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COUNTERMEASURES OF BURIED STEEL PIPES AGAINST SURFACE FAULT RAPTURE

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SUMMARY

Several model tests were carried out to demonstrate the behavior of buried pipes due to surface fault rupture. Effect of two types of surface fault, horizontal fault and thrust fault were studied. For horizontal fault rupture, two soil containers, which are a fixed container and a movable container, were used. Model pipes were buried in the model ground. Then, horizontal displacement was applied to induce shear rupture. Tests were conducted under several conditions of depth of the pipes, diameter of the pipes, angle between the pipes and shear rupture plane, and degree of compaction of the model ground. Test results showed that the maximum bending moment increased with the buried depth, the degree of compaction, the diameter of pipe, and the angle. Based on these tests, three kinds of ideas on simple countermeasures against fault rupture were derived. Effectiveness of a countermeasure, mixing backfill soil with a light-weight material, was proved by conducting additional tests. For oblique thrust fault rupture, two soil containers were used also. One movable container was lifted with an angle of 30 degrees. Test results showed that the maximum bending moment increased with buried depth, degree of compaction of the model ground. The proposed countermeasure was effective for thrust fault rapture also.

INTRODUCTION

Surface fault rupture causes severe damage to facilities such as pipelines, bridges, buildings and electric power transmission towers. In 1999, gas pipelines, water pipelines and electric power transmission towers were severely damaged due to surface fault ruptures during the two big earthquakes occurred in Turkey and Taiwan. The author investigated the damages in both countries. Damage to gas pipelines during an earthquake in New Zealand was also investigated. Based on theses investigations, model tests for buried pipes were conducted to demonstrate the behavior of pipes due to fault ruptures. Moreover, simple countermeasure methods for buried pipelines were proposed. And additional model tests were conducted to demonstrate the effectiveness of the countermeasures.

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DAMAGE OF BURIED PIPES DUE TO SURFACE FAULT RUPTURES DURING THREE EARTHQUAKES

In Turkey, a belt of alluvial lowland extends from the south coast of Izumit Bay to Adapazarı City through Sapanca Lake. A fault striking east-west through this lowland region ruptured during the 1999 Kocaeli earthquake. Roads, bridges, buried pipes etc. suffered damages due to fault displacement. Loss of coastal lands and ground subsidence also resulted, in this low land. Damages to steel water pipes due to surface fault rupture were reported at several sites. Of them, a water pipe made of steel with a diameter of 2.4 m damaged at Kullar due to right-lateral strike-slip. Figure 1 shows brief map at the damaged site. Photo 1 shows surface fault rupture near the damaged site. Displacement of the fault rupture was estimated 3.2 m based on the differential displacement of wall. Angle of the water pipe to the surface fault rupture was about 60°.

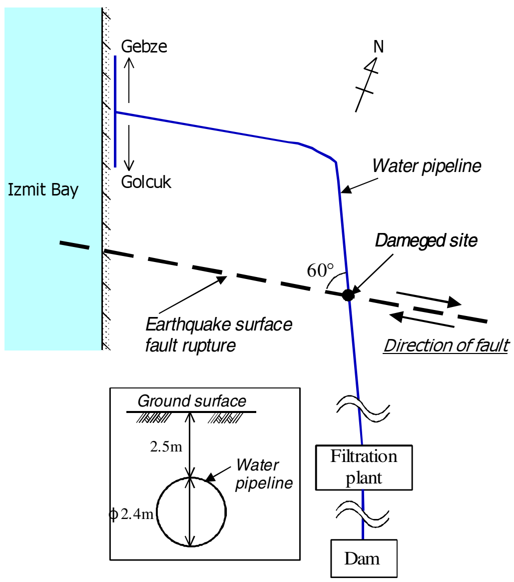

Figure 1 Brief map at damaged site for water pipeline at Kullar in Turkey

Photo 1 Surface fault rupture near the damaged site of water pipeline at Kullar in Turkey

