DEFORMATION RISK OF BURIED PIPELINE DUE TO FAULT BASED ON ELASTICITY THEORY OF DISLOCATION

Yue PAN[1] and Yasuko KUWATA[2]

[1]Student member of JSCE, Dept. of Civil Eng., Graduate School of Engineering, Kobe University
(Rokkodai 1, Nada-ku, Kobe 657-8501, Japan)
E-mail: 209t136t@stu.kobe-u.ac.jp
[2]Member of JSCE, Dept. of Civil Eng., Graduate School of Engineering, Kobe University
(Rokkodai 1, Nada-ku, Kobe 657-8501, Japan)
E-mail: kuwata@kobe-u.ac.jp (Corresponding Author)

Seismic fault displacement has a great threat to various types of civil structures. Locaiton and the amont of displacement have much uncertaintily for carrying out the countermeasure of fault movement. Therefoere, the current countermeasures are done by that the possible surface displacement on the active faults crossing the buried pipeline is estimated by the empirical formula. By the way, even though the fault displacement does not appear on the groud surface, the ground strain due to the fault dislocation may cause damage to the pipeline. Objective of this study is to make clear the possible deformation of buried pipelines caused by fault disloactions based on elasticity theory of dislocation and to provide data basis for exploring the fault countermeasures of buried pipelines.

Key Words : *buried pipeline, fault crossing, deformation, elasticity theory of dislocation*

1. INTRODUCTION

As a phenomenon of seismicity, if the earthquake magnitude reaches M7 or above, fault dislocation is easy to appear on the ground surface. Therefore, for mitigating the damage caused by the faults, targeted countermeasures need to be put forward. As early as after the 1971 San Fernando earthquake in the United States, California formulated an act about active faults to restrict building construction near the fault[1)]. Subsequently, various countries and regions in the world have begun to formulate countermeasures against the damage caused by the faults. Among them, the most common method is to set the setback standard for faults, that is, to prohibit the construction of structures near faults, or to adjust and limit the types and standards of structures. However, most of the restrictions on the faults are only related to the buildings. In fact, linear civil structures such as buried pipelines, roadway and railway are difficult to setback from the fault.

Overseas, as a means to avoid the collapse risk of buildings near the fault, there are legal restrictions on residence and construction. In the 1971 San Fernando earthquake in California, US, it was found that the serious earthquake disasters were distributed in a belt[1)], and it is necessary to pay attention to the disaster zones related to active faults in land use planning[2), 3)]. During the earthquake, more than 80% of the buildings on the surface fault were damaged, while only 30% of the buildings far away from the fault were damaged[3)]. Refering to the damage ata, Alquist-Priolo Earthquake Fault Zoning Act was enacted to restrict the buildings near the fault[4)]. Also in Utah, “Guidelines for evaluating surface-fault-rupture hazards in Utah” was formulated in 2003, which shows the setback distance of faults according to different forms of residential buildings. In Europe, Eurocode 8 (Design of structures for earthquake resistance) strictly prohibited the construction of important structures near active faults in 1998. In 1994, China issued “Code for investigation of geotechnical engineering (GB 50021-94)”, which clearly stipulated the safe distance between major projects and active faults. In Taiwan, after the Chi-chi earthquake in 1999, faced with the problems of reconstruction of buildings collapsed on the fault, they have permanently banned the reconstruction of buildings on the fault[5)].

In Japan, the long-period evaluation of active faults has been progressing steadily since the Kobe earthquake in 1995. Though active faults have been identified, most of them are in the surrounding areas where many houses and buildings already built. Unlike other countries, legal measures to avoid risks cannot be taken. As mentioned above, even if the linear civil structures could not be avoided by the setback-way as buildings, it is necessary to discuss the concept of setback distance to determine the danger range from faults in the space and put up some countermeasures.

During an earthquake, many uncertain factors exist in the fault displacement on the surface. Thus, it is difficult to empirically estimate the surface fault displacement at the crosssection of fault line in the active faults map and buried pipeline by using parameters of the fault length and earthquake magnitude. Moreover, in the seismic design of the buried pipeline, under a given surface fault displacement as an external force, the pipeline response is examined in the model that the block-shape ground moves on the border of the fault. It is not sufficiently considered that the ground deformation occurs when the fault does not reach the ground surface. It is necessary to clarify the ground strain distribution due to the fault dislocation. The purpose of this study is to calculate the ground deformation caused by fault movement by using the elasticity theory of dislocation and to clarify the range of large pipe strain due to the fault dislocation by the fault parameters.

