Bull. ERS, No.16 (1983)

RECENT RESEARCH ON SEISMIC BEHAVIORS OF BURIED PIPELINES IN CHINA

by

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INTRODUCTION

This is one of the reports of the Japan-China cooperative research in earthquake engineering performed in the period of two months from January 16 to March 15, 1982, during which the first author stayed at the Institute of Industrial Science, University of Tokyo, to which the second author belongs. The contents of this paper have resulted from numerous discussions between the authors made during the aforementioned period.

This paper consists of three parts. Chapter 2 deals with the buried pipeline damage observed after the 1975 Haicheng and the 1976 Tangshan earthquakes. It is worth noting that the findings made in Chapter 2 from the recent Chinese experience are generally in good agreement with the results of similar studies on the Japanese data previously performed by the second author. Interested readers should refer to References (1) through (5). Chapter 3 briefly describes the results of explosion tests on buried pipes recently conducted in China. The general concept of the relative displacement between the pipe and its surrounding soil conclusively observed during these tests has been reflected in the present Chinese code for the seismic examination of buried pipelines. Chapter 4 explains how the two important formulae in the aforementioned Chinese code have been derived. Comments are added with regard to an apparent inconsistency that seems to be present in these formulae.

DAMAGE TO PIPELINES DURING HAICHENG AND TANGSHAN EARTHQUAKES

Field investigation on earthquake damage usually brings about valuable and instructive informations to both earthquake engineering research and seismic design and construction practices of various structures. It has been recognized as one of the effective and indispensable ways in developing and pushing forward the science and technology of earthquake engineering.

During the 1975 Haicheng and the catastrophic 1976 Tangshan earthquakes, damage investigations on various kinds of buried pipelines at site were carried out. Below will be given a concise yet in a more or less extent description on observed damages during these earthquakes. As a necessary replenishment and supplement, some more damage informations from some earlier Chinese earthquakes will be cited selectionally.

DAMAGE TO BURIED PIPELINES: Damage to buried pipelines during both Haicheng and Tangshan earthquakes showed a wide variety of failure modes. It is preferred to have them elucidated according to their causes.

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1) DAMAGE CAUSED BY FAULT ACTION: During the Tangshan earthquake, the intensity in Tangshan city, the epicentral area, was 10-11. A terrible ground rupture as long as 10 km occurred round the stretch of Jixiang Road in Lunan District of the city, running at an angle of 40-50 degrees from the north to the east. This surface trace was found to take the same run and approximately the same position as those of the causative rupture in the bedrock lying far down below. The Jixiang Road was cut off by a 1.25m horizontal offset and an over 0.6m vertical difference in road surfaces. Near the fault, generated were closely distributed ground cracks, staggers, uplifts and subsidences, and other large ground displacements, which threw irresistible attacks resulting in verious damage to pipelines buried there.

Photo 1 shows a ϕ1000 R/C buried pipeline undergoing a horizontal stagger as great as about 80cm and a pulling out of 20cm or so at the pipe connection. Photo 2 is showing a ϕ200 castiron pipeline located in the East Water Supply Plant suffering from a 22cm vertical stagger and a 3cm pulling apart at the joint. Photo 3 is an example of a R/C buried pipeline severely cracked. Photoes 4-6 indicate several castiron pipelines having the same 300mm diameter experiencing serious damages of changeable failure modes including staggering, crushing, fracture, circumferential crack, joint pulled out, and even bending and twisting.

2) DAMAGE CAUSED BY SLIDE AT RIVER BANKS: Landslides at river banks often accompany ground staggers, ground cracking, and pronounced movements as well as differential settlements during a strong shock. This seems to be the reason that led to a number of severe damages to pipelines embedded along the river bank and nearby.

During the Haicheng earthquake, two steel pipelines crossing the Liao River were cracked. A ϕ700 R/C buried pipeline laid in the Yingkou Paper Mill of Yingkou city (intensity 8) was crushed as shown in Photo 7. Photoes 8 and 9 give the views of a flange break and the bending of a steel pipeline which passed across a river with the slide of river bank taking place.

During the Tangshan earthquake, two steel pipelines crossing the Hai River in Tianjin area (intensity 7-8) were damaged at the castiron connections at or near the river side. Photo 10 shows the bent parts of a steel pipeline squeezed flat in the Tanggu Alkali Factory near a river bank and within the area of intensity 8. A ϕ500 steel pipeline of a chemical factory in Hangu suffered similar damage as shown in Photo 11 owing to the same reason.

In Tangshan City, there were six steel pipelines crossing the Dou River at different places. All of them were unexceptionally damaged, displaying varying sorts of failure. Photo 12 shows one of those severe damage. Photo 13 is another representative damaged example which had buckled as a result of the face to face inward soil movements of banks of the Dou River, the middle point of the pipeline tilting up as high as 2.5m.

3) DAMAGE CAUSED BY LIQUEFACTION: Within the zone of sand liquefaction, ground failures of various kinds often took place owing to the occurrence of drastic sand spewing and water spouting. Pipelines buried in such regions would undergo severe damage, even those in lower intensity area like 7 were not luckily immuned from some damage.

One wellknown example in the Haicheng earthquake was the city of Panjin where the intensity was 7. Buried pipelines there were heavily tormented by the large-area sand liquefaction. Pipelines even including steel ones suffered damage. Photo 14 shows a natural gas pipeline being uplifted 0.5-1.0m high by the sandvent in the pipe ditch. Photo 15 is a steel pipe repaired by welding after having been damaged by ground failure in the region of sand liquefaction appearing.

To demonstrate the disadvantageous aspects of sand liquefaction on buried pipelines, some investigation data of damage rate collected from the city of Panjin will be presented. A pipeline consisting of 50-95mm diameter pipes took a damage rate of 1.6 No/km, the thread joints being pulled off at 25 places within a total length of 16km. Castiron pipelines with rigid joints using cement mortar as filling material underwent a damage rate of 0.61 No/km, and were entirely paralyzed because of the leakage of gas at damaged joints. A ϕ1200 R/C pipeline in this city was also damaged with joints pulled apart as shown in Photo 16.

During the Tangshan earthquake, buried pipelines near sanitary backfills or old river courses where liquefaction of sand or light sandy clay took place were heavily damaged. Photo 17 shows the fracture of a steel pipeline elbow resulted from the subsidences of ground surface. Pipelines in Tanggu (intensity 8) were severely damaged with a damage rate over 4 No/km. In Hangu area (intensity 9), sand vents and water spouts were more serious resulting in a slumping of ground surface greater than 60cm at some places. The damage rate of a ϕ150 and 7km long castiron pipeline was found even higher than 10 No/km.

4) DAMAGE CAUSED BY SEISMIC SHAKING: Strains would be induced in pipelines buried in roughly homogeneous ground condition by seismic wave propagation that creates ground vibration along the route of the pipeline. Once the ground vibration rises up to a certain strong degree, damage will fall upon buried pipelines, especially those having rigid joints and those made of low strength and low ductility material. Damage investigations conducted by Japanese scholars have shown that the main response of straight pipelines to seismic wave propagation is the longitudinal strain, which leads to the main mode of axial damage correspondingly, including circumferential cracking at either pipe barrel or pipeline joints and loosening or pulling out of joints.

During both Haicheng and Tangshan earthquakes, it was found that evidences there and here rose again in supporting this point of view. Photoes 18-20 provide some convincing sights telling buried pipelines cracked, pulled loose or apart near or right at the pipeline joints by imposed axial strain.

5) DAMAGE CAUSED BY INCOMPATIBLE DEFORMATIONS: Pipelines might be severely damaged if their deformations during a strong earthquake are coercively restricted by virtue of different reasons which bring about incompatible deformations of pipelines at the relevant connecting position. Some typical instances follow.

(a) One representative example is the pipeline crossing and rigidly fixed at wall. Deformation of pipelines coming out of the ground and passing through the rather rigid walls of buildings would be forcibly restricted at the connection point, hence stimulating considerably large stresses and ending up with occurring damages of changeable modes during an earthquake shock. Photoes 21 and 22 are two such severely damaged examples, the former being steel pipeline, the latter castiron.

(b) Accessories and fittings of pipeline system such as elbows, tees, and crosses at pipeline junctions were liable to break owing to the stress concentration aroused during a strong shock. It is obvious that individual branches of pipelines in different runs converging in to the same junction would have their deformations severely restricted with each other there, thus forming a vulnerable part of the pipeline system. Photoes 23-24 show a number of elbows and other pipeline fittings damaged in varying patterns during both Haicheng and Tangshan earthquakes.

6) DAMAGE CAUSED BY CORROSION AND POOR QUALITY OF WELDING: Both steel and castiron pipelines corroded may incur heavy damage under the attack of earthquake shocks.

During the Haicheng earthquake, the intensity of Anshan City was only 7 and the ground condition of the major part of the city can be grouped into the second category according to the China seismic design codes. Only three damage were observed within a total length over 50km of pipelines consisting of 75-900mm diameter steel pipes. Two among the three were due to bad corrosion, while the third one due to the appearance of ground crack nearby. Photo 25 indicates a longitudinal crack on the pipeline body, which was a scarcely seen pattern of damage.

Another example to be cited was in Yingkou City, where a large number of corroded castiron pipelines were seriously damaged at various localities of the pipelines with different damage modes as shown in Photoes 26-28.

On the other hand, damage to steel pipelines as a result of poor workmanship of welding were also not short of performances.

During the Haicheng Earthquake, a 21.5km long pipeline for natural gas transmission was damaged at 18 places, the damage rate being 0.84.

Photo 29 shows the rupture at a welded section of a $\phi 400$ steel pipeline in Tangshan City.

PARAMETERS AFFECTING PIPELINE DAMAGE: Four parameters, namely the intensity of earthquake, the ground condition, the pipe size, and the deformability of joint, are to be discussed below.

1) EFFECT OF INTENSITY: Table 1-1 and Table 1-2 list the rate of damage versus intensity during Haicheng and Tangshan earthquakes, respectively. It can be seen from these Tables that higher intensity implies heavier damage as could be imagined.