Photo 2 Damaged gas pipeline at Wu Xi Bridge in Taiwan

Photo 3 Surface fault rupture at damaged site of gas pipeline

Photo 4 Undamaged gas pipeline at Wakatane in New Zealand

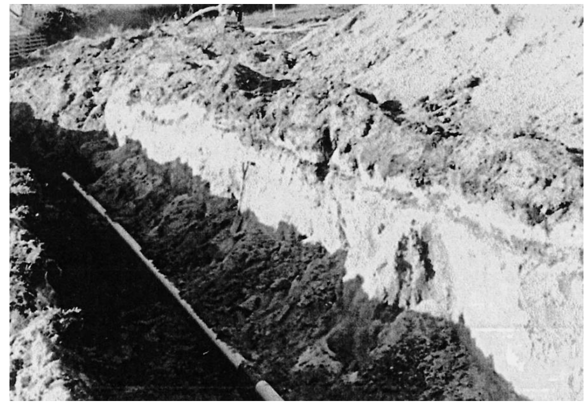

Photo 5 Surface fault rupture at undamaged site of gas pipeline

The 1999 Chichi earthquake caused huge surface fault ruptures. Total length of the fault was estimated as about 125 km. The fault named "Chehlungpu fault" was an thrust fault. Maximum vertical displacement was almost 10 m. A dam, several road bridge, many buried pipes, houses, transmission towers and etc were severely damaged due to the fault ruptures. Water and gas pipelines were damaged at many sites. Of them, two steel gas pipes bent due to surface fault rupture at the approach road of Wu Xi Bridge as shown in Photo 2. Diameters of these pipes were 100 mm and 200 mm. Photo 3 shows the damaged site. Though the photo was taken one month after the earthquake, reverse type of fault rupture was observed.

The 1987 Edgecumbe earthquake caused surface fault rupture at Whakatane in New Zealand. Photo 4 shows the fault rupture. This fault was normal type fault. Vertical and horizontal displacements were 2.2 m and 1.2 m, respectively. A steel gas pipe with 114 mm in diameter had been buried across the fault. Angle of the pipe to the fault was about 45 degree. Though the large displacement occurred in vertical and horizontal directions, the pipe has no damage as shown in Photo 5 (Berrill[1], 2002).

MODEL TESTS TO DEMONSTRATE THE BEHAVIOR OF BURIED PIPES DUE TO HORIZONTAL FAULT RUPTURE

Model shear tests were carried out to demonstrate the behavior of buried pipes due to horizontal fault rupture. Two soil containers, which are fixed container and movable container, were used as shown in Figure 2 and Photo 6. Soil used was "Chiba sand" with 3.4 % of fines content. Grain-size distribution curve is shown in Figure 3. The maximum dry density is 1.629 g/cm^3. Pipes used were copper pipes. Strain gauges were pasted on the model pipes as shown in Figure 4. The model pipes were buried in the model ground. Then, horizontal displacement was applied up to 10 cm to induce shear rupture, by pulling the movable soil container. Tests were conducted under several conditions of depth of the pipes, diameter of the pipes, angle between the pipes and shear rupture plane, and degree of compaction of the model ground. Definition of the angle is explained on Figure 5.

Photo 7 was taken after 10 cm of displacement to see the buried pipe, by excavating the soil. As shown in this photo, model pipes bent due to shear force at two points which were about 10 cm from the shear rupture plane. Figure 6 shows typical relationships between displacements of the movable soil container