2. EVALUATION METHOD

In the field of seismology, the deformation of ground surface around fault has been discussed by using the elasticity theory of dislocation. Steketee (1958)[6] first introduced the concept of dislocation in the field of metal material theory and crystal structure theory into fault research, and regarded seismic fault as a huge dislocation in homogeneous earth medium, which is not discrete dislocations such as crystal structure but continuous. Chinnery[7] and Okada[8] expanded the formulation from point source to rectangle fault.

For example, Hirano and Hada[9] have verified that the south area of Kobe are intermittently moved up to the Koyo fault caused by the Kobe earthquake, comparing the horizontal displacement with the Chinnery's formula. The estimation by the formulation suggested that the source fault of Koyo fault has reached from 0.2 to 0.5 km underground.

The elasticity theory of dislocation proposed by Okada[8] assumes that the ground surface is horizontal, the sediment is a homogeneous and continuous geological structure, and a homogeneous and isotropic semi infinite elastomer. In addition, it is assumed that the fault is considered as a earthquake fault, whose plane and type is rectangular, and the sliding in the fault plane is consistent. For this reason, Okusa and Tani[10] pointed out the problems of using the elasticity theory of dislocation: topography and geological structure of sediment on the earth's crust. On this basis, the elasticity theory of dislocation was applied to estimate the ground deformation and shear strain in the important facilities such as nuclear power plant[11].

With regard to the heterogeneity and anisotropy of sediment, the numerical analysis and other detailed studies should be conduted in the future. With this as a premis, this study aims at discussing the deformation risk of buried pipe from the deformation of ground surface caused by the fault dislocation of an isotropic semi infinite elastomer assumed by the elasticity theory of dislocation.

In the seismic design of buried pipelines, seismic performane is checked by the pipe strain in the axial direction of the buried pipe which is generated by the ground strain caused by ground motion and grounds deformation. In this study, the strike-slip fault and reverse fault are targeted. The distribution characteristics of axial strain of buried pipe orthogonal to the fault are discussed and studied its characteristics by changing fault parameters. Assuming that no slip nor yielding occurs between the buried pipe and the ground, and the ground strain is directly transmitted to the buried pipe. Further, although the buried pipe is buried about 1 m under the ground, the pipe strain is regarded as the same as the surface ground strain.

Now, let a fault along the x-axis in the horizontal xy plane and a pipeline in the y-axis direction orthogonal to the fault. Also, take the z-axis in the vertical direction of the xy plane.

Assuming that the displacement of ground surface in the case strike-slip fault u_x, u_y, u_z , in the x-axis, y-axis, and z-axis direction respectively, the displacement in x-direction is superior to that in z-direction, and the pipe strain ε can be evaluated as follows.

$$\varepsilon = \frac{\partial u_y}{\partial y} + \frac{\partial^2 u_x}{\partial y^2} \cdot \frac{D}{2} \qquad (1)$$

where, D is the diameter of the pipe.

On the other hand, in the evaluation of pipe strain of reverse fault, it is assumed that the displacement in z-direction is superior to that in x-direction in the right angle direction of pipe axis, and the following formula is used for evaluation.

$$\varepsilon = \frac{\partial u_y}{\partial y} + \frac{\partial^2 u_z}{\partial y^2} \cdot \frac{D}{2} \qquad (2)$$

In the above two equations, the first term on the right represents axial strain and the second term represents bending strain.

3. CASE STUDY BY FALUT DEPTH

(1) Parameter setting

According to the standard values of fault length and average fault slip under various magnitudes, set the fault length is 40 km and the fault slip is 2 m. In addition, as listed in Table 1 and Table 2 the fault width is set as 20 km and the Lame constants λ and μ of the medium is assumed to be 32 GPa, respectively. The dip angle of the fault is 90 degrees and the range of calculation is 120 km by120 km in the xy plane as shown in Fig. 1. The vertical distance from the bottom of the fault to the ground surface $Z_{s,b}$ is set as case study parameters as 20.2, 20.5, 21, 22 and 25 km, respectively.