2) EFFECT OF GROUND CONDITION: A striking contrast to explain the important effect of ground condition upon pipeline damage during the Haicheng earthquake was found in Panjin and Anshan of the same intensity 7 but of unequal ground conditions. The damage rate observed in Anshan where the ground condition belongs to second category was nearly 0, while that in Panjin where the ground condition was third category and sand spewing and water spouting took place in a considerably big area reached as high as 1.6 No/km for steel pipelines with diameters smaller than 150mm.

During the Tangshan earthquake, ground condition showed even greater influences on pipeline damage. Lower intensity area, Hangu, of third category ground condition suffered a damage rate over 10 No/km which was much higher than that of higher intensity area, Tangshan, of second category ground.

3) EFFECT OF DEFORMABILITY OF JOINT: Rigid joints using material such as cement mortar and asbestos cement as filler were easily damaged or liable to leak owing to the poor deformability. In contrast to this, flexible joints with rubber ring as gasket were capable of withstanding much bigger joint deformation so as to mitigate the pipeline damage to a conspicuous degree.

In Yingkou City, $\phi 75$-$\phi 150$ asbestos pipelines with rigid joints experienced a damage rate up to 22.1 No/km, while those of flexible joints only 1.51 No/km.

In Tanggu area, $\phi 100$-$\phi 200$ asbestos pipelines took a damage rate as high as 15.9, while those of flexible joints almost zero.

Recent tests on deformability of different sorts of joints performed in China showed that the ultimate deformation of flexible joints in axial direction was about two hundredfold that of rigid joints or even more.

Damage data suggested that joints be the weakest link of the pipeline against earthquakes. For instance in Tangshan City, the percentage of damage appearing at joints amounted to 79.6%.

4) EFFECTS OF PIPE SIZE: Damage data from both Haicheng and Tangshan earthquakes revealed a trend that the damage rate varied inversely with the pipe size. That is, as the pipe size increases, the rate of damage decreases. Fig. 1-1 to Fig. 1-4 are damage rate versus pipe size relationships obtained from collected pipeline damage data. Since the actual situation was very much complicated, these data are only of qualitative sense.

DAMAGE INFORMATION FROM SOME EARLIER CHINESE EARTHQUAKES:

1) On Nov. 13, 1965, an earthquake of magnitude 6.7 broke out in Wylumuqi region with epicentral intensity 8. No damage at all was found in buried pipelines laid in Wylumuqi City of intensity 7. Castiron pipelines of 150-200mm diameters in Wulung Steel Plant within the area of intensity 8 were investigated, and still no damage appeared.

2) On March 8 and 22, 1966, two strong earthquakes with magnitudes 6.8 and 7.2, respectively, occurred near Xingtai City. In Milu County (intensity 7, second category ground), ϕ100-ϕ300 castiron buried pipelines were intact. In Kenli County (intensity 7, third category ground), only one damage to a ϕ800 castiron pipeline was observed as a result of the soil staggering nearby.

3) On July 18, 1970, a strong earthquake shock of magnitude 7.4 took place in Bohai Sea area. During this earthquake, no sand liquefaction appeared and hence no damage was observed in Tanggu as well as in Hangu where the intensity was 6.

4) On Jan. 1, 1970, a strong earthquake of magnitude 7.7 emerged in Tonghai County, Yuannan province, the intensity of the epicentral area being 10. In Yuqi county, where the intensity was 7 and the subsoil was rocky clay, a ϕ200 castiron pipeline buried there generally stood well during the earthquake. But some damage, for example, damage at threaded joints and cracks in pipeline barrels, occurred to pipelines laid in the epicentral area.

A BRIEF SUMMARY: A brief summary can be outlined based on the damage information aforepresented.

1) The main causes contributing to pipeline damage may be grouped as follows:

(a) Ground failure: Causative faults, landslides, sand liquefaction and other adverse terrains lead to various ground failures such as ground staggering, ground ruptures and fissures, uplifting and slumping of the ground surface, twisting and bending, and big soil movements. It can be concluded that ground failure will bring about irresistible damage of changeable modes to buried pipeline within such disadvantageous regions.

(b) Ground vibration: Seismic wave propagation forces the buried pipeline to vibrate and deform according to the deformation of the surrounding soil. The primary response of pipeline to this is the axial strain along the route, which will cause damage such as circumferential cracks at pipeline barrels or at joints and the loosening or pulling out of joints in the longitudinal direction.

(c) Incompatible deformation of pipelines

(d) Inadequate strength and poor deformability of pipelines including the joints as a result of corrosion of metals, poor quality of workmanship, and the usage of low strength and low ductility materials.

While the first two are external causes, the last two can be considered as internal causes of pipeline itself.

2) Based upon the inspection on buried pipeline damage observed during Haicheng and Tangshan earthquakes, the following general comments may be made.

(a) In areas where ground failures appeared, buried pipeline unexceptionally suffered serious damage. Even in region of intensity 7, for instance in Panjin city, steel pipelines were damaged, let alone castiron ones with rigid joints.

(b) In areas where no ground failure took place, pipeline damage were dependent upon intensity as well as ground condition. Generally speaking, in region of intensity 7, various sorts of buried pipelines were safe. In region of intensity 8, castiron pipelines, mainly those of small diameters and with rigid joints, or badly corroded, suffered damage to a certain extent. In region of intensity 9, buried steel pipelines were kept intact, except for those corroded or poorly welded. In region of intensity 10 or higher, even steel pipelines were not exempted from damage.

3) It was again proved that buried pipelines are generally damaged by the imposed ground displacement of surrounding soils. Various sorts of large displacement induced by ground failure are common during a strong ground shaking and they produce extremely severe effects to ordinarily designed buried pipelines. It seemed not only the strength, but also the deformability of the pipeline system to comply with the externally imposed ground displacement that would play the main role of earthquake resistance.

One example to support this point of view was the damage difference observed between pipelines with rigid and flexible joints. Damage information demonstrated that many rigid joints with cement mortar as filler became water-filtrating, water- or gas-leaking, or pulled out, making the whole pipeline paralysed. On the opposite side, some pipelines with flexible joints using rubber ring as gasket survived the earthquakes.

VIBRATION TESTS FOR BURIED PIPELINES

Explosion tests were carried out in China in order to gain more knowledge on the dynamic behaviour of buried pipelines subjected to earthquake ground motion. The soil condition of the site where the tests were performed was firm brownish sandy clay with the bedrock situated deeply below. The sizes of tested pipelines were 159mm in diameter and 6mm in thickness. The weight of dynamite used for each test ranged from 6 to 45kg, and the explosion distance as shown in Fig. 2-1 was in the range of 20-50m. The depth of explosive source was 2.2m for all the cases tested.

The main contents to observe in the test were strains as well as displacements for pipelines and soils (at bottom of ditches) in a contrast manner.

A set of tests for measuring longitudinal spring constants of surrounding soil against pipes were also carried out in order to examine the more reasonable model for seismic analysis of buried pipelines subjected to seismic wave propagation.

VIBRATION TEST OF STRAIGHT PIPELINES: The layout of the test is shown in Fig. 2-1. The dynamic behaviors of two straight pipelines A and B were studied. While the backfill in ditch B was the tamped soil for all the cases, three different backfill conditions were used for ditch A as shown in Fig. 2-1.

Table 2-1 provides a comparison of soil displacement amplitudes at section I in different ditches during longitudinal explosions. A typical example of measured records of the soil for ditches A and B is given in Fig. 2-2.

Table 2-2 lists the longitudinal displacement amplitudes at section I of pipelines and soils in both ditches A and B. The ratio of displacement amplitude of the pipeline to that of the corresponding soil and the relative displacement amplitude between them in the longitudinal direction are also included. Fig. 2-3 shows an example of measured displacement records for pipelines and soils and their comparison.

Table 2-3 offers the axial strain amplitudes observed at section I of pipelines A and B and the relevant ratios as well. Fig. 2-4 compares the axial strain record of pipeline A (with full loose soil as backfill) with that of pipeline B.

It was noted that the flexural strain appearing in pipelines in all longitudinal explosion cases were nearly zero.

For more reasons than one, a number of oblique explosions were arranged and conducted. One instance of explosion applied the dynamite weighing 20kg at an explosion distance of 37m from the explosive source to the middle point of the nearer tested pipeline (see Fig. 2-1). The ratio of the measured longitudinal displacement amplitudes of pipelines to those of corresponding soils were 0.55 (pipeline A) and 0.78 (pipeline B), respectively. The ratio of the axial strain amplitude of pipeline A to that of pipeline B was 0.73.

Some lateral explosion tests were also done. It should be pointed out that the flexural strains arising in pipelines during various explosions were still neglegible. In a certain explosion of this sort applying dynamite of 20kg at explosion distance of 44m, the ratio of observed lateral displacement amplitudes of pipelines to those of corresponding soils were 0.93 (pipeline A) and 0.90 (pipeline B), respectively. Fig. 2-5 shows records of lateral displacement of both pipelines and soils during that explosion.

From the test results given above, the following conclusions can be drawn:

1) Different kinds of backfill do not cast appreciable effect upon the displacement of the soil produced at the bottom of the ditch during a ground motion. It is due to the fact that the existance of a ditch is so insignificant as compared with its adjoining immense land.

2) As a matter of fact the relative displacements do occur, no matter what kind of backfill is used, and in what direction the explosion takes place.

3) The value of the relative displacement between a pipeline and the surrounding soil is related to the tightness of backfills. The looser the backfill, the greater the relative displacement becomes.

4) The axial strain in straight pipelines decreases with the increase of the pipeline-soil relative displacement as has been testified during either longitudinal or oblique explosion tests.

5) The flexural strain in buried pipelines of small diameters can be neglected. So is it even in lateral vibration cases for those pipelines.