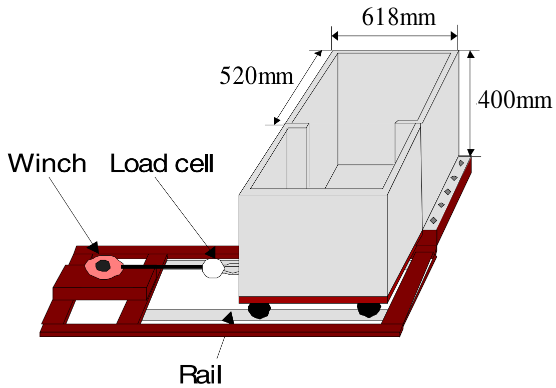

Figure 2 Test equipment for horizontal fault rupture

Photo 6 Sheared soil

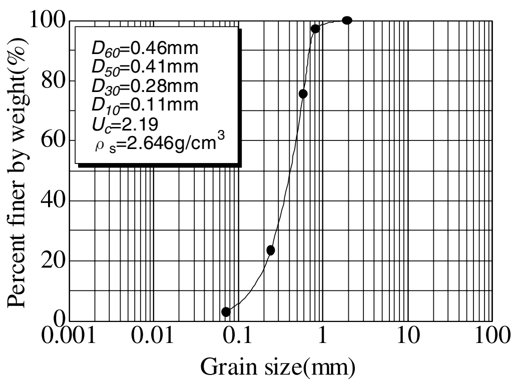

Figure 3 Grain-size distribution curve of Chiba sand

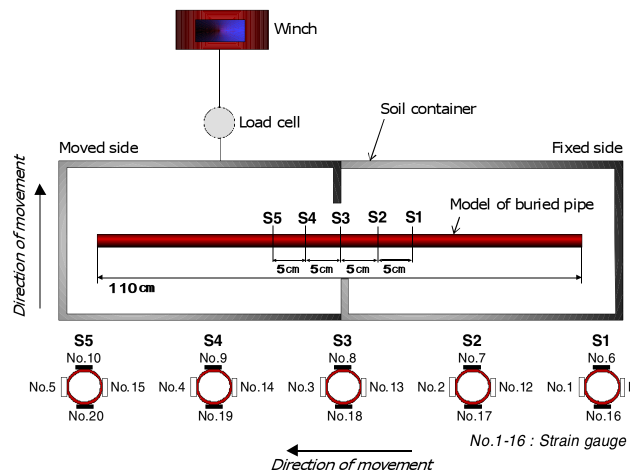

Figure 4 Positions of pasted strain gauges

and recorded strains. Two types of relationships were observed; i) strain had a peak value before 10 cm of displacement (Type 1), and ii) the strain increased with displacement up to 10 cm but had no peak value (Type 2). The former type was observed mainly in the case that buried depth was shallow. In the latter type, the maximum strain was defined as the strain at 10 cm of the displacement. Figure 7 compares the distribution of the maximum strain, thus defined, in different buried depth. The maximum strain increased with the depth as shown in this figure. Figure 8 shows distribution of final displacement of pipes in different buried depth. If the buried depth is shallow, buried pipe hardly bent in horizontal direction. Figures 9 and 10 show distribution of heaving of the ground surface, measured just after 10 cm of displacement. As shown in these figures, heaving occurred if the buried depth is shallow. This implies that jump out phenomena occurred if buried depth was shallow.

