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MECHANISM OF PIPELINE FAILURES CAUSED BY SOIL LIQUEFACTION DURING THE 1983 NIHONKAI-CHUBU EARTHQUAKE

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When continuous (arc-welded) steel pipelines fail, they show different appearances of fracture depending on the type or process of loading owing to the ductile property of steel. Based on this fact, morphological observation was made on twelve failures in continuous steel pipelines that took place during the 1983 Nihonkai-chubu earthquake. The greater part of them appeared to have been caused by reciprocal (or dynamic) compression and tension, rather than by static (or permanent) ground displacement. The mechanism of dynamic ground motion associated with soil liquefaction, therefore, should be made clear in order to establish effective countermeasures for buried pipelines.

Key Words: *earthquake, soil liquefaction, buried pipeline, steel pipeline, seismic damage*

1. INTRODUCTION

The Japanese experiences of disastrous earthquakes indicate that damage to buried pipelines is much heavier during earthquakes associated with soil liquefaction than during those without soil liquefaction.

In order to establish effective earthquake countermeasures—with particular reference to soil liquefaction—it is essential to investigate the mechanism of seismic deformation in the ground associated with soil liquefaction that could damage buried pipelines.

Roughly speaking, there are two modes of seismic strain in the ground, One is dynamic strain, or alternating tension and compression. The other is one-way, or static, strain. This is typically represented by a collapse of soil caused by a landslide.

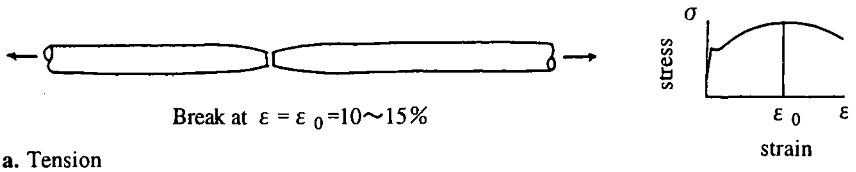
Liquefaction-susceptible soils generally form rather flat topography. Large ground deformations, therefore, can rarely be seen except in collapse of embankments, although sand volcanoes and associated ground subsidence are readily apparent. This fact makes it difficult to determine, after an earthquake, what type of ground deformation has been responsible for pipeline damage. It will be rather convenient, therefore, to investigate failures in continuous (arc-welded) steel pipelines. This is because they are stiff as well as ductile and are far less susceptible to failure than other pipelines, such as thread-jointed steel pipelines and conventional cast-iron pipelines. Owing mainly to the ductility, the process of fracture is reflected in the mode of deformation in the fractured parts thus suggesting the process of loading during the earthquake.

We have never experienced seismic damage to continuous steel pipelines of greater diameters, except for damage to old pipelines at welded joints that were poorly welded. As for smaller-diameter pipelines (roughly, 100 mm or less in diameter), we had several failures in continuous steel pipelines during the Nihonkai-chubu earthquake of August, 1983. Although some of those failures were probably due to poor welding, they still appeared to have been subjected to the complex process of deformation during the earthquake.

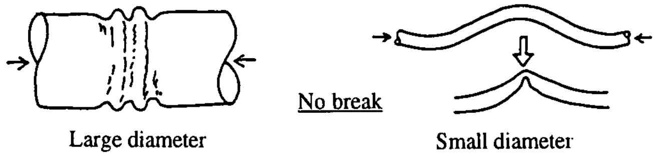
This paper intends to make clear the mechanism of those failures, mainly through the morphological observation of the failures.

Twelve of seventeen failures in medium-pressure gas pipelines were investigated; the remaining failures were at the flanges and other fittings.

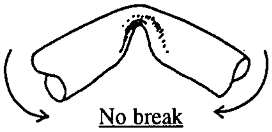
The information on the described failures is mainly from the Report of the Japan Gas Association (abbreviated as JGA, hereinafter),[1] as well as from the present author's personal observations as a member of the Task Group of JGA for publishing the above mentioned report.



a. Tension



b. Compression



c. Bending

Fig. 1 Deformation in continuous steel pipe under large static loads

2. BEHAVIOR OF STEEL PIPE UNDER STATIC LOADS

Before looking at the actual pipeline failures, it will help us to know how a steel pipe behaves when subjected to a great static load of tension, compression, or bending.