Table 1 Fault paraeter

Length of fault, L (km)		40
Width of fault, W (km)		20
Dip angle of fault, δ (deg.)		90
Degree of sub-duct, θ (deg.)	strike-slip fault	0
	reverse fault	90
Lame constant, λ (GPa)		32
Lame constant, μ (GPa)		32
Element dislocation, e (m)		2

Table 2 The distance from the bottom of the fault to the ground surface, $Z_{s,b}$(km)

Case 1	20.2
Case 2	20.5
Case 3	21.0
Case 4	22.0
Case 5	25.0

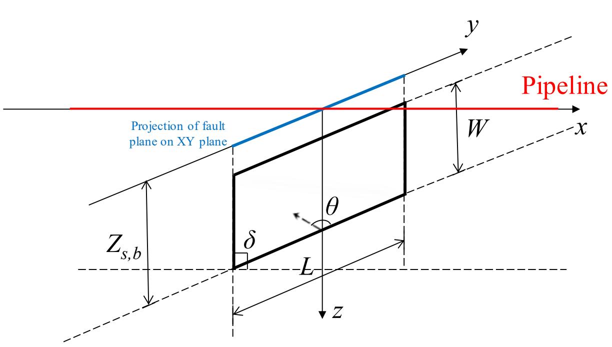


Fig. 1 Calculation model

When it is assumed that the pipeline follows the y-axis direction and passes through the midpoint of the fault projection on the x-axis crossing the fault, the coordinate range of the fault plane in the y-direction is 0 to 40 km and the pipeline intersects at $y = 20$ km.

In addition, as shown in Eqs. (1) and (2) above, when calculating the bending strain of pipe, the diameter of pipe is required as one of the calculation parameters. Therefore, the diameter of pipe is set as two cases: 100 mm and 800 mm.

(2) Result of calculation

As shown in the above table, the data are sorted into two categories: strike-slip fault and reverse fault, and the calculations of case 1 to case 5 are carried out respectively.

a) Strike-slip fault

Fig. 2 shows the horizontal displacement U_x along pipeline for case 1 to case 5. Horizontal displacement occurs symmetrically with a fault as the dandary. As the fault plane of strike-slip fault is closer to the surface, the surface deformation caused by the fault dislocation increases. Meanwhile, the horizontal displacement U_y along the pipeline does not generate when the pipeline across at the center of fault line. Therefore, in the case of the strike slip fault, the pipe strain is predominant to the bending strain caused by the horizontal displacement U_x.

The pipe strain distribution in the case of strike-slip fault are compared with the diameters of 100 mm and 800 mm, as shown in Fig. 3 and Fig. 4. Both figures show the pipe strains with 120 km length and with 2 km length near the fault line, respectively. While there are some amount of displacement within 20 km far from the fault line as shown in Fig.2, the pipe strain are significant within 0.5 km from the fault line. There is a gap of more than three times between the maximum strain caused by fault whose tops are 200 m and 500 m underground.

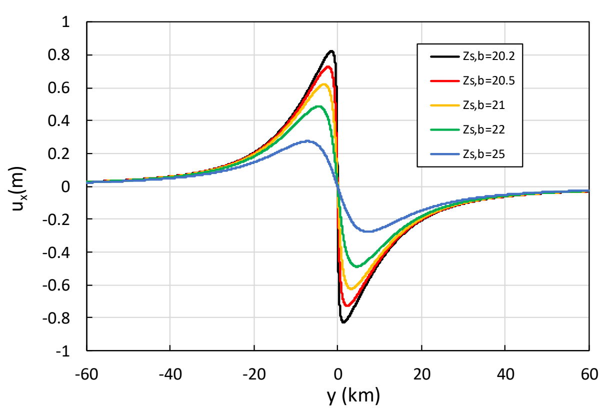
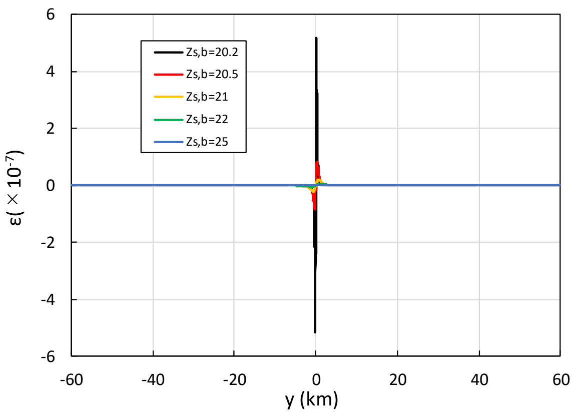
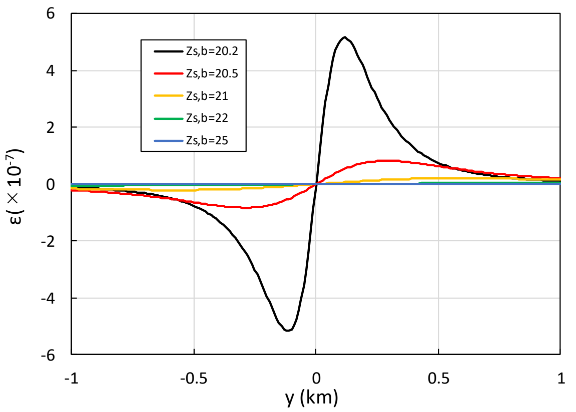