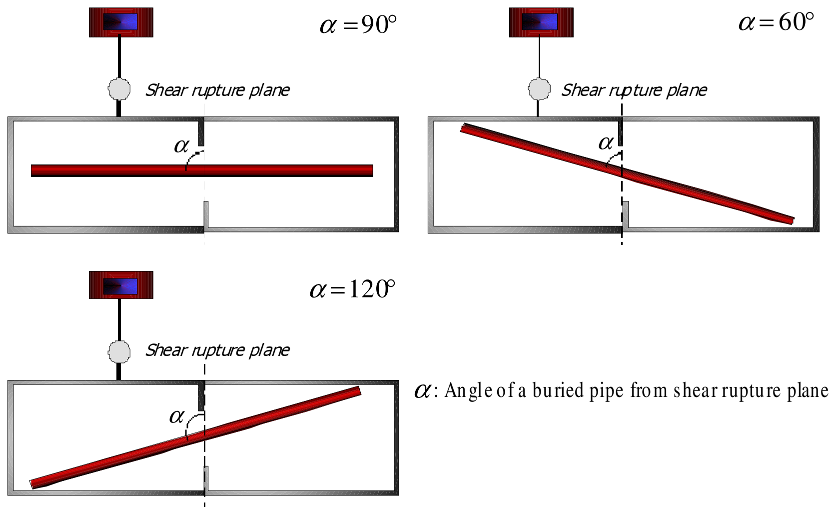

Figure 5 Definition of angle of a buried pipe from shear rupture plane

Photo 7 Photo after the shear test of a pipe buried with an angle of 90°

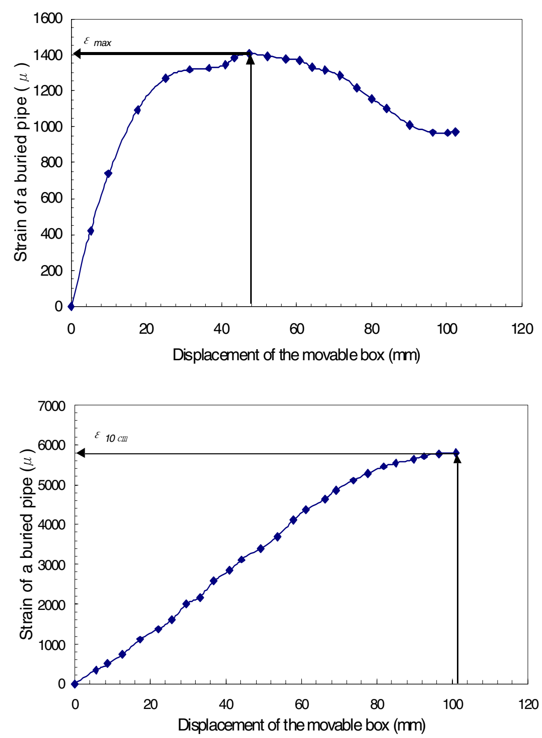

Figure 6 Typical relationship between displacement of box and strain

Based on the measured strain, bending moment was calculated. Figures 11 to 13 show relationships among the calculated maximum bending moment and buried depth, diameter, angle and degree of compaction. The maximum bending moment increased with the buried depth, the degree of compaction, the diameter of pipe, and the angle.

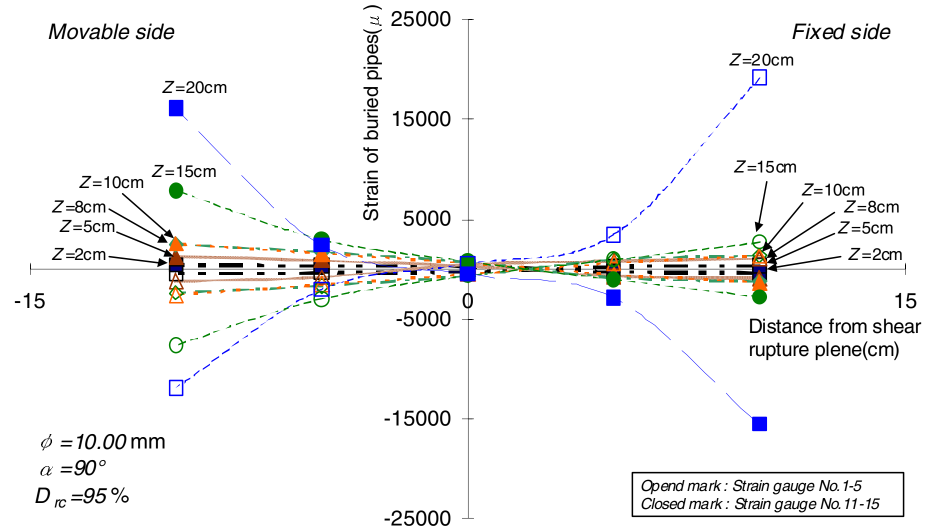

Figure 7 Comparison of the distribution of maximum strain with different buried depth

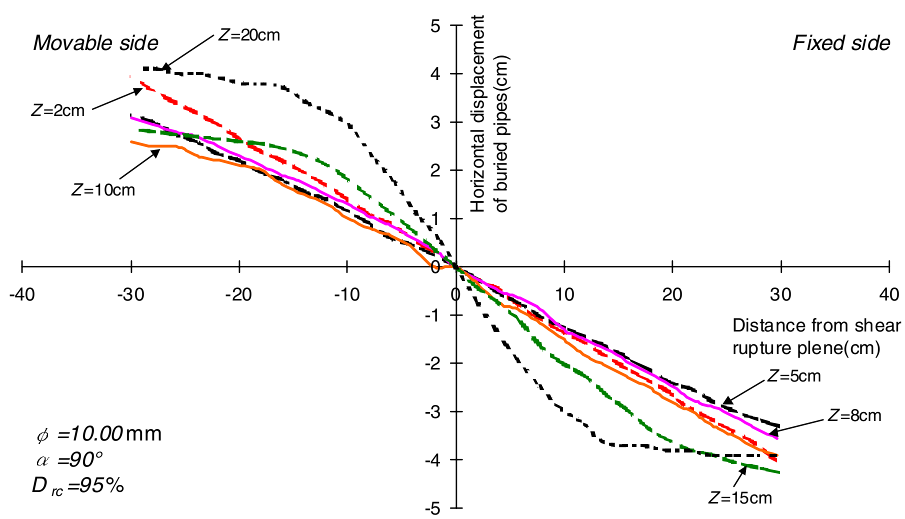

Figure 8 Comparison of the distribution of final displacement of pipes with different buried depth