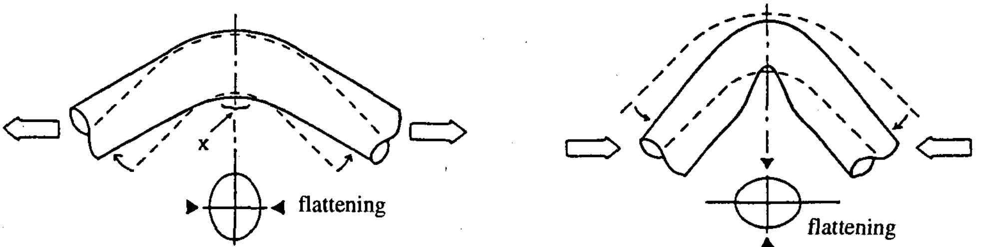
Fig. 1 shows the schematic behavior of a straight steel pipe subjected to tension, compression and bending. If a pipe were subjected to tension, fracture would take place when the axial strain exceeded the homogeneous elongation limit, ε_0, which is about 10 to 15 percent for common, mild steel. This means that a pipeline can withstand extremely large deformation before fracturing. If a small-diameter pipe were subjected to a compressive force, then beam-mode buckling would occur, evincing a sinusoidal deformation in the case of a buried pipeline. The wavelength of the sinusoidal shape is determined as a function of the ratio of flexural rigidity of the pipe to the stiffness of the soil (e.g., Timoshenko2), Nishio3)). The pipe would finally collapse, showing a flattened cross section. A typical example of beam-mode buckling was presented during the 1978 Miyagiken-oki earthquake with a 50-mm-diameter gas pipeline showing buckling in sinusoidal shape (Nishio3)). For a larger-diameter pipe, shell-mode buckling is likely to take precedence over beam-mode buckling, evincing accordion-shaped foldings. A 400-mm-diameter gas pipeline which buckled in accordion-shape during the 1971 San Fernando earthquake offered a rare example of shell-mode buckling (Lee and Ariman4)).

It should be noted that compressive deformation would never break a pipe, to cause leakage of gas or liquid, however great the degree of compression.

As for bending a straight pipe, the mode of deformation will be very similar to that of a pipe subjected to beam-mode buckling (see **Fig. 1**). As in the case of buckling, a pipe will never break no matter how sharp the bending angle.

Fig. 2 shows the schematic behavior of an elbow subjected to tension (or resulting outward bending) and compression (or inward bending).

In the case of tension, the cross-section of the elbow will be flattened in the direction perpendicular to the plane containing the pipeline axis. In contrast, the direction of flattening will be parallel with the plane of pipeline axis in the case of compression.



(extension in the vertical direction)
a. Tension (outward bending)

(extension in the horizontal direction)
b. Compression (inward bending)

Fig. 2 Deformation in bend under large static loads

If the elbow's curvature radius were very short and the elbow's angle small, a great tensile strain (*in the direction of pipeline axis*) would be concentrated in a small area on the inner surface of the curvature (the location indicated as x in **Fig. 2a**) by tensile deformation. The elbow would occasionally fracture in the region of x; the tensile deformation in the pipeline at failure would be relatively small. By increasing the elbow's angle (e.g., from 22.5 degree to 45 degree), the flexibility of elbow increases, and the elbow can withstand far greater tensile deformation. This fact can be inferred from elastic calculations on buried pipelines containing elbows (e.g., calculations by the author[5),6)]).

On the other hand, compressive deformation can never break the elbow. It is similar in this respect to the bending of a straight pipe.

Thus, a pipeline will never break due to static compression although a significant degree of plastic deformation may occur. Static tension can break a pipeline; a fairly great displacement of ground, however, will be necessary in order to fracture it.

In contrast, reciprocal compression and tension in the range of plastic deformation can break a pipe with a relatively small amplitude of displacement. Once a steel has undergone a plastic compression, a tensile deformation that follows can easily fracture the steel. This phenomenon is similar to so-called low-cycle fatigue. The greater the degree of plastic derormation (both in compression and tension), the smaller the cycle number that trigger the breakage.

It should be noted that even in the case of repeated compression and tension, the final fracture (separation of pipe material) will take place during the tensile deformation. Most of us may have experienced a similar effect in breaking a wire by repeated manual bending and pulling.