Fig.2 Displacement in x-direction, Ux in the case of strike-slip fault.

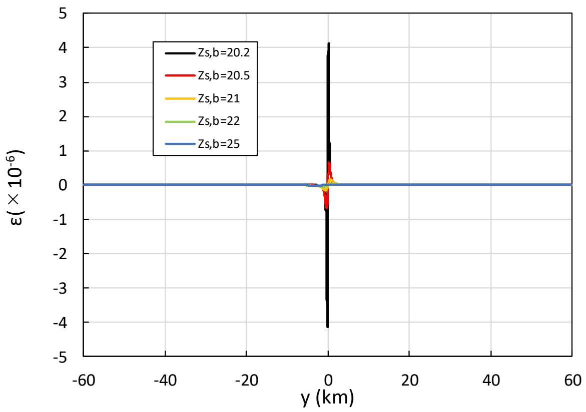


(a) Total 120 km along the pipe axis

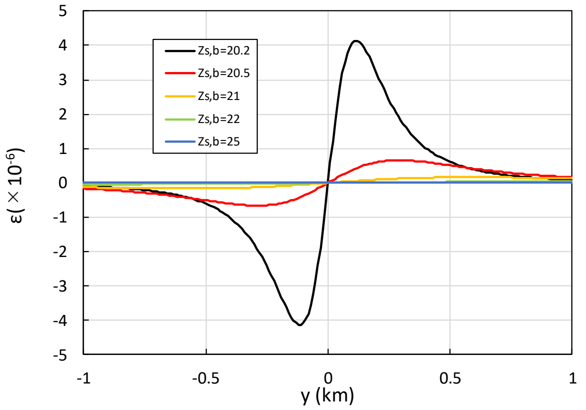


(b) 2 km near the fault

Fig.3 Pipe strain when *D*=100mm, in the case of strike-slip fault.



(a) Total 120 km along the pipe axis



(b) 2 km near the fault

Fig.4 Pipe strain when *D*=800mm, in the case of strike-slip fault

When the pipe diameter is 800mm, the maximum strain of buried pipe near the ground caused by the strike fault is about 4×10^{-6}. On the other hand, the yield pipe strain used in the seismic design is on the order of 10^{-3} to 10^{-2}. Therefore, in the case of this calculation model, the pipe strain caused by th strike-slip fault is not enough to cause damage to the pipeline.

b) Reverse fault

Like the strike-slip faults, the impact to the vertical displacement U_z by the fault depth in the case of reverse fault are obtained as shown in Fig. 5. The vertical displacement U_z due to the reverse fault is greater than the lateral displacement U_x due to the strike-slip fault in all the fault depth cases. The shallower the depth, the greater the surface displacement. In case of the reverse fault, the horizontal displacement U_y along the pipeline also observerd. The pipe strain is influenced by both displacements U_y and U_z.

Similarly, the pipe strain distribution in the case of reverse fault are compared with the diameters of 100 mm and 800 mm, as shown in Fig. 6 and Fig. 7. As the same as the strike-slip fault, the pipe strain is sign-