Subgrade reaction was estimated also at each position of strain gauge, based on the calculated bending moment. Relative displacement between a pipe and surrounding soil at the position was estimated by the measured strain and displacement of the shear box. Figures 14 and 15 show relationships between the relative displacement and subgrde reaction for two buried depths. If the buried depth is shallow, the relative displacement- subgrade reaction curves had peaks. On the contrary, the curves for deeper cases had no obvious peaks. The maximum subgrade reaction increased with the buried depth and degree of compaction.

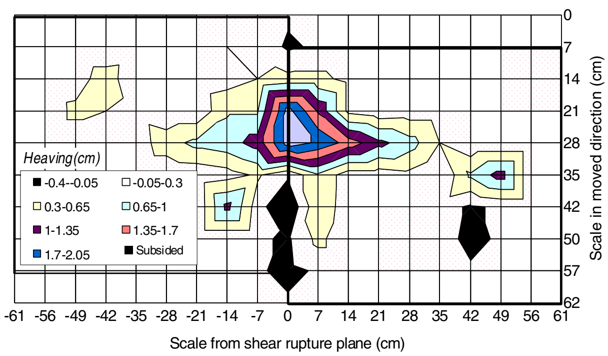

Figure 9 Distribution of heaving of the ground surface (Z=2cm)

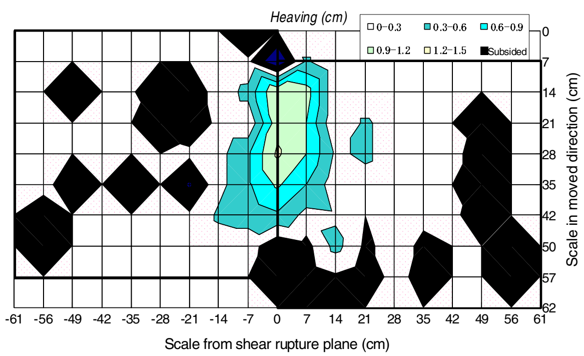

Figure 10 Distribution of heaving of the ground surface (Z=20cm)