3. MORPHOLOGICAL REVIEW OF TWELVE FAILURES IN STEEL PIPELINES

Failures in welded steel pipelines were observed in three districts supplied with gas. The three gas utility enterprises involved were Noshiro City Gas, Wakami Town Gas, and Oga City Gas.

Sketches of the twelve failures are shown in **Figs. 3** to **14**. The numbers for these failures correspond to the serial numbers used in Ref. 1 for describing seventeen failures in medium-pressure pipelines in the above districts.

The cause of deformation in the pipelines, that is surmised on the basis of morphological obsevation of the fractures, is described in each Figure.

The direction of permanent ground deformation is indicated in most of the Figures with wide arrows in the rough failure location maps. These arrows indicate the final state of deformation in the ground, i.e., whether tension or compression, and the direction of the deformation.The state of final deformations for failure locations in Noshiro city was based on the investigation by Hamada et al.[7)] by means of aerial-photographic analysis. While that for failure locations in Wakami and Oga was judged from the shape of the damaged pipelines as observed on removing the soil for failure investigation.

The direction of elbow flattening in **Fig. 3** (Noshiro-No.1) was perpendicular to the plane

Address	Nagane, Noshiro	Nominal diameter／Thickness	80／4.2 mm
Location of break	22.5° elbow, heat affected zone		
Primary cause of failure	Static tensile deformation (?)		

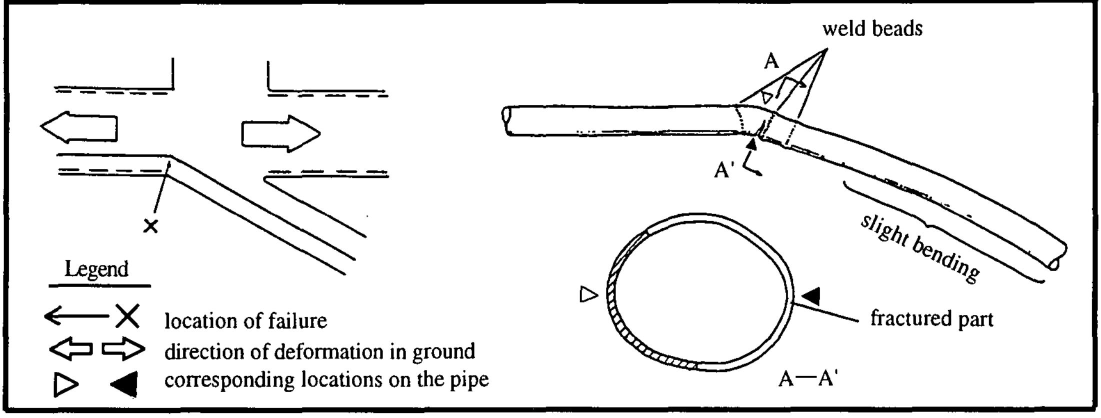


Fig. 3 Failure, Noshiro-No.1

Address	Tagomukai, Noshiro	Nominal diameter／Thickness	80／4.2 mm
Location of break	Field-adjusted joint, heat affected zone		
Primary cause of failure	Repeated compression and tension		

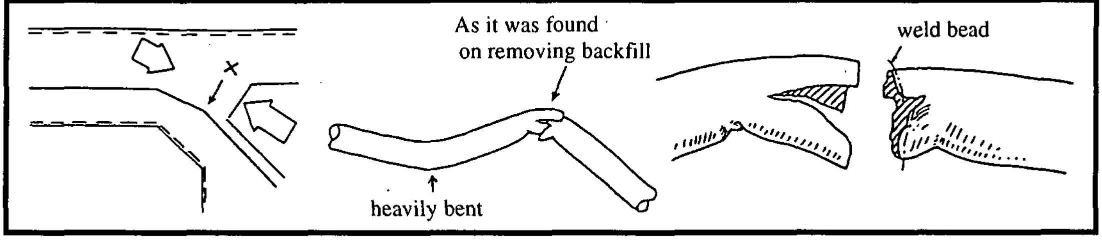


Fig.4 Failure, Noshiro-No.2

containing the pipeline axis. This elbow deformation, therefore, is attributed to tensile load (refer to **Fig. 2**). A slight bending at the straight part also suggests that tensile force was predominant in this location.