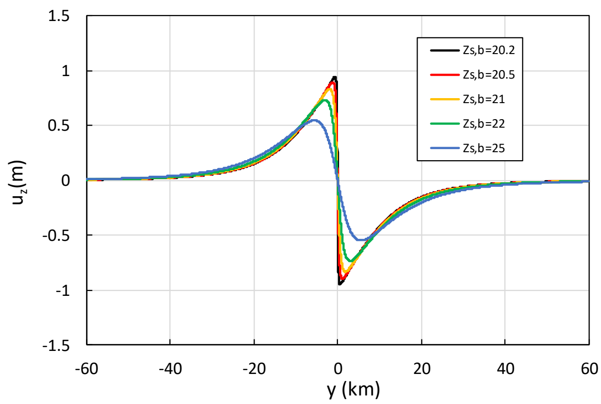
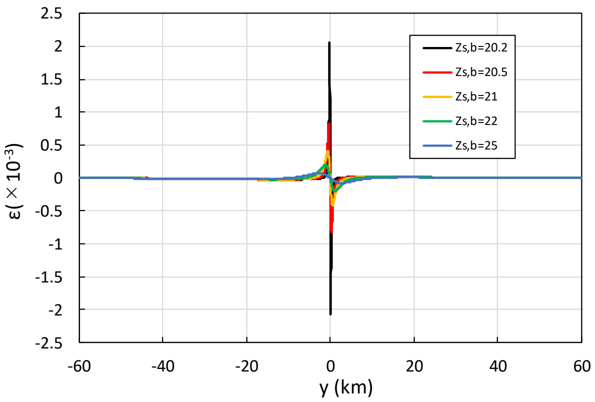
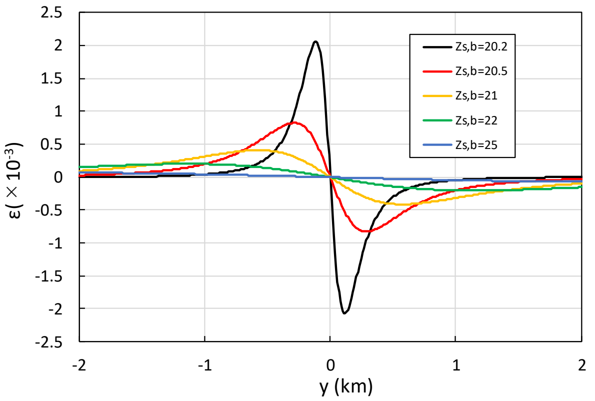


Fig.5 Displacement in z-direction, *Uz* in the case of reverse fault

ificant within 0.5 km from the fault line. Since the diameter is basically independent to the displacement of the buried pipe near the ground surface caused by the reverse fault, according to Eq.(2), it can be inferred that the axial pipe strain caused by the reverse fault is much greater than the bending strain of the pipe caused by it.