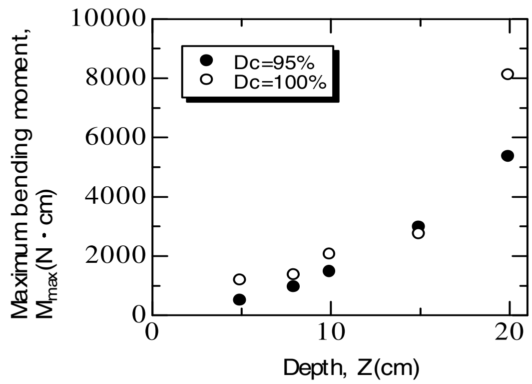

Figure 11 Relationship between buried depth and maximum bending moment

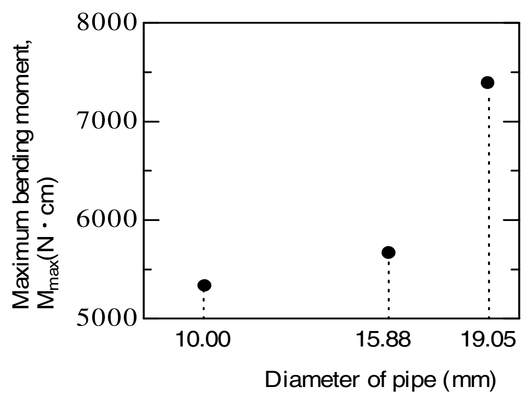

Figure 12 Relationship between diameter of pipes and maximum bending moment

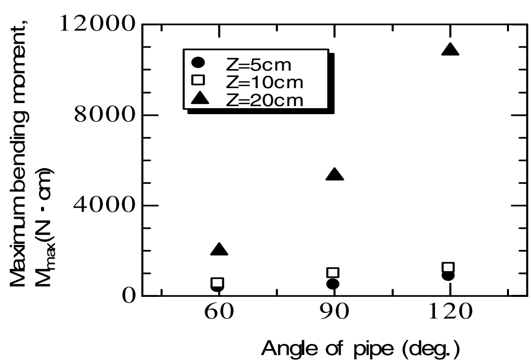

Figure 13 Relationship between angle of pipes and maximum bending moment

DEA OF COUNTERMEASURES DERIVED FROM MODEL TESTS AND ADDITIONAL TESTS TO DEMONSTRATE THEIR EFFECTIVENESS

Base on case histories and model tests, the following three simple ideas for countermeasures against surface fault rupture were derived as shown in Figures 16 to 18:

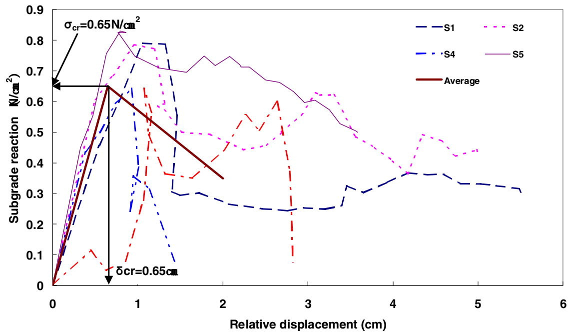

Figure 14 Relationship between relative displacement and subgrade reaction (Z=2cm)

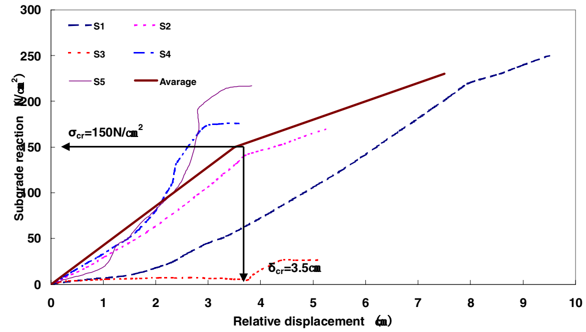

Figure 15 Relationship between relative displacement and subgrade reaction (Z=20cm)

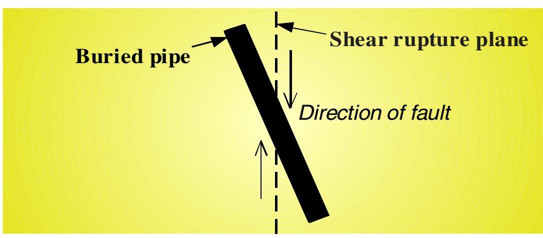

Figure 16 An idea of countermeasure by the appropriate angle of pipeline with the direction of a fault