VIBRATION TEST OF BENT PIPELINES: The test arrangement is shown in Fig. 2-6. Pipeline C with a bent segment was laid in parallel with a straight pipeline B. The size of pipeline C, the sectional area of the ditches, and the instrumentation remained identical with those in straight pipeline tests. Four kinds of backfills, namely tamped soil, full loose soil, shallow loose soil, and scobs were used for ditch C, while only tamped soil was used for ditch B. Section I in pipeline C was set at the middle of the bent part for measuring both the axial and flexural strains in longitudinal explosion tests.

Table 2-4 provides measured strain amplitudes, axial as well as flexural, and some relevant comparisons. It can be seen that flexural strains become in most cases predominant over axial ones. It might be considered as the essential characteristic of a bent pipeline. Fig. 2-7 offers a set of observed strain records including both axial and flexural.

TEST OF LONGITUDINAL SPRING CONSTANT OF SOIL: Two methods were applied in the test, intending to get a mutual check on test results of longitudinal spring constant of surrounding soil supporting the pipeline inside. Below will be given a brief description of the test.

1) PIPE-PUSH METHOD: The test arrangement and the instrumentation are shown in Fig. 2-8. The tested pipeline was pushed at its one end through an oil jack. The longitudinal force P applied at the pipe end was gradually increased until a slippage of the pipeline took place along the interface with surrounding soil. Longitudinal displacements at both near and far ends of the pipeline were measured. To designate the near end displacement subtracting the compressive deformation of the pipeline as Δ, we can draw out P versus Δ curves. Fig. 2-9 to Fig. 2-12 are P-Δ curves for tested pipelines embedded in different backfills. Table 2-5 gives the values of longitudinal spring constant of the soil against the pipeline obtained from the tests. The friction forces along the soil-pipe interface measured at the moment of pipe slippage taking place are also listed in the same table.

2) HAMMER-HIT METHOD: This method is to hit the tested pipeline by its end in the longitudinal direction to generate a vibration curve that can be measured. The values of the soil spring constant were calculated applying an established formula in use of the period of vibration picked up from the record of pipeline vibration. Table 2-6 shows the results of the experiment.

It can be seen from the tables that the results by two different ways are in reasonable agreement.

CHINA SEISMIC CODE FORMULAE FOR BURIED PIPELINES IN EARTHQUAKE REGION

REQUIREMENTS FOR AXIAL ELONGATION AND STRESS AT JOINTS: In the Public Works Seismic Design Code of China (TJ32-78), formulae for the examination of buried pipeline subjected to earthquake ground motion are provided.

For pipelines with bell and spigot joints under the action of shear wave propagation, the allowable axial elongation of pipe joints should meet the requirement of the following expression

$$\sum_{i=1}^{n} [u]_i > 66\ \zeta\ K_h\ T_m^2 \qquad (1)$$

And for pipelines continuous or with rigid joints, the axial stress induced by shear wave propagation should satisfy the following relation

$$[R_i] > 94E\ \zeta\ \frac{K_h\ T_m}{V_s} \qquad (2)$$

in which,

g = Acceleration of gravity (981 cm/sec^2)

n = Number of joints within a half of the apparent wave length

$$n = \frac{V_s \times T_m}{\sqrt{2} \times l} \qquad (3)$$

V_s = Velocity of transverse wave propagating in the ground during an earthquake (cm/sec)

T_m = Predominant period of the ground (sec)

l = Length of the pipe segment (cm)

ζ = Transfer coefficient, less than unity

$$\zeta = \frac{1}{1 + \frac{EFD}{2 \times V_s^2}} \qquad (4)$$

E = Modulus of elasticity of pipe material (kg/cm^2)

F = Cross sectional area of pipe (cm^2)

D = Average diameter of pipe (cm)

K_h = Horizontal seismic coefficient

$[u]_i$ = Allowable elongation of a single joint under internal working pressure (cm)

$[R_i]$ = Tensile or compressive design strength of pipe or joint material (kg/cm^2)

GENERAL BACKGROUND FOR THE FORMULAE: The propagation of shear wave at an incident angle of 45° as shown in Fig. 3-1 is assumed. It can be easily shown that the seismic effect on the axial behaviors of pipe becomes the greatest in this condition. Let the wave length of the propagating shear wave be L, then the apparent wave length along the axis of the pipe becomes $L' = \sqrt{2}L$. By denoting the displacement amplitude of the propagating shear wave by A, the apparent displacement in the direction of pipe axis may be expressed by $A' = A/\sqrt{2}$.

Let us first consider the soil without pipe. From the above considerations, the distribution of the soil displacement U_s along the pipe axis is given by

$$U_s = A' \sin \frac{2\pi X'}{L'} \qquad (5)$$

and the soil strain in X' direction becomes

$$\varepsilon_s = \frac{du_s}{dX'} = A' \frac{2\pi}{L'} \cos \frac{2\ X'}{L'} = \frac{A}{\sqrt{2}} \frac{2\ \pi}{\sqrt{2}\ L} \cos \frac{2\pi X'}{L'} = \frac{\pi\ A}{L} \cos \frac{2\pi X'}{L'} \tag{6}$$

Let the transfer coefficient of soil strain to pipe strain be denoted by ζ (< 1), then the axial pipe strain can be expressed as

$$\varepsilon_p = \zeta\ \varepsilon_s = \frac{\zeta \pi A}{L} \cos \frac{2\pi X'}{L'} \tag{7}$$

Fig. 3-2 (a), (b) and (c) schematically show the distributions of U_s, ε_s and ε_p, respectively, along the pipe axis X'. As can be seen from Fig. 3-2 (c), the axial pipe strain ε_p varies sinusoidally along the pipe axis. However, if pipe joints are flexible with finite stiffness in the axial direction, it may be assumed that the total elongation (or contraction) δ of the pipeline over the half of the apparent wave length be equally shared by the n joints within that region. Over the critical half wave length as shown in Fig. 3-2 (a), the total elongation (or contraction) at the pipe should be given by

$$\delta = 2 \times \zeta \times \frac{A}{\sqrt{2}} = \sqrt{2}\ \zeta\ A \tag{8}$$

from which the average pipe strain within the one half of the apparent wave length is obtained as

$$\bar{\varepsilon}_p = \frac{\delta}{L'/2} = \frac{2\zeta A}{L} = \frac{2}{\pi} \frac{\zeta \pi A}{L} = 0.64 |\varepsilon_p|_{max} \tag{9}$$

For the pipeline to be safe against joint slip-out, it is required that

$$\delta < \frac{1}{F_s} \times 0.64 |\varepsilon_p|_{max} \frac{L'}{2} \tag{10}$$

where F_s is the factor of safety. By putting

$$|\varepsilon_p|_{max} = \frac{[U]_i}{l} \tag{11}$$

into Eq.(9),

$$\delta < \frac{0.64}{F_s} [U]_i \frac{L'/2}{l} = \frac{0.64}{F_s}\ n\ [U]_i = \frac{0.64}{F_s} \Sigma[U]_i \tag{12}$$

or

$$\Sigma[U]_i > \frac{F_s}{0.64} \delta = \frac{F_s}{0.64} \sqrt{2}\zeta\ A \tag{13}$$

The displacement amplitude A may be expressed by using the horizontal seismic coefficient K_h as

$$A = \frac{K_h\ g\ T_m^2}{4\pi^2} \tag{14}$$

hence

$$\Sigma[U]_i > \frac{\sqrt{2}\ \ g\ \ F_s}{0.64 \times 4\pi^2}\ \zeta\ K_h\ T_m^2 \tag{15}$$

By putting $g = 980\ cm/s^2$, $F_s = 1.2$ into Eq. (15),

$$\Sigma[U]_i > 66\zeta\ K_h\ T_m^2 \tag{16}$$

If the pipeline is continuous or with rigid joints, the following inequality should be satisfied

$$\frac{[R_i]}{F_s} > E\ |\varepsilon_p|_{max} = E\ \frac{\zeta\pi A}{L} \tag{17}$$

from which

$$[R_i] > F_s\ \frac{\zeta E\pi}{L}\ \frac{K_h\ g\ T_m^2}{4\pi^2} = F_s\ \frac{\zeta E}{V_s\ T_m}\ \frac{K_h\ g\ T_m^2}{4\ \pi}$$

$$= \frac{F_s g}{4\ \pi}\ E\zeta\ \frac{K_h\ T_m}{V_s} \tag{18}$$

By putting $g = 980\ cm/s$ and $F_s = 1.2$ into Eq. (18),

$$[R_i] > 94\ E\zeta\ \frac{K_h\ T_m}{V_s} \tag{19}$$

Eqs. (16) and (19) are the forms of the formulae adopted in the present Chinese code.

TRANSFER COEFFICIENT: In the derivation of transfer coefficient ζ given by Eq. (4), it was first assumed that ζ be of the form [Ref.(9)]

$$\zeta = \frac{1}{1 + \frac{\alpha\ E\ F\ D}{V_s^2}} \tag{20}$$

The factor α in Eq. (20) was empirically determined by using the observed damage data during the Haicheng and the Tangshan earthquake in the following manner.

If pipeline damage occurred according to the assumptions described above, from Eq. (15) the following relation should stand for the critical undamaged cases:

$$n[U]_i = 55\ \frac{K_h\ T_m^2}{1 + \frac{E\ F\ D}{V_s^2}} \tag{21}$$

in which $F_s = 1.0$ was assumed. Therefore,

$$\alpha = \frac{V_s^2}{E F D} \left(\frac{55 K_h T_m^2}{n [U]_i} - 1 \right) \tag{22}$$

Table 3-1 summarized the computed values of α and the relevant data for the four such critical cases. Since the results seem to show that α is not very sensitive to the parameters used, α = 1/2 was tentatively assumed, resulting in the form of transfer coefficient given by Eq. (4).