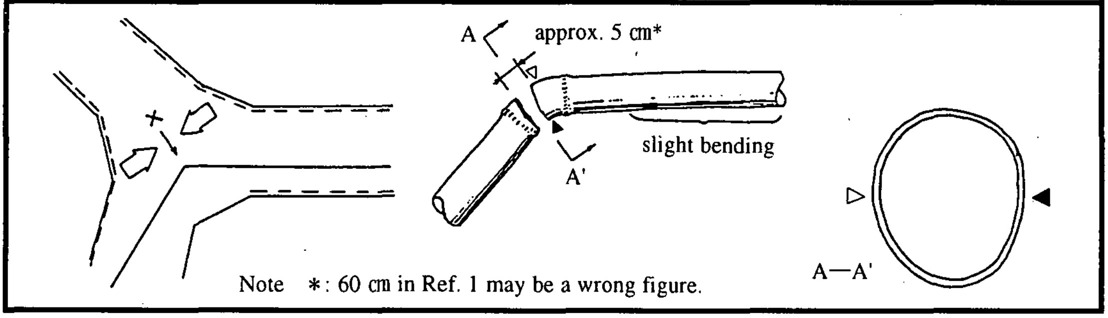
Fig. 7 (Wakami-No.1) shows a considerably high degree of contraction in the pipe cross-section at the fractured part. This suggests that the fracture was of the ductile type due to static tensile load. The separation of the fracture surfaces show a large permanent (static) displacement in the ground that is considered to be due to a landslide.

The above two failures can be attributed to static tensile deformation in the ground. Most of the other failures, however, show evidence that both compressive and tensile forces acted on the pipelines.

The failure of Noshiro-No. 2 (**Fig. 4**) shows that once separated, the fracture surfaces collided heavily several times to gouge each other. This collision should naturally be due to repeated ground compression and tension. Evidently, the final deformation was compressive. The bending of the straight part of the pipeline, and the severe deformation in the pipe giving the appearance of snake's neck, are the result of beam-mode buckling. The greater part of this buckling deformations might be caused by the final (or permanent) displacement of the ground.

The failure processes at Oga-Nos. 3 and 4 (**Figs. 12** and **14**, respectively) are considered to be more or less similar to that of Noshiro-No. 2. It should be noted that the cross-section at the

Address	Nagasaki, Noshiro	Nominal diameter／Thickness	80／4.2 mm
Location of break	45° elbow, heat affected zone		
Primary cause of failure	Tension preceded by slight buckling (due to compression)		



Note *: 60 cm in Ref. 1 may be a wrong figure.

Fig. 5 Failure, Noshiro-No. 3

Address	Nagasaki, Noshiro	Nominal diameter／Thickness	80／4.2 mm
Location of break	45° elbow, weld bead and heat-affected zone		
Primary cause of failure	Repeated compression and tension (finally separated due to landslide)		

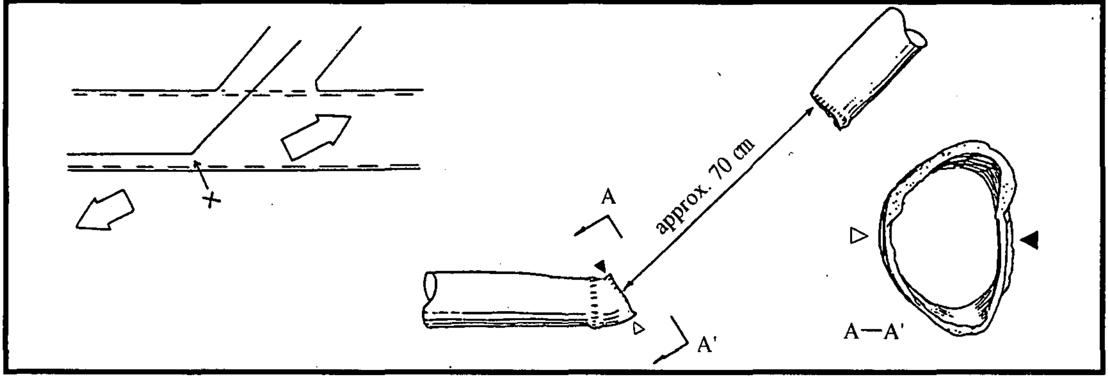
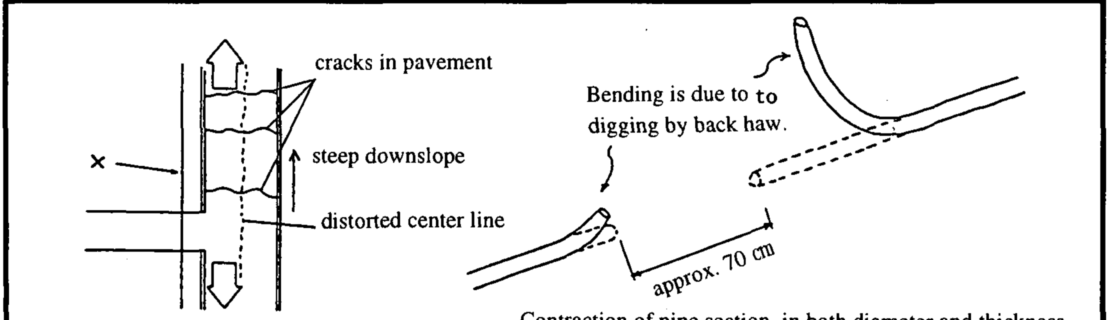