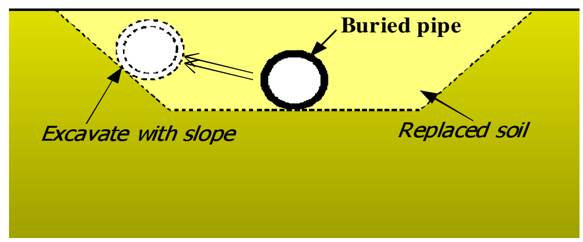

Figure 17 An idea of countermeasure by excavation with a slope

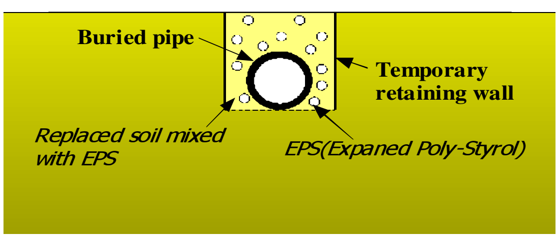

Figure 18 An idea of countermeasure by mixing EPS in replaced soil

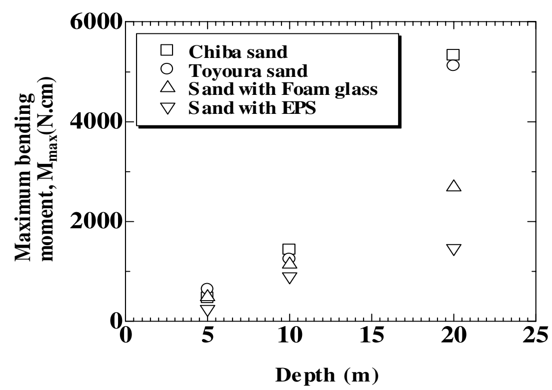

Figure 19 Comparison of moment of pipes among different kind of soils

(1) bury a pipe with appropriate angle to the direction of fault,
(2) excavate the ground with some slopes then backfill the excavated trench with a soil, and
(3) backfill a excavated trench by a mixed soil with a light-weigh material, such as EPS (expanded polystyrene) .

The authors conducted additional model tests to demonstrate the effectiveness of the third countermeasure method. In the tests, Chiba sand was mixed with two kinds of light-weight materials, EPS and foam glass.

Total unit weight of the mixed soil and degree of compaction of soil particles were adjusted as 9.8 kN/m^3 and 95%, respectively. Tests for Toyoura sand which is clean sand were also conducted. Test methods were same as the method mentioned above. Figure 19 compares the maximum bending moment for the four kinds of soils. As shown in this figure, the maximum bending moments of the model pipes in the mixed soils with EPS or foam glass were smaller than the moment of the pipe in Chiba sand or Toyoura sand only. Therefore, it can be said that the third countermeasure method, backfill the trench by a mixed soil with a light-weight material, is effective to prevent damage of the pipe.

MODEL TESTS TO DEMONSTRATE THE BEHAVIOR OF BURIED PIPES DUE TO THRUST FAULT RUPTURE

For thrust fault, model tests were also conducted to demonstrate of the behavior of buried pipes and effectiveness of the countermeasure by mixing a light-weight material. In this test, two soil containers, which are fixed container and movable container shown in Figure 20, were used. Angle of shear rupture plane was 30 degrees. The movable container was climbed up along the shear rupture plane, by pulling a wire for 10 cm in displacement. Photo 8 shows oblique thrust fault rupture observed on the ground surface. Soils and model pipes used were same ones as the tests for horizontal fault rupture. Strain gauges were also pasted on the pipes. Tests were carried out under several conditions of depth of the buried pipes and degree of compaction of the ground.