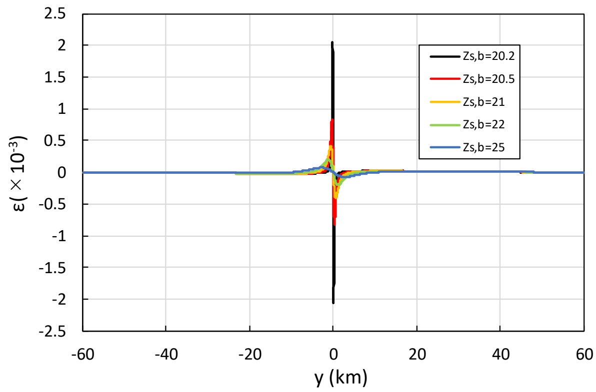


(a) Total 120 km along the pipe axis

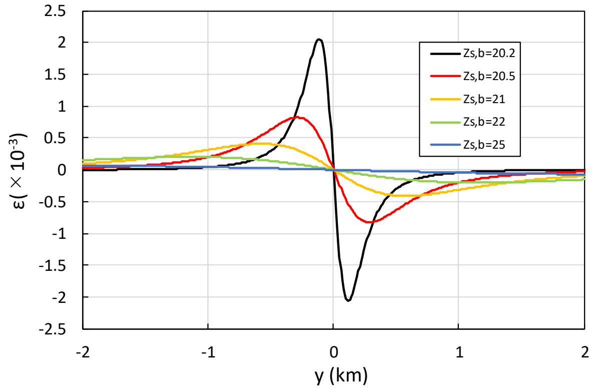


(b) 4 km near the fault

Fig.6 Pipe strain when *D*=100mm, in the case of reverse fault



(a) Total 120 km along the pipe axis



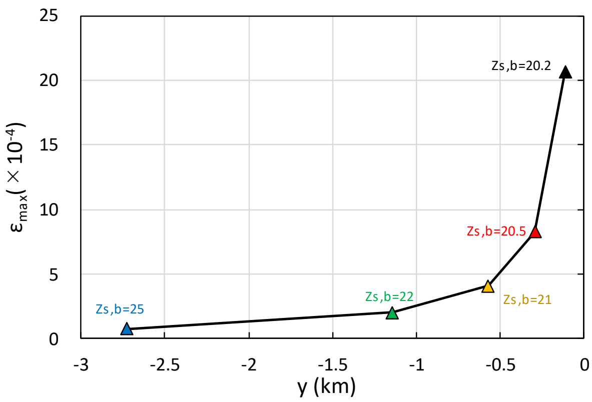
(b) 4 km near the fault

Fig.7 Pipe strain when *D*=800mm, in the case of reverse fault

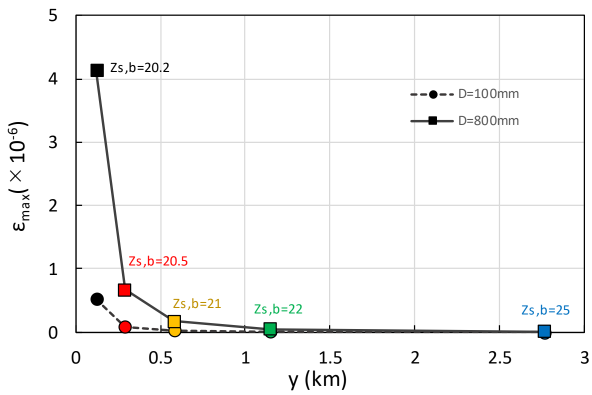
c) Coordinate of peak strain in each case

In the design of buried pipeline crossing the fault line, not only the amount of pipe strain but also the location far from the fault is important. As shown in Figs. 3, 4, 6 and 7, as the depth of fault increases, the coordinate far from the fault where the pipe strain is maximum. Fig. 8 shows the relationship between the maximum pipe strain and its coordinate from the fault line. Texts near the marker indicate the case of fault depth. In the case of reverse fault, there is only one line because the pipe strain due to the bending strain has little effect on the total pipe strain. In the strike-slip fault, there are different peaks according to different diameters. However, as mentioned in the previous strain calculation Eqs. (1) (2), the abscissa of the peak pipe strain on the pipeline is independent of the diameter.

As the depth of the fault increases, the location of the maximum pipe strain of the pipeline becomes also close to the fault line. The farther the fault is from the surface, the maximum pipe strain gradually decreases, and the farther the maximum strain is from the fault.



(a) Reverse fault



(b) Strike-slip fault

Fig.8 maximum strain in different Z_s,

4. CASE STUDY BY ASPERITY DISTRIBUTION

(1) Parameter setting

In the elastic theory of dislocation, the dislocation is assumed to be unique on the face of fault. Recent studies on seismology indicates the presence of asperity on the fault surface. In order to explore the influence of asperity distribution on the pipe strain, the similar parameters in the last chapter are set. The distance from the bottom of the fault to ground surface, $Z_{s,b}$ is set to be constance as 20.5 km.

Sliding amount of asperity is known to be twice the average sliding amount of fault. The width of asperity is about 50 % of the fault width, 10 km. The area of asperity is 20 % of the total fault area. When the fault surface is divided by 2 km in the length and 2 km in the width, small fault elements account 20 in the length and 10 in the width as shown in the calculation model shown in Fig.1. The asperity fault elements account for 8 × 5 squares[12]. In order to keep the same earthquake moment as shown in the calculation with unique slip of fault, the slip of rest part of fault whithout asperity is set to be 1.5m.

Table 3 The parameters of fault

Length of fault, L (km)		40
Width of fault, W (km)		20
Dsip angle of fault, δ (deg.)		90
Degree of subduct, θ (deg.)	strike-slip fault	0
	reverse fault	90
Lame constant, λ (GPa)		32
Lame constant, μ (GPa)		32
Average slip, e (m)		2
The distance from the bottom of the fault to ground surface, $Z_{s,b}$ (km)		20.5

Table 4 The parameters of asperity

Width of asperity (km)	10
Area of asperity (km$^{2)}$	160
Length of asperity (km)	16
Slip of asperity elements (m)	4
Slip of rest part of fault (m)	1.5

Table 5 The position of asperity and its probability in each case.

Case	Distance from upper end of asperity to upper end of fault (km)	Probability
Case 1	2	0.240
Case 2	4	0.264
Case 3	6	0.254
Case 4	8	0.242

(2) Different vertical position of asperity in reverse fault

Since the depth change of asperity has little effect on strike slip fault, only the reverse fault is discussed.