COMMENTS ON THE PRESENT CHINESE FORMULAE: The form of transfer coefficient ζ given by Eq. (20) was assumed because of the apparent effect of pipe size observed during past experiences (see Figs. 1-1 through 1-5). However, if a buried pipeline is assumed as being supported by elastic axial foundation with a spring constant K_1 (kg/cm/cm) per unit length of pipe, the transfer coefficient should take the following form

$$\zeta = \frac{1}{1 + \frac{2\pi^2 EF}{K_1 L^2}} \tag{23}$$

or by putting $L = V_s T_m$

$$\zeta = \frac{1}{1 + \frac{2\pi^2}{K_1 D\ T_m^2} \frac{EFD}{V_s^2}} \tag{24}$$

If this is so, we have

$$\alpha = \frac{2\pi^2}{K_1 D\ T_m^2}$$

which should be extremely sensitive to T_m. In addition, if it is assumed that the elastic support by soil can be represented by

$$K_1 = k_1 \pi\ D$$

where k_1(kg/cm^2/cm) is the spring constant per unit surface area of pipe,

$$\alpha = \frac{2\pi}{k_1\ D^2 T_m^2}$$

which should then be sensitive to D. Although it is difficult to say at present whether the pertinent soil property be described by K_1, k_1, or some other quantities, more examination is definitely needed with respect to the value of and the so-called "observed critical limit of not being damaged".

ACKNOWLEDGEMENT

The authors would like to express their appreciation to Mr.Genkichi Hara and, through him, to the Kajima Foundation for the financial support which made this cooperative research possible and successfully performed.

Many thanks go to Mr.Sheng Shijie and his cooperators for their generosity of kindly offering very useful and plentiful damage information of buried pipelines observed during Haicheng and Tangshan earthquakes as well as the background material for the Chinese Code formulae described in the paper. Help from Prof. Keizaburo Kubo in preparing the paper is also appreciated.

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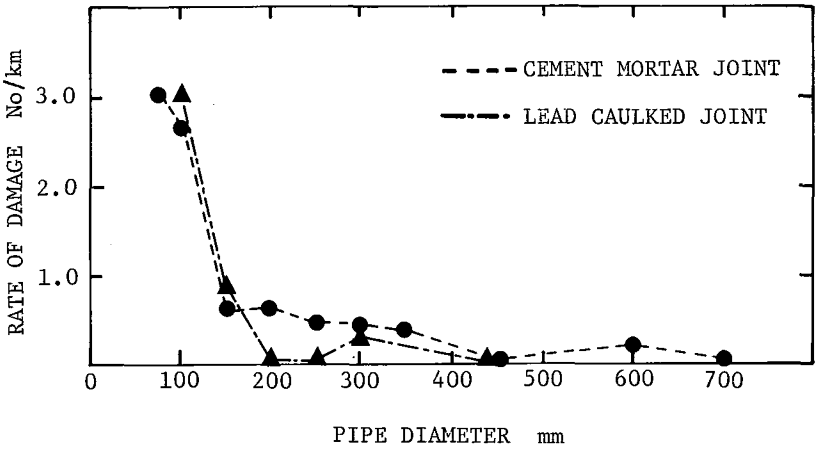


Fig.1-1. Damage Rate Versus Pipe Size
(Cast Iron Pipe, Yingkou)

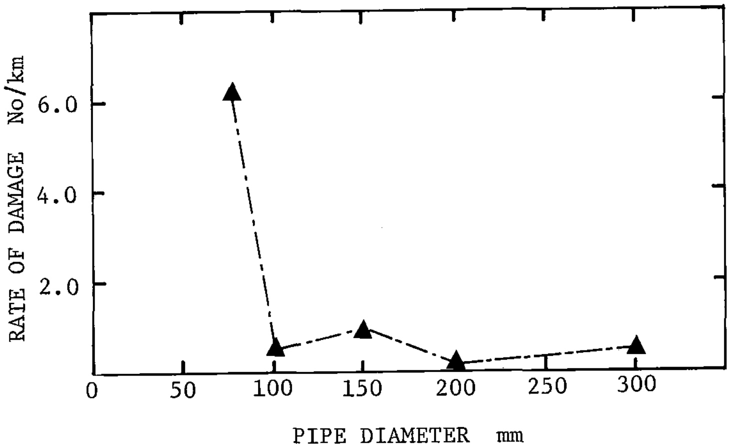


Fig.1-2. Damage Rate Versus Pipe Size
(Cast Iron Pipe, Dashichao)

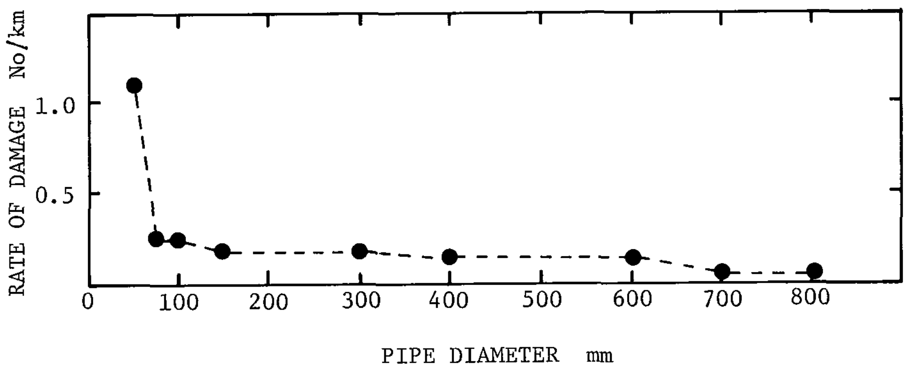


Fig.1-3. Damage Rate Versus Pipe Size
(Cast Iron Pipe, Tianjin)

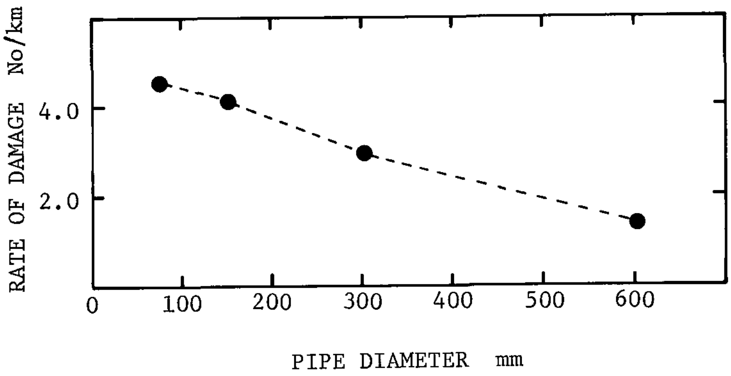


Fig.1-4. Damage Rate Versus Pipe Size (Cast Iron Pipe, Tanggu)

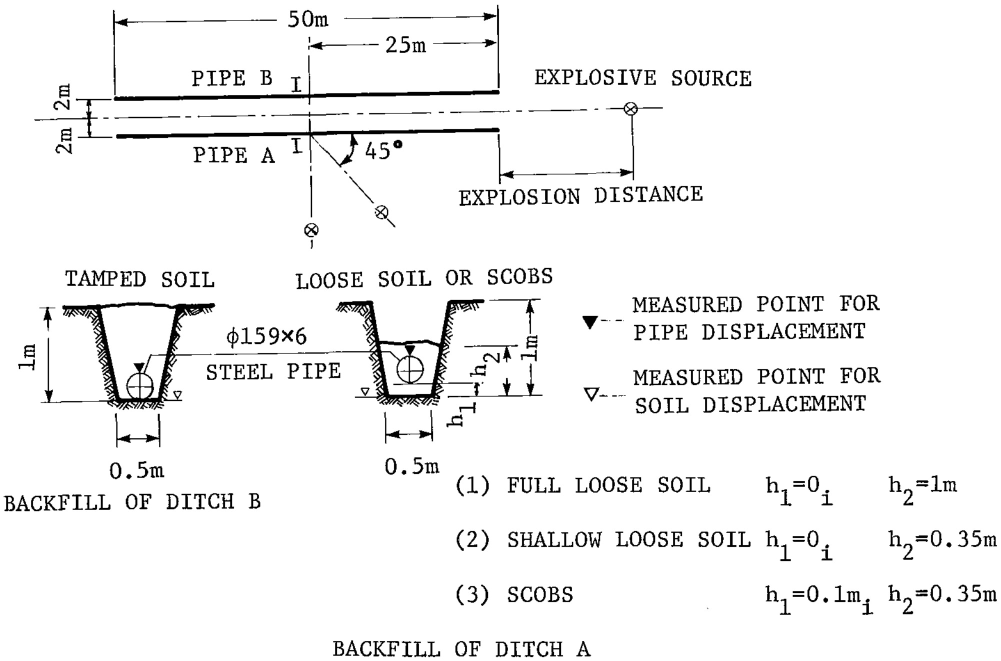


Fig.2-1. Explosion Test Arrangement for Pipes A and B

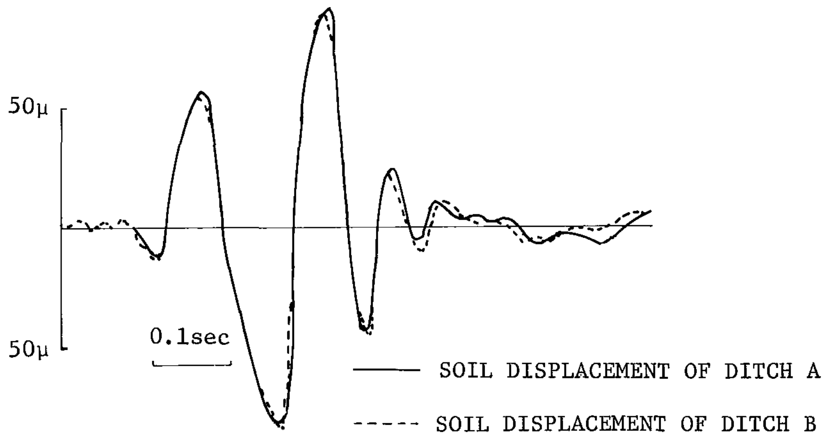


Fig.2-2. Comparision of Soil Displacements
(Backfill of Ditch A Being Shallow Loose Soil)