Fig. 6 Failure, Noshiro-No. 4

Address	Gomyoko, Wakami	Nominal diameter／Thickness	40／3.5 mm
Location of break	Pipe body (straight part)		
Primary cause of failure	Static tensile deformation due to landslide		



Contraction of pipe section, in both diameter and thickness, was observed in fracture surfaces.

Fig. 7 Failure, Wakami-No. 1

Address	Tamanoike, Wakami	Nominal diameter／Thickness	40／3.5 mm
Location of break	Pipe body (straight part)		
Primary cause of failure	Repeated compression and tension (broken by tension at buckled part)		

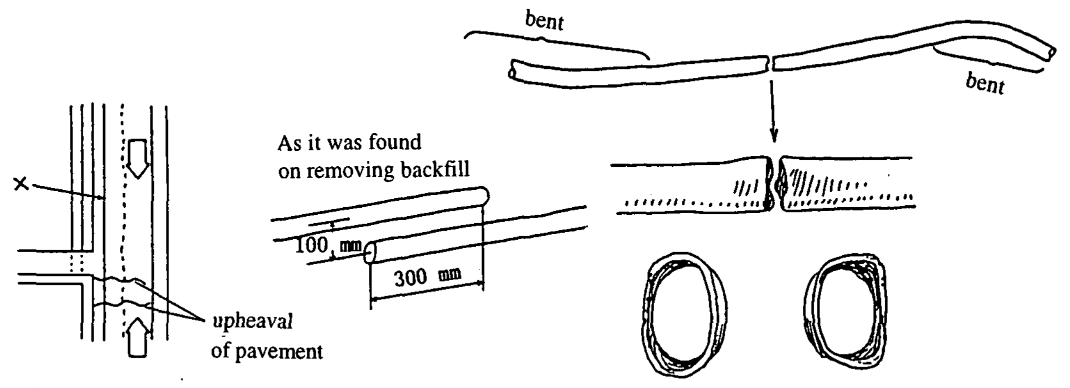


Fig. 8 Failure, Wakami-No. 4

Address	Ohgata	Nominal diameter／Thickness	80／4.2 mm
Location of break	Weld bead of 90° bend		
Primary cause of failure	Static compression (poor quality of weld)		

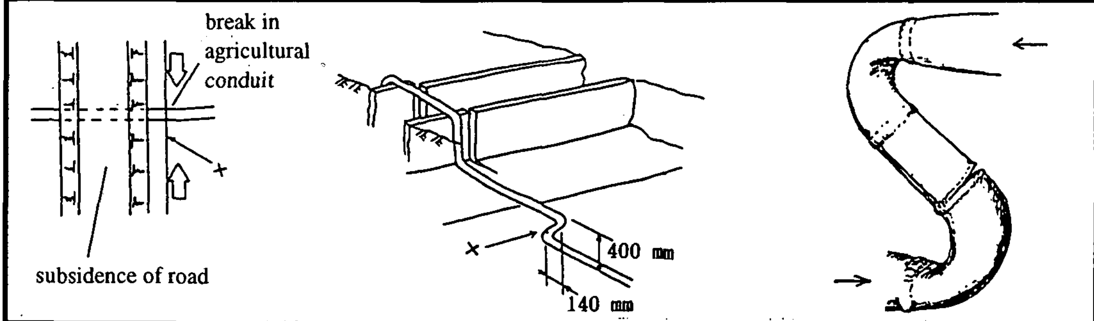


Fig. 9 Failure, Wakami-No. 5

Address	Iriai, Oga	Nominal diameter／Thickness	80／4.2 mm
Location of break	Weld bead of 45° elbow		
Primary cause of failure	Compression (slight buckling) followd by tension; primarily, poor weld		