According to the depth distribution of asperity[13], the two cases with the lowest probability of existence of asperity are ignored, that is, the two extreme positions at the top and bottom of the fault plane. Four cases of asperity from case 1 to case 4 as shown in Table 5 are considered. The probability is recalcurated within four cases from the depth distribution of asperity[13]. The diagrams of the position of asperity are shown in Fig. 9. The mean, μ and standard deviation, σ in combination with the pipe strain caused by the four cases are obtained and shown along the pipeline in Fig.10. The calculation results of the same parameters without asperity ($Z_{s,\,b}$=20.5, e = 2) are compared with the calculation results of various positions of asperity in same figures.

According to Fig.10, the pipe strain caused by the reverse fault is basically not discrete in the near fault part of the pipeline: There is a large dispersion between 1 and 2 km away from the fault, but it has no effect on the maximum pipe strain.

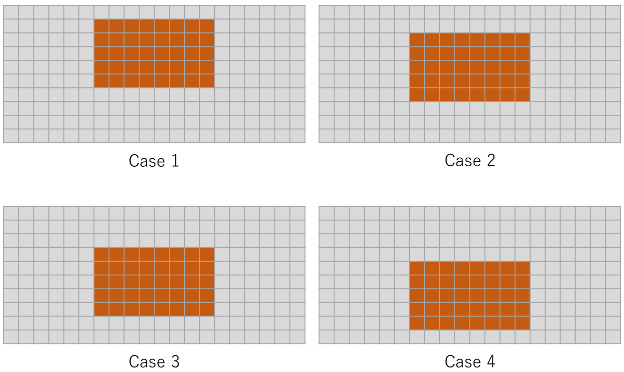


Fig.9 Asperity position at different depths.(2×2km)

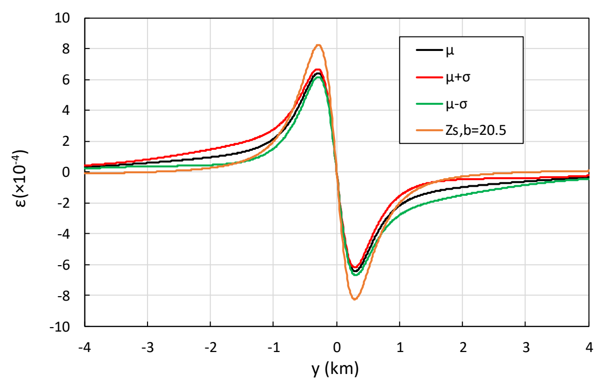


Fig.10 Mean ± standard deviation of pipe strain due to the vertical position of aspecity and pipe strain with unique slip with $Z_{s,b}$=20.5km in the case of reverse fault

Table 6 The position of asperity in each case.

Case	Distance from the left end of asperity to the left end of fault (km)	Probability
Case 5	4	0.4
Case 6	8	0.4
Case 1	12	0.2
Case 7	16	-
Case 8	20	-

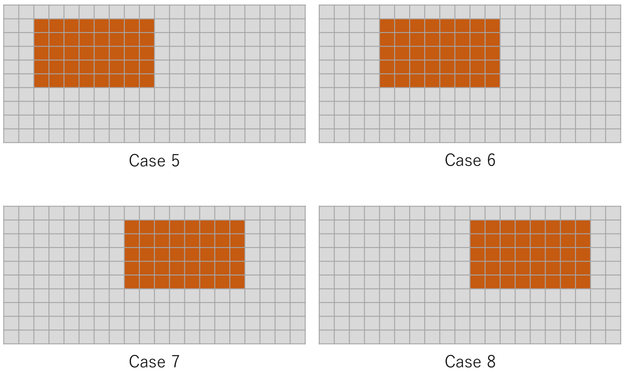


Fig.11 Asperity at different horizontal positions(2×2km)

The maximum pipe strain caused by the fault with asperity is less than that without asperity. The reason is that the pipe strain is affected by the slip of shallow part of fault. The slip of shallower element in the case without the asperity is 2 m while that with asperity is 1.5 m. The probability of asperity at the upper end of the fault is too small to be considered. Although the depth of asperity will affect the pipe strain, the maximum pipe strain caused by the fault with asperity will not change much or exceed that caused by the fault without asperity because the formation displacement near the surface remains unchanged.

Under the design of buried pipeline, no condideration of variation of asperity distribution is a safer design.