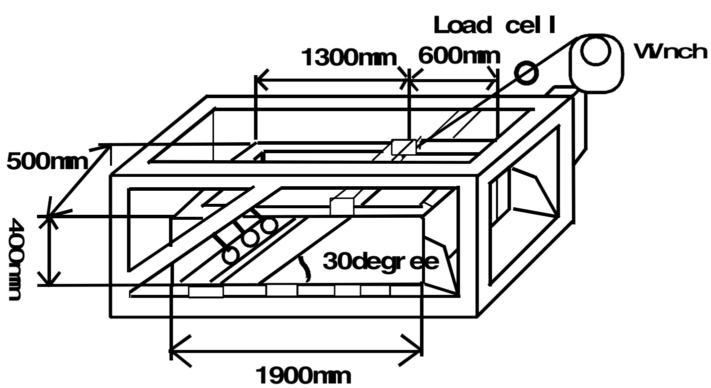

Figure 20 Test equipment for thrust fault

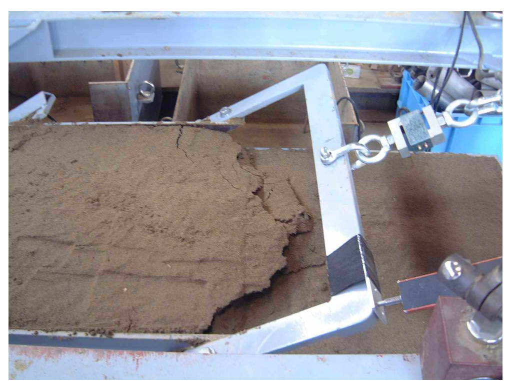

Photo 8 Observed thrust fault

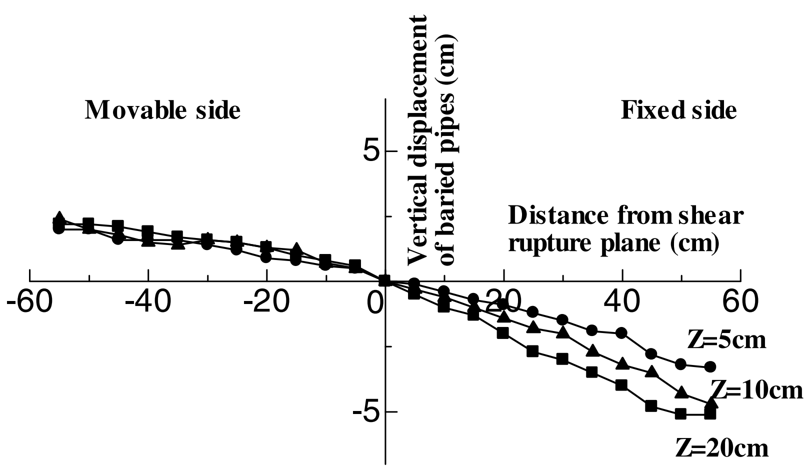

Figure 21 Comparison of the distribution of final displacement of pipes with different buried depth

Figure 21 shows distribution of final displacement of pipes in different buried depth. If the buried depth is shallow, the buried pipe hardly bent as same as the tests for horizontal fault rupture. One remarkable phenomenon was that the buried pipe bent at one point only in movable soil container which means hanging side, if the buried depth is shallow. On the contrary, if the buried depth is deep, the buried pipe bent at two points in both sides from shear rupture plane as same as the tests for horizontal fault rupture.

Bending moment was calculated based on measured strain. Figure 22 shows relationship among the maximum bending moment, buried depth and degree of compaction. The maximum bending moment increased with the depth and degree of compaction as similar as Figure 11. Therefore it was estimated that bending moment can be reduced if a light-weight material is mixed in a backfill soil. Then additional tests were carried out by using the same mixed soil as the tests for horizontal fault rupture. Figure 23 compares the maximum bending moment of the pipes in the mixed soil with the moment of those in Chiba sand. As shown in this figure, the bending moment could be reduced by using the light-weight material.

CONCLUSIONS

Damages of buried pipes due to surface fault ruptures were reviewed. Then several model tests to demonstrate the mechanism of the damage to buried pipes, and effectiveness of a countermeasure, were conducted. The following conclusions were derived through these studies:

(1) Surface fault rupture causes severe damages to buried pipes.

(2) Bending moment of buried pipes due to fault ruptures is affected by density of soil, depth of the pipe, diameter of the pipe, angle of the pipe to the fault and type of fault.

(3) Backfilling a excavate trench by a mixed soil with a light-weight material such as EPS is effective to prevent the damage of pipes due to surface fault rupture.

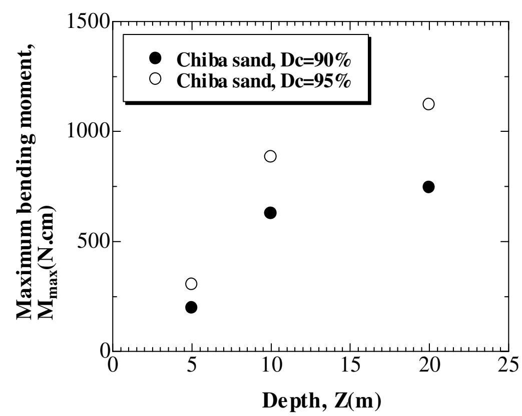

Figure 22 Relationship between buried depth and maximum bending moment

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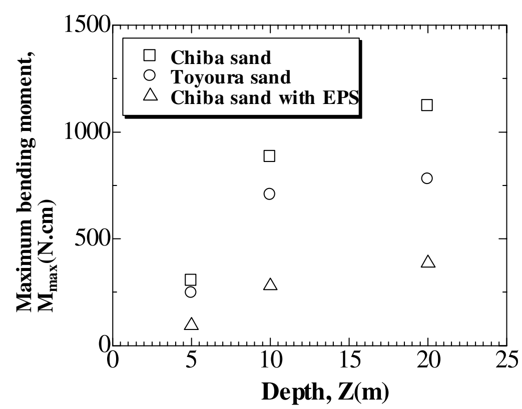

Figure 23 Comparison of moment of pipes among different kind of soils

REFERENCE

1. Berrill, J. private communication., 2002.