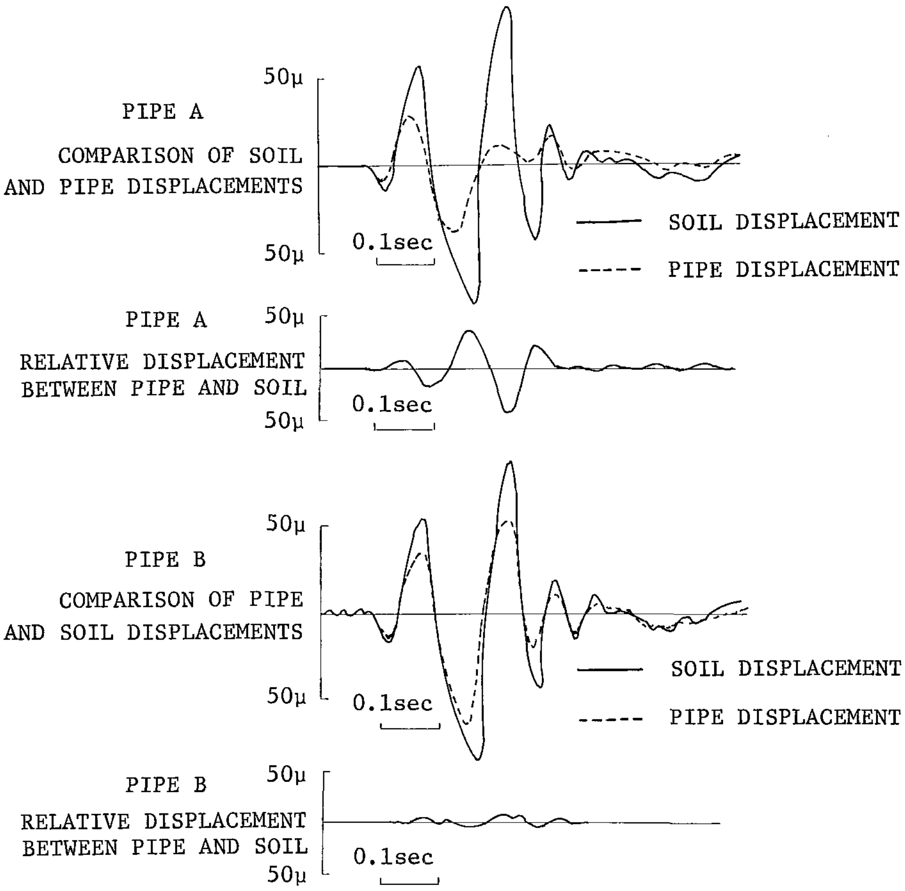


Fig.2-3. Pipe and Soil Displacement Records
(Backfill of Ditch A Being Shallow Loose Soil)

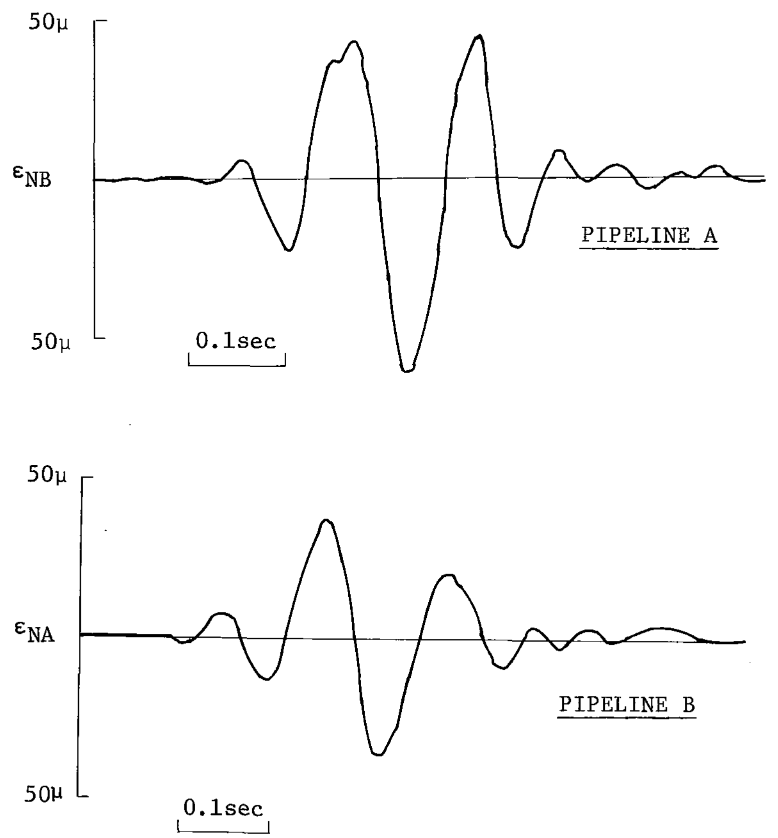


Fig.2-4. Axial Strain Records of Pipelines A and B
(Backfill of Ditch A Being Full Loose Soil)

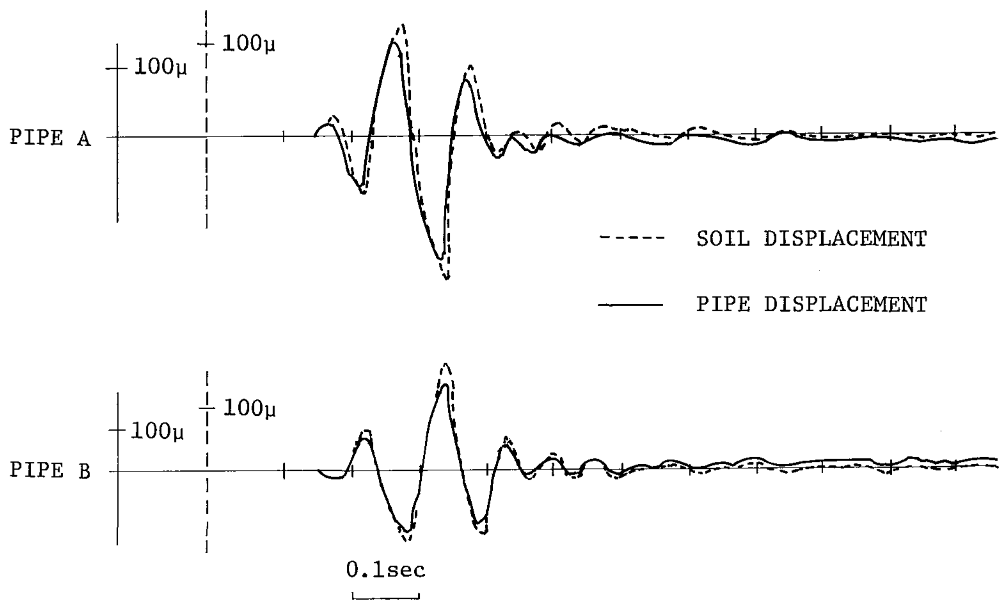


Fig.2-5. Pipe and Soil Displacement Records for Lateral Explosion

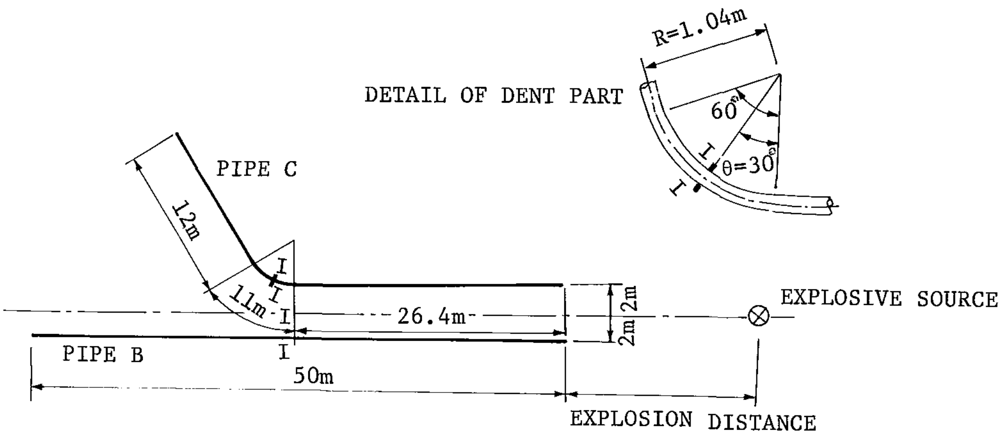


Fig.2-6. Explosion Test Arrangement of Pipes C and B

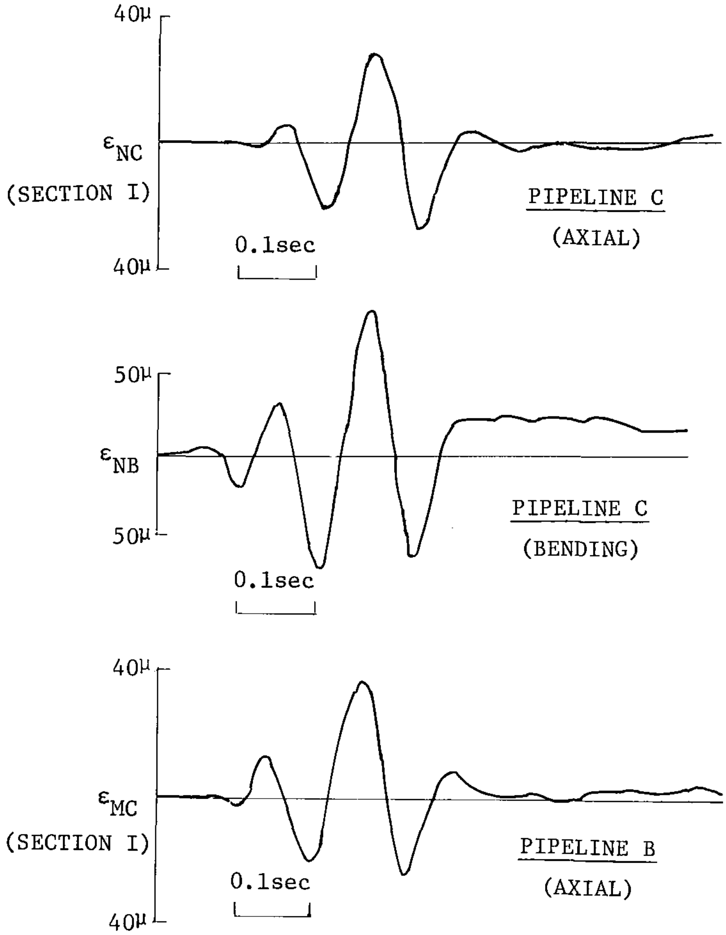


Fig.2-7. Strain Records of Pipes C and B
(Backfill of Ditch C Being Full Loose Soil)