(3) Different horizontal position of asperity in strike-slip fault

In the previous part, it was discussed that the asperity changing in the depth direction leads to different strains of the pipeline assumed to be set near the surface. It can be seen that the change of depth will mainly have a great impact on the strain caused by the reverse fault. Therefore, it can be reasonably guessed whether the strain caused by strike-slip fault will change due to the change of horizontal position of asperity. According to this, four cases are designed as Table 6 and Fig.11. Additionally, case 1 can be

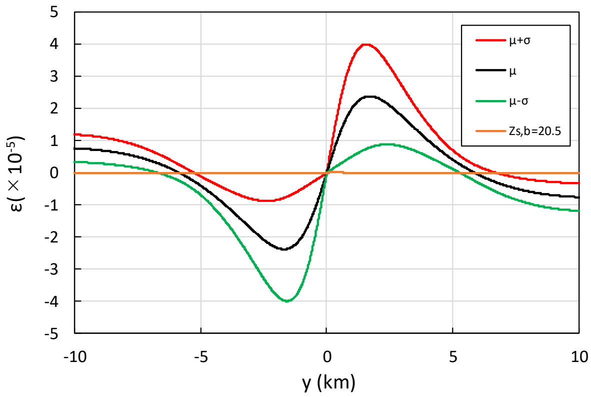


Fig.12 Mean ± standard deviation of pipe strain due to the horizontal position of aspecity and pipe strain with unique slip with $Z_{s,b}$=20.5km in the case of strike-slip fault

used with the same parameters in Fig.9 and Table 5, except for the degree of subduction.

In the cases of the fault with asperity, the axial strain of buried pipe caused by strike-slip fault increases greatly if midpoint of asperity becomes far from the pipeline, and the axial strain is much greater than the bending strain. Only the case with a diameter of 100 mm is shown here as an example.

As the position of asperity is shown in Fig.11, case 5 and case 8 in pairs, case 6 and case 7 in pairs, they are symmetrical relative to the fault centerline, the pipe strain calculation results in these pairs are also symmetrical about the y-axis. Therefore, only take the data at one side of the fault centerline case 5, case 6 and case 1 to calculate the mean and standard deviation. Since there is no data on the horizontal distribution of asperity, it is assumed that the probability of occurrence of each case is the same as shown in Table 6. The mean and standard deviation of pipel strain caused by various asperity positions are obtained.

According to Fig.12, in these cases, the pipe strain caused by the asperity is relatively discrete. Different from the previous part is that the pipe strain caused by the fault with asperity is much greater than that without asperity.

The following consideration can be made: In the case of strike-slip fault, when the buried pipe passes through the symmetry axis of the fault plane, the axial strain of the pipe is almost 0. When asperity exists, because the displacement of fault plane is inconsistent, the fault displacement is concentrated in the asperity part, where has a much greater impact on the pipe strain than other parts. As in case 5 and case 6 shown in Fig. 11, the position of the pipeline is on the central line of the whole fault, but not the central line of asperity, which makes the axial strain get larger, and the peak value of the displacement of the pipeline in the case of strike-slip fault is not necessary at the position passing through the central line of the fault. In addition, the displacement of asperity itself is twice that of non asperity fault, resulting in the calculated pipe strain being much greater than that of faults without asperity.

Therefore, the effect of asperity on the strain of shallow buried pipe in strike-slip fault needs to be considered in the design process.

5. CONCLUSIVE REMARKS

In this sudy, assuming that the fault plane is perpendicular to the ground surface and the pipeline is shallow buried near the ground surface, the buried pipeline passes through the midpoint of the projection of the fault plane on the ground surface, the pipe strain caused by the surface displacement calculated based on elasticity theory of dislocation is discussed. Followings can be summarized as conclusive remaks.

- As the depth of the fault increases, the location of the maximum pipe strain becomes also close to the fault line. By this way, the falut hazard zone by the fault depth can be determined even though the fault displacement does not appear on the ground surface.
- As for the variation of asperity position, the variation of vertical position for the reverse fault is not so much effect on the pipe strain and the design without asperity is a safer design. On the other hand, the variation of horizontal position of asperity due to the strike-slip fault is large and the effect of asperity on the pipe strain in the strike-slip fault needs to be considered in the design process.
- In all cases, the buried pipeline caused by the faults based on elasticity theory of dislocation has a large strain near the fault.

During the transformation of pipeline strike and buried depth, the influence of fault on pipe deformation is necessary to continue to study in the future. What is more noteworthy is that in practice, the shallow sediment is often a weak stratum, and the strain caused by it may cause greater damage to the pipeline. Therefore, it is important to do some experiments to simulate the actual situation, so as to help formulate a set of effective countermeasures for the deformation of surrounding pipelines caused by faults.

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