacement (*Dmax*) versus earthquake magnitude (*M*)

σ in Table 2.3 is the standard deviation and it is becoming more important when deciding upon the design-basis fault displacement. Based on the research of Wells (1994), fault displacement data of 60 earthquakes in East Asia, as well as the maximum fault displacement of the M 8.0 Wenchuan Earthquake, 2008, were supplemented. The new empirical relationship between $D_{\max}$ and the magnitude was obtained using 186 earthquake data values. As shown in Table 2.4 and Fig. 2.1, the result of the regression is improved and the standard deviation σ in Table 2.4 is 0.38.

Table 2.4. Regressions of maximum fault displacement (*Dmax*) and earthquake magnitude (*M*)

Authors	Equation	*r*	σ	data	Magnitude Range	Slip type
This paper	$\log D_{\max} = 0.67M_s - 4.53$	0.82	0.38	186	4.6~8.7	strike-slip, normal, and reverse faulting
Wells, 1994	$\log D_{\max} = 0.82M_m - 5.46$	0.78	0.42	80	4.6~8.5	strike-slip, normal, and reverse faulting

Note: *r* is the correlation coefficient

3. THE PROCESS OF FAULT MOVEMENT BASED ON RECORDS NEAR THE FAULT

Near-fault ground motions are different from ordinary ground motions in that they often contain strong coherent dynamic long period pulses and permanent ground displacements. Strong ground motions recorded on digital accelerographs in recent earthquakes, including the 1985 Michoacan, 1999 Chi-chi, 1999 Kocaeli and 2008 Wenchuan earthquakes, contain both dynamic ground motions and static ground displacements. Those near fault recordings made it possible to study deeply the characteristics of fault movement. However, there are also considerable offsets of baseline of the near fault accelerograms. The reasons of the offset of baseline are more complex than those occurred in other near field recordings with farther fault distance. Therefore, general baseline correction schemes for near field recordings, as pointed out by Boore (2001). The displacement time histories after baseline correction during the Chi-chi and Wenchuan earthquakes are shown in Fig. 3.1-3.3.

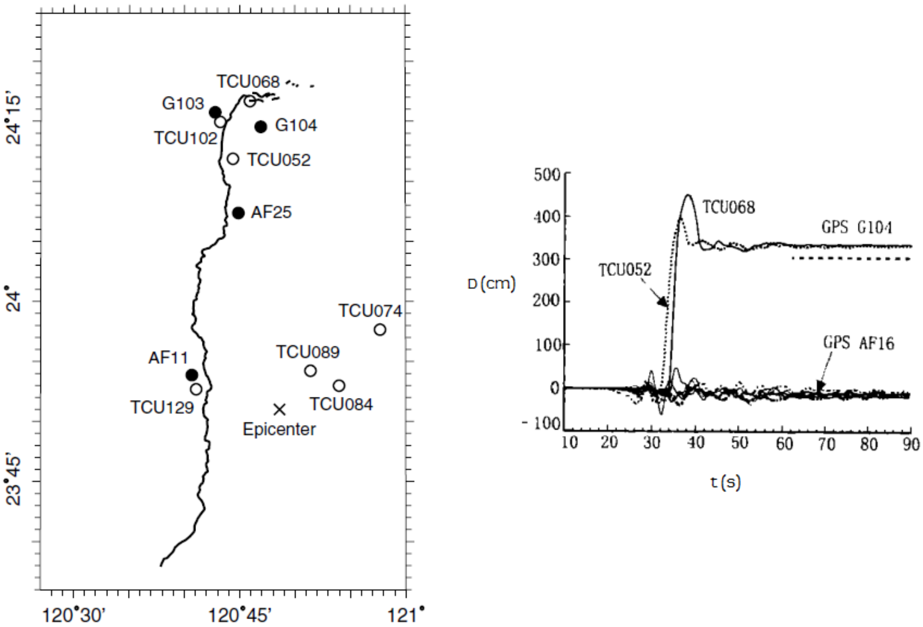

Figure 3.1 Distribution of a part of near fault accelerographs stations during Chi-chi earthquake and the vertical displacement time histories after baseline correction (Wang, 2004)