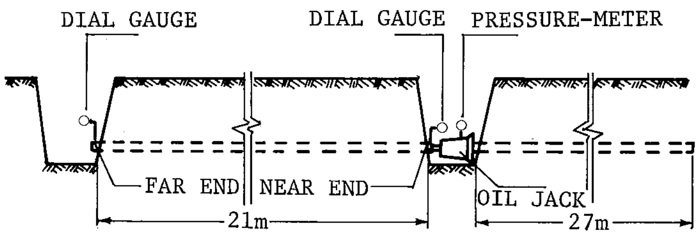


Fig.2-8. Scheme of Pipe-Push Test

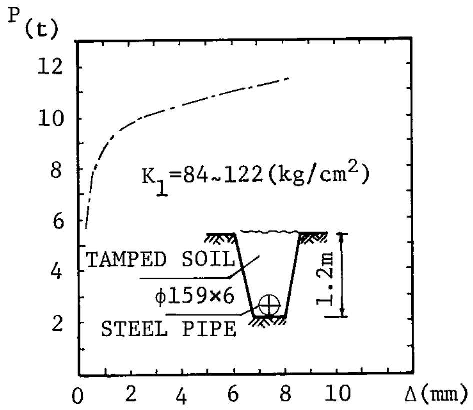


Fig.2-9. Force Versus Displacement Relationship Measured for Case of Tamped Soil Backfill

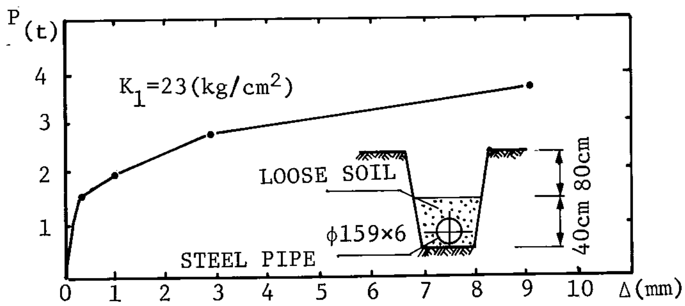


Fig.2-10. Force Versus Displacement Relationship Measured for Case of Shallow Loose Soil Backfill

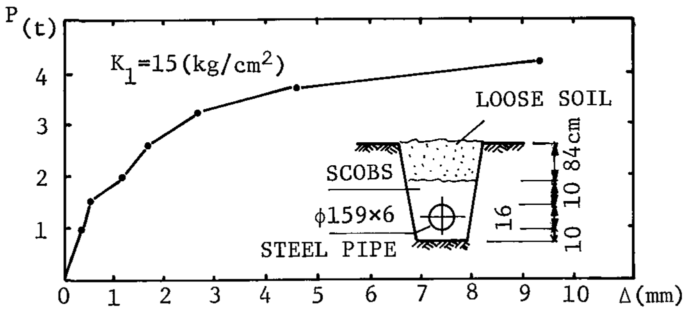


Fig.2-11. Force Versus Displacement Relationship Measured for Case of Scobs Backfill Topped with Loose Soil

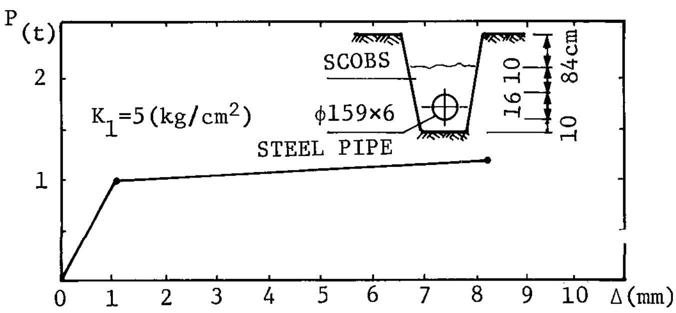


Fig.2-12. Force Versus Displacement Relationship Measured for Case of Shallow Scobs Backfill

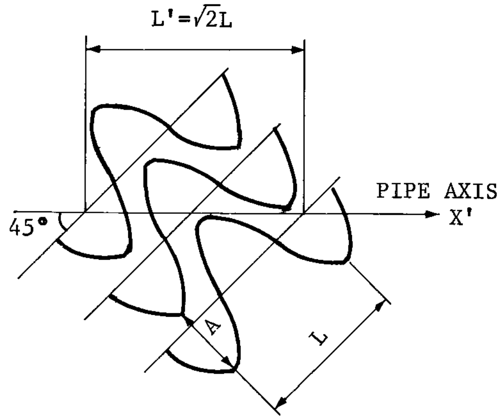


Fig. 3-1

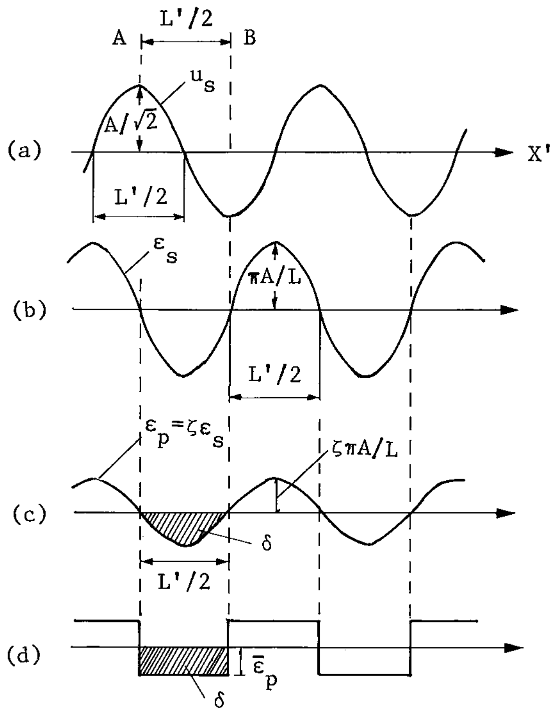


Fig.3-2. Schematic Drawings of Soil and Pipe Strains

Table 1-1. Damage Rate Versus Earthquake Intensity (1975 Haicheng Earthquake)

LOCALITY	GROUND CONDITION	INTENSITY	DAMAGE RATE
ANSHAN	II	7	0
YINGKOU	II	8	0.65
HAICHENG AND DASHIQIAO	II	9	7.65

Table 1-2. Damage Rate Versus Intensity (1976 Tangshan Earthquake)

LOCALITY	GROUND CONDITION	INTENSITY	RATE OF DAMAGE
TIANJIN	III	7-8	0.18
TANGGU	III	8	4.18
HANGU	III	9	10.00

Table 2-1. Comparison of Measured Soil Displacement Amplitudes (10^{-6}m)

NO.	EXPLOSIVE SOURCE			DITCH A		DITCH B		RATIO
	WEIGHT OF DYNAMITE (Kg)	BURIED DEPTH (m)	EXPLOSION DISTANCE (m)	BACKFILL	Δ_{SA}	BACKFILL	Δ_{SB}	Δ_{SA}/Δ_{SB}
1	30	2.2	38	LOOSE SOIL (FULL)	60	TAMPED SOIL	60	1.00
2	30	2.2	45	LOOSE SOIL (SHALLOW)	56	TAMPED SOIL	50	1.12
3	24	2.2	24	SCOBS	67	TAMPED SOIL	67	1.00

Table 2-2. Comparison of Measured Pipe and Soil Displacement Amplitudes (10^{-6}m) and Relative Displacement Amplitudes (10^{-6}m) Between Pipe and Soil

NO.	PIPELINE A					PIPELINE B				
	BACKFILL	PIPE DISPLACEMENT Δ_{PA}	SOIL DISPLACEMENT Δ_{SA}	Δ_{PA}/Δ_{SA}	RELATIVE DISPLACEMENT Δ_{rA}	BACKFILL	PIPE DISPLACEMENT Δ_{PB}	SOIL DISPLACEMENT Δ_{SB}	Δ_{PB}/Δ_{SB}	RELATIVE DISPLACEMENT Δ_{rB}
1	LOOSE SOIL (FULL)	42	60	0.70	18	TAMPED SOIL	48	60	0.80	12
2	LOOSE SOIL	27	56	0.48	21	TAMPED SOIL	37	50	0.74	13
3	SCOBS	14	67	0.21	53	TAMPED SOIL	54	67	0.81	13

Table 2-3. Measured Axial Strains in Pipelines A and B

NO.	PIPE A		PIPE B		RATIO OF STRAINS
	BACKFILL	AXIAL STRAIN ε_{NA}	BACKFILL	AXIAL STRAIN ε_{NB}	$\varepsilon_{NA}/\varepsilon_{NB}$
1	LOOSE SOIL (FULL)	15.8	TAMPED SOIL	25.5	0.62
2	LOOSE SOIL (SHALLOW)	12.1	TAMPED SOIL	23.4	0.49
3	SCOBS	5.2	TAMPED SOIL	28.6	0.18

Table 2-4. Measured Strains (10^{-6}) In Bent Pipeline C and Straight Pipeline B

NO.		1	2	3	4
EXPLOSIVE SOURCE	WEIGHT OF DYNAMITE (Kg)	6.0	30.0	30.0	24.0
	BURIED DEPTH (m)	2.2	2.2	2.2	2.2
	EXPLOSION DISTANCE (m)	21.0	31.0	28.0	25.0
PIPE C	BACKFILL	TAMPED SOIL	LOOSE SOIL (FULL)	LOOSE SOIL (SHALLOW)	SCOBS
	ε_{NC} (AXIAL)	1.9	12.0	10.3	6.7
	ε_{MC} (FLEXURAL)	4.2	17.5	13.6	8.0
	$\varepsilon_{MC}/\varepsilon_{NC}$	2.21	1.46	1.32	1.20
PIPE B	BACKFILL	TAMPED SOIL	TAMPED SOIL	TAMPED SOIL	TAMPED SOIL
	ε_{NB} (AXIAL)	13.4	34.6	30.4	28.8
	$\varepsilon_{NC}/\varepsilon_{NB}$	0.14	0.35	0.34	0.23
	$\varepsilon_{MC}/\varepsilon_{NB}$	0.32	0.51	0.45	0.28

Table 2-5. Values of Spring Constant and Friction Force by Pipe-Push Test

BACKFILL	SPRING CONSTANT K_1 (Kg/cm^2)	FRICTION FORCE F_1 (t/m)
TAMPED SOIL	103	0.37
LOOSE SOIL (SHALLOW)	23	0.10
SCOBS SURMOUNTED WITH LOOSE SOIL	15	0.08
SCOBS	5	0.05

Table 2-6. Values of Spring Constant by Hammer-Hit Test

BACKFILL	PERIOD OF VIBRATION Tg_1 (sec)	SPRING CONSTANT K_1 (Kg/cm^2)
TAMPED SOIL	0.008	120
LOOSE SOIL (FULL)	0.010	95
LOOSE SOIL (SHALLOW)	0.015	40
SCOBS	0.030	10

Table 3-1. Determination of Transfer Coefficient

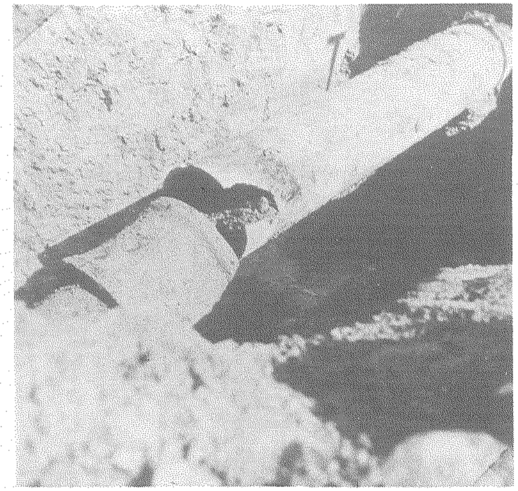
CASE	D [cm]	E [kg/cm^2]	F [cm^2]	$[U]_i$ [cm]	n	K_h	T_m (ζ)	V_s^* (m/s)	α
1	21	1.1×10^6	65.97	0.05	4.65	0.4	0.3	88	0.40
2	15.94	1.1×10^6	47.60	0.05	5.30	0.2	0.5	60	0.40
3	46.35	1.1×10^6	196.58	0.004	3.53	0.2	0.5	60	0.69
4	61.55	1.1×10^6	290.72	0.004	4.95	0.2	0.7	60	0.48

* Measured at site and multiplied by 2/3.

1. ϕ 1000 R/C Pipe Undergoing Horizontal Stagger in Fault Rupture Zone in Tangshan

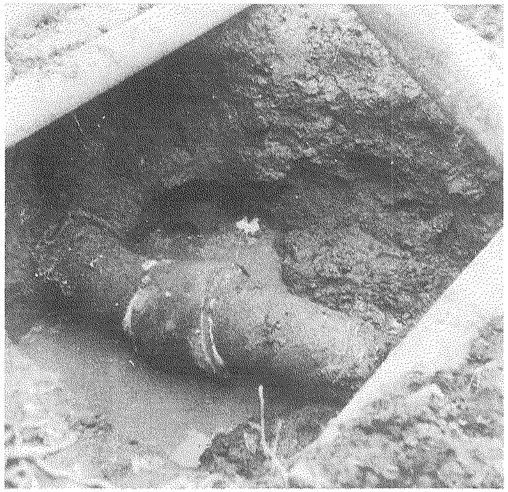
2. ϕ 200 Pulled-out Castiron Pipe Showing Stagger in Tangshan

3. Severely Cracked R/C Pipe in Tangshan

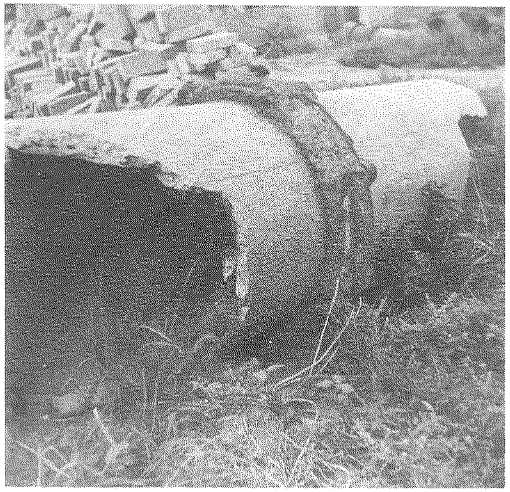


4. ϕ 300 Castiron Pipe Damaged in Tangshan (1)

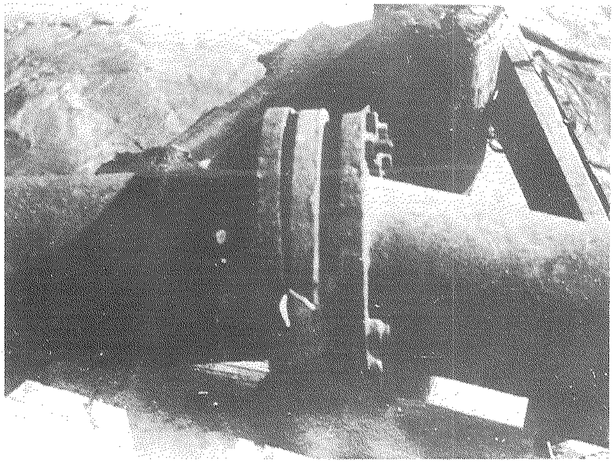
5. ϕ 300 Castiron Pipe Damaged in Tangshan (2)



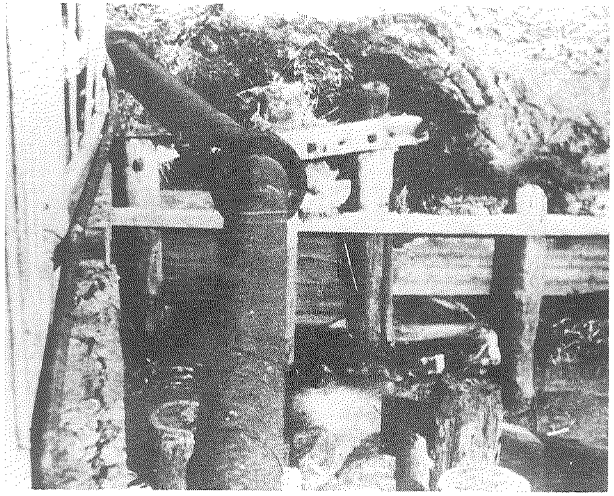
6. ϕ 300 Castiron Pipe Damaged in Tangshan (3)



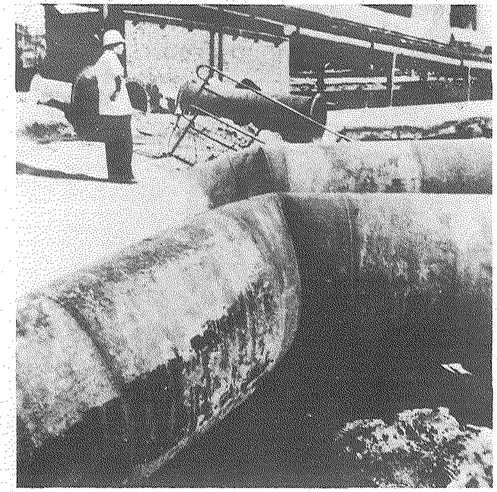
7. ϕ 700 R/C Pipe Damaged in Yingkou by Haicheng Earthquake



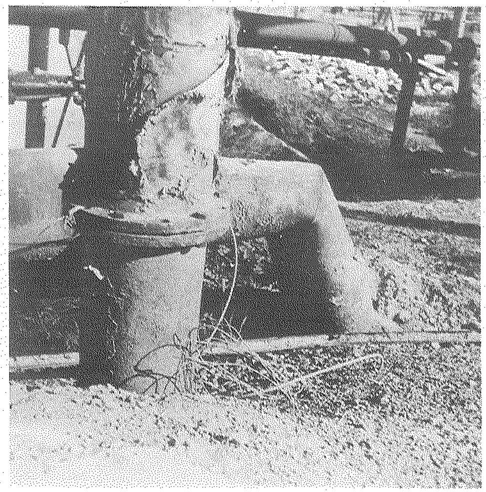
8. Flange Break of Steel Pipe Near River Bank



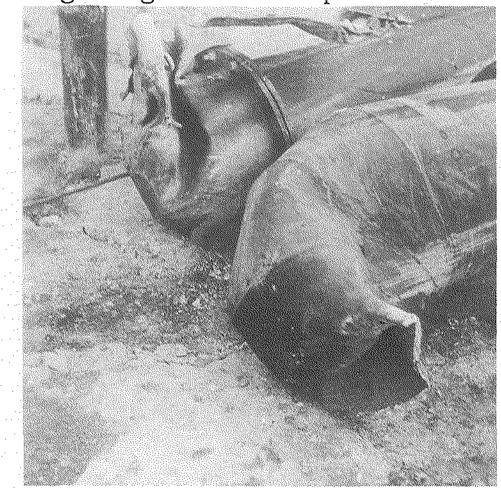
9. Bending of Steel Pipe due to River Bank Slide