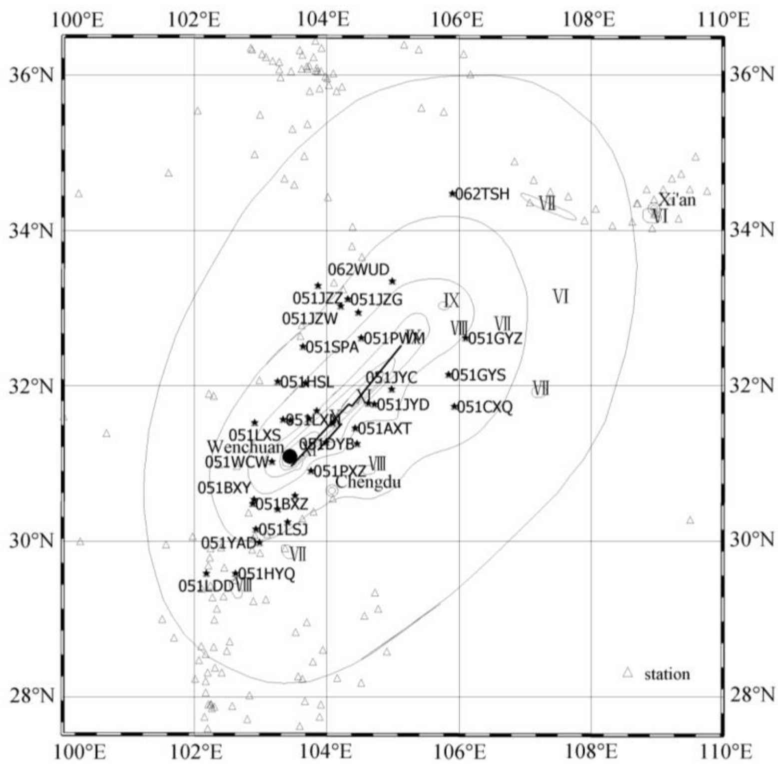

Figure 3.2 Distribution of a part of near fault accelerograph stations during Wenchuan earthquake

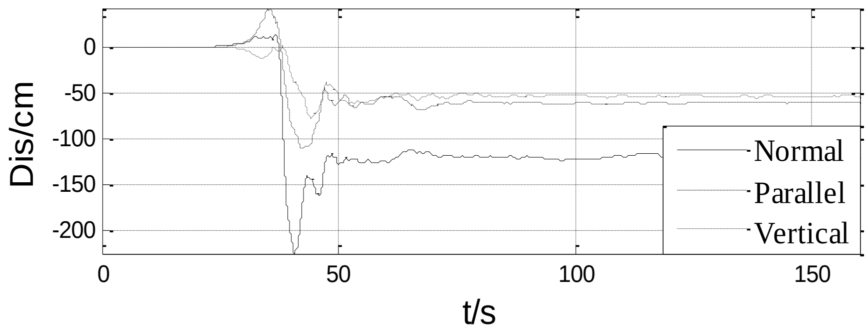

Figure 3.3 Three-component displacement time histories after baseline correction (051MZQ station)

Based on those recordings near the fault， the fault movement lasts about 14 seconds. At the begging, there is a small reverse fault (sometimes not very obvious), the fault movement comes up to a maximum point, and then down to a relatively fixed value from the maximum value, which is also named as permanent fault displacement (PFD). In this paper, it is assumed that the maximum displacement of fault movement (MFD) is about 15% larger than PFD as shown in Figure 3.4.