10. Bent Steel Pipe Squeezed Flat Near River Bank in Tanggu Alkali Factory during Tangshan Earthquake

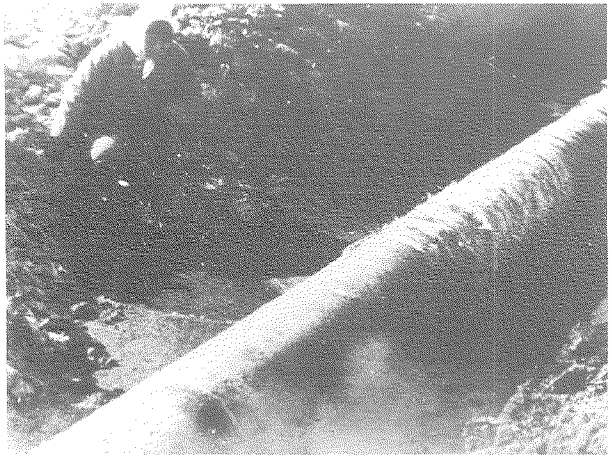


11. ϕ 500 Steel Pipe in Hangu Showing Similar Damage as in Photo 10



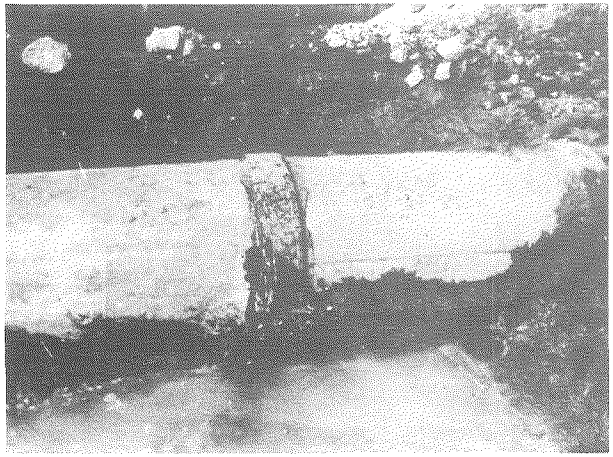
12. Damaged Steel Pipes at River Crossing in Tangshan

13. Buckled Steel Pipe due to Shortening Caused by Inward Bank Slides in Tangshan

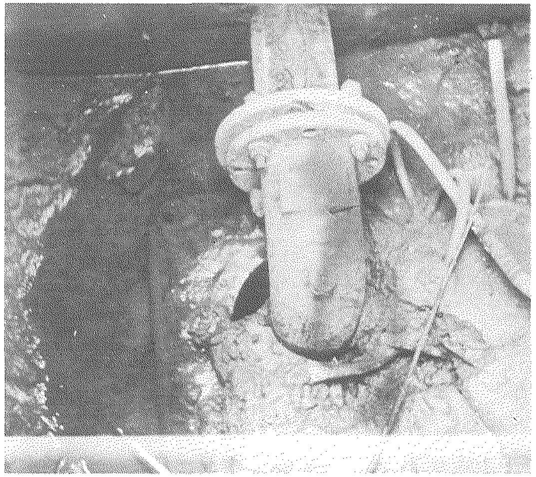


14. Natural Gas Pipe Uplifted by Sand Vent Caused by Liquefaction in Panjin

15. Repaired Steel Pipe After Damaged Caused by Liquefaction in Panjin

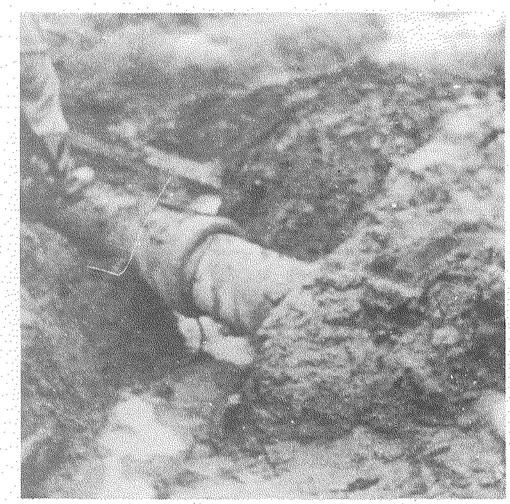


16. ϕ 1200 R/C Pipe Joint Pulled Apart in Panjin

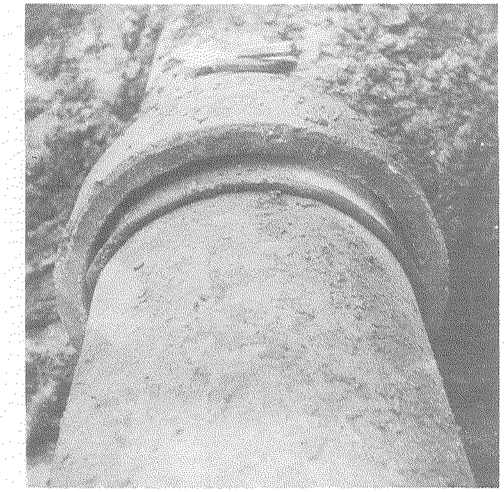


17. Steel Elbow Fractured by Subsidence due to Liquefaction

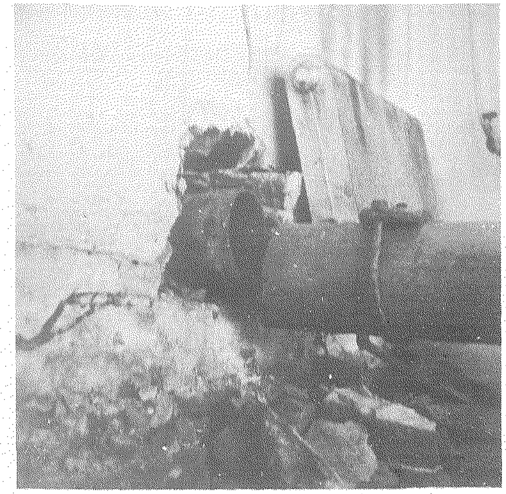
18. Pipe Damage Possibly Caused by Imposed Axial Strain (1)



19. Pipe Damage Possibly Caused by Imposed Axial Strain (2)



20. Pipe Damage Possibly Caused by Imposed Axial Strain (3)

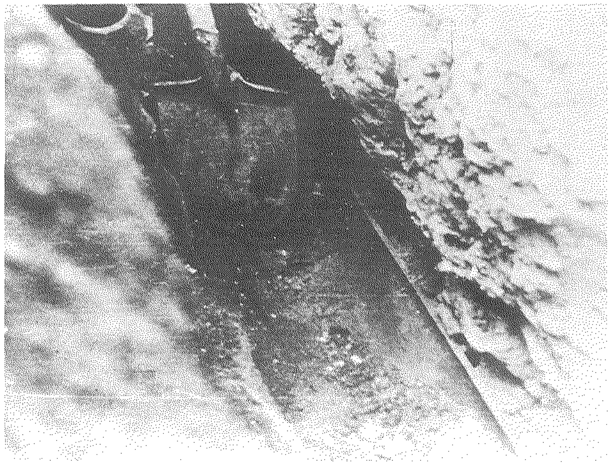


21. Damage of Steel Pipe at Wall Crossing

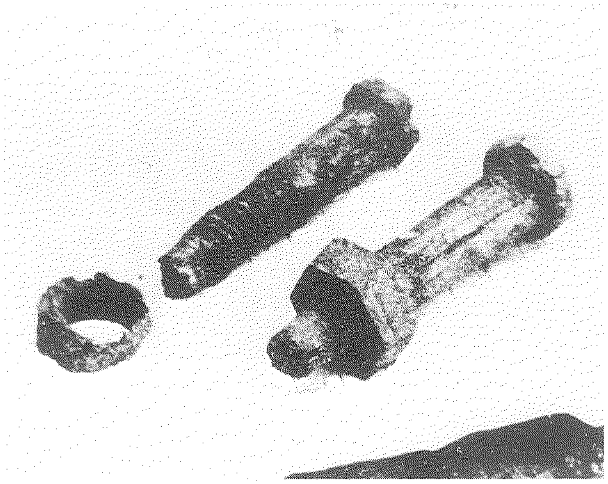
22. Damage of Castiron Pipe at Wall Crossing

23. Damage to Pipe Fittings (1)

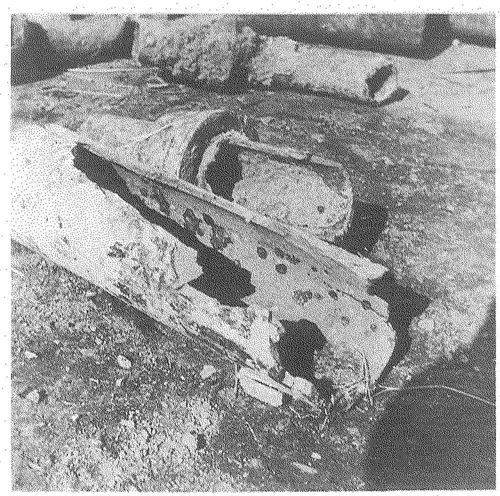
24. Damage to Pipe Fittings (2)



25. Longitudinal Crack of Pipe

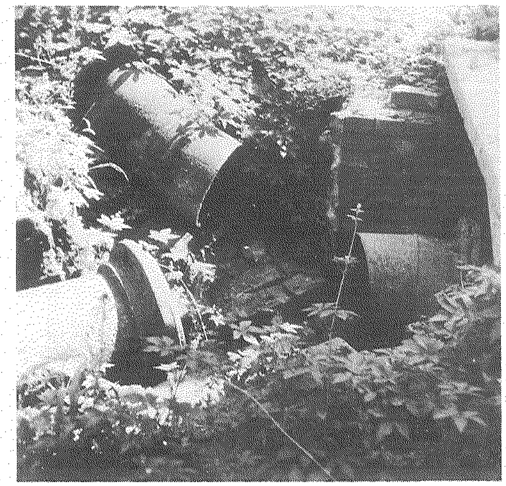


26. Damage to Corroded Castiron Pipes in Yingkou (1)



27. Damage to Corroded Castiron Pipes in Yingkou (2)

28. Damage to Corroded Castiron Pipes in Yingkou (3)



29. Rupture of Welded Section (ϕ 400) in Tangshan