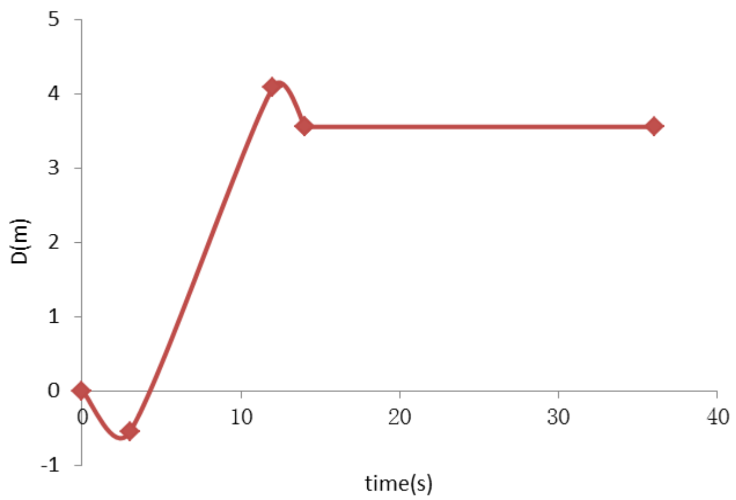

Figure 3.4 Relationship between MFD and PFD

4. STUDY CASE: AN OIL PIPELINE CROSSING THE XIAOJIANG FAULT

The Xiaojiang fault zone, within the Yunnan Province, China, is one of the most active fault zones of the south-eastern edge of the Tibetan Plateau, as shown in Fig. 4.1. This N–S trending 400 km long fault zone defines the southern part of the eastern boundary of the Sichuan–Yunnan Block, which is escaping south-eastward from the Tibet Plateau and rotating around the Eastern Himalayan Syntaxis. The middle section of the fault zone splits into two branches. Each branch fault consists of several en echelon faults. Basins of various ages have developed on the step-overs between the secondary faults. The left-lateral strike－slip rate along the eastern branch is up to 9 mm/a, and that on the western branch is 7 mm/a. More than 10 M⩾6 historic earthquakes have occurred along the fault zone. The largest was the 1833 Songming earthquake of M=8. The average strong earthquake recurrence interval is 2000–2500 years.

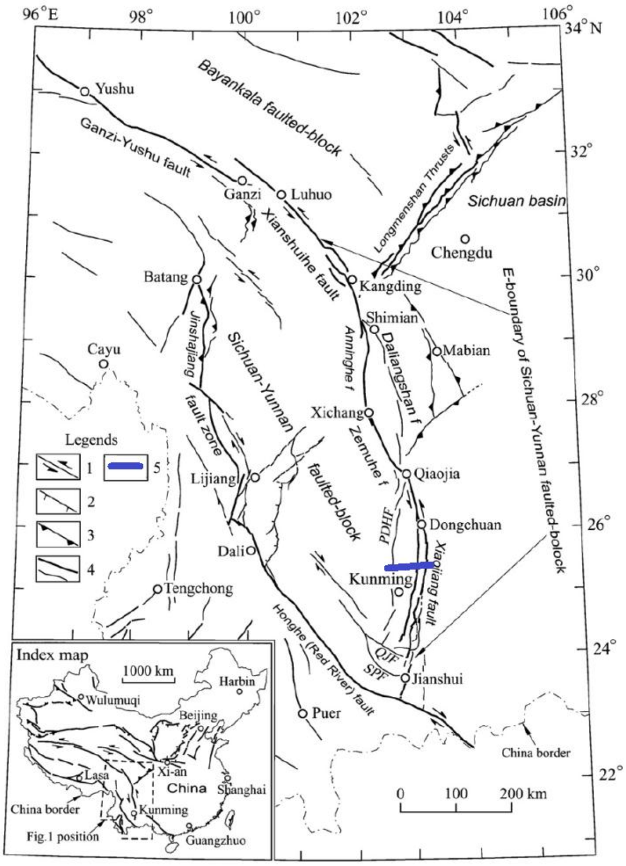

Figure 4.1 A simplified map of active faults around the south-eastern edge of the Tibetan Plateau
Legend explanation: (1) Active strike-slip fault; (2) active normal fault; (3) active reverse fault or thrust; (4) major (thick line) and secondary (thin line) active faults; (5) oil pipeline.

An oil pipeline crosses Xiaojiang fault with a crossing angle 86 °on the north of Kuming city, and the route of pipeline passes through the denser-population area. The diameter is 1.016m and the thickness is 0.021m. X70-HD2 steel grade pipes are used in this pipeline and the buried depth is larger than 1.2m to consider that the farmer can keep on planting. The fault study concludes that this fault has the potential of releasing an earthquake as large as magnitude 7.0 with maximum surface rupture displacements of 3.5m horizontally and 0.6m vertically in the future 100 years. The total fault displacement is about 3.552m.

A 3-dimension shell-spring FEM is adopted to analyse the response of this oil pipeline under the large fault movement. As shown in Fig. 4.2, the soil springs are deposited in the hoop direction of pipe. Compared with other analytical models, it is easy for this model to consider the situation when the soil conditions on the both side of the fault are different ($K1 \neq K2$). The pipeline segment near fault is modelled with a plastic shell element in order to consider the effect of local buckling and section deformation. The material property of pipe can be considered as an elastic one when it is far from the fault. To reduce the calculating time of whole model, an equivalent spring is applied at both ends of the shell model. The equivalent spring is obtained as:

$$F = \sqrt{1.5\pi Z\gamma AD\mu E\Delta_L} \tag{3.1}$$

Where, F is the force; Δ_L is the elongation of equivalent spring; Z is the buried depth; γ is the density of surrounding soil; μ is friction coefficient; A is the area of pipe section; D is the diameter of pipe and E is the elastic stiffness of pipe.

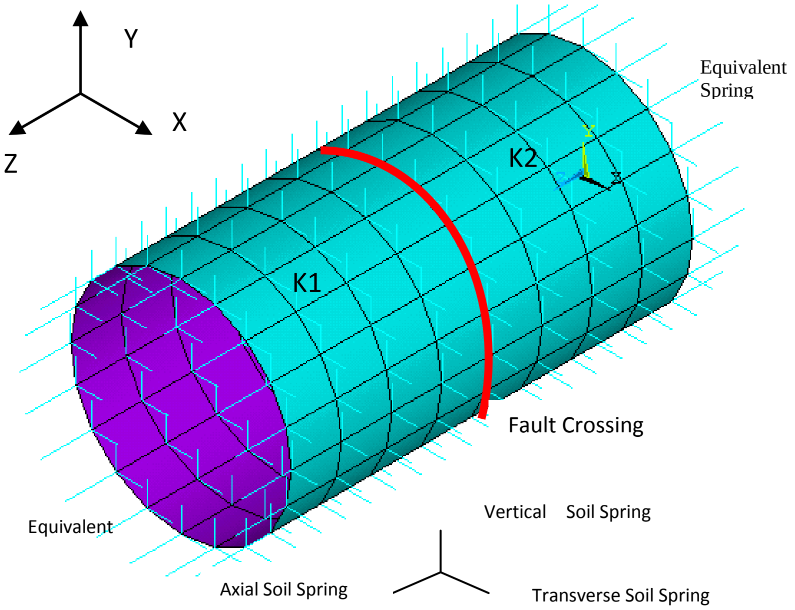

Figure 4.2 Analysis Shell Model

The fault displacement time history as shown in Fig. 3.4 is as a "dynamic" input to the shell model (without considering the damping ratio), the Axial strain in the oil pipeline under the fault displacement is shown in Table 4.1 and Fig. 4.3. A static analysis with the permanent fault displacement (3.552 m) is also carried out. As shown in Fig.4.3, the axial strain of static analysis is not equal to the last residual strain in the pipeline of dynamic analysis, is a little larger than it and less than the Max. strain.

Table 4.1 Axial strain in the oil pipeline under the fault displacement.

Time(s)	Fault displacement(m)	Max. Strain (%)
0	0	0
0.5	-0.05498	0.0164
1	-0.11	0.0331
1.5	-0.1926	0.0586
2	-0.316	0.0952
2.5	-0.50125	0.1412
3	-0.5491(=-15% • PFD)	0.1517
4	-0.3401	0.0852
6	0.6428	0.2332
7	1.328	0.5625
8	1.786	0.796
10	2.93	1.201
11	3.508	1.284
12	4.085(MFD=1.15 • PFD)	1.3067
13	3.817	1.239
13.4	3.615	1.19
14	3.552(=PFD)	1.17

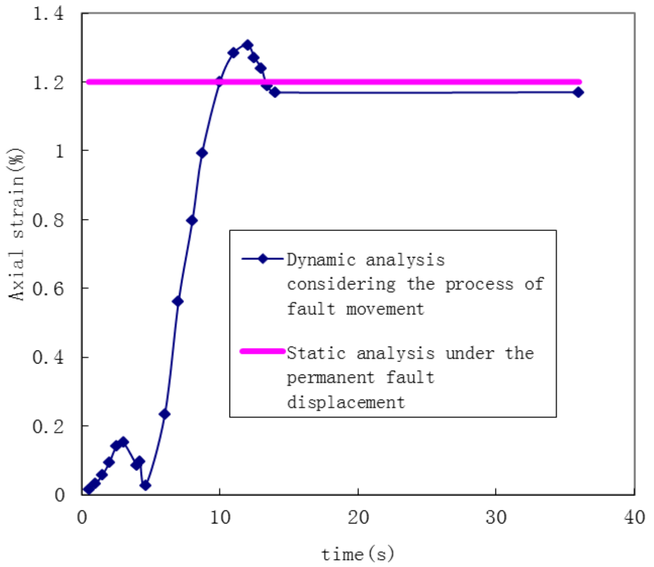

Figure 4.3 Axial strain obtained by dynamic analysis and static analysis

It should be noticed that the recordings near fault are not enough to obtain a good model for the process of fault movement. At present, the static analysis can satisfy the need of seismic design for a pipeline crossing the fault.

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