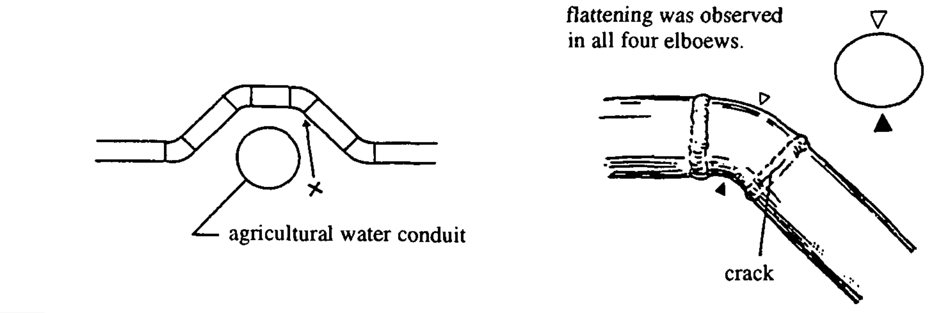


Fig. 10 Failure, Oga-No. 1

Address	Iriai, Oga	Nominal diameter／Thickness	100／4.5 mm
Location of break	22.5° bend		
Primary cause of failure	Repeated compression and tension		

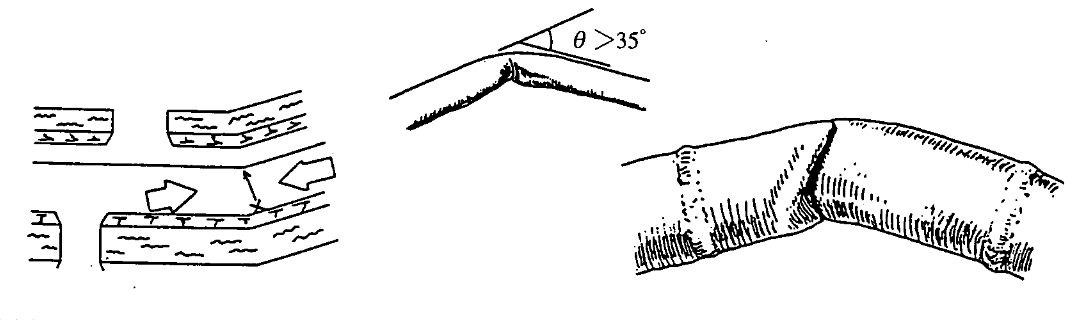


Fig. 11 Failure, Oga-No. 2

Address	Wakimoto, Oga	Nominal diameter／Thickness	100／4.5 mm
Location of break	Heat affected zone (weld of straight pipes)		
Primary cause of failure	Repeated compression and tension		

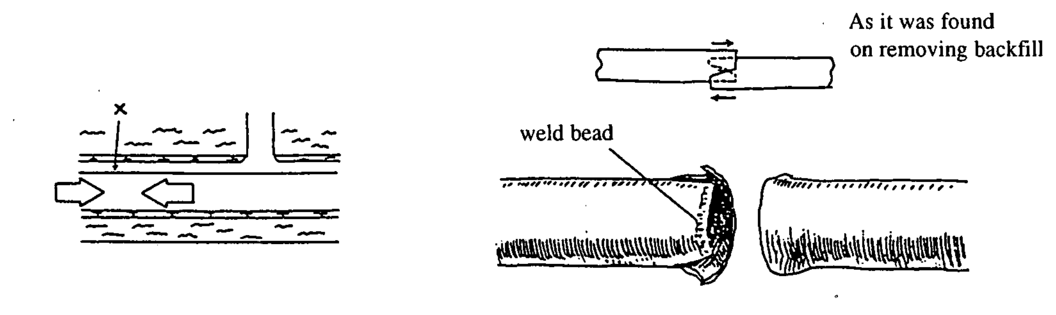


Fig. 12 Failure, Oga-No. 3

Address	Wakimoto, Oga	Nominal diameter／Thickness	100／4.5 mm
Location of break	45° elbow, heat affected zone and weld bead		
Primary cause of failure	Probably tension preceded by compression (slight buckling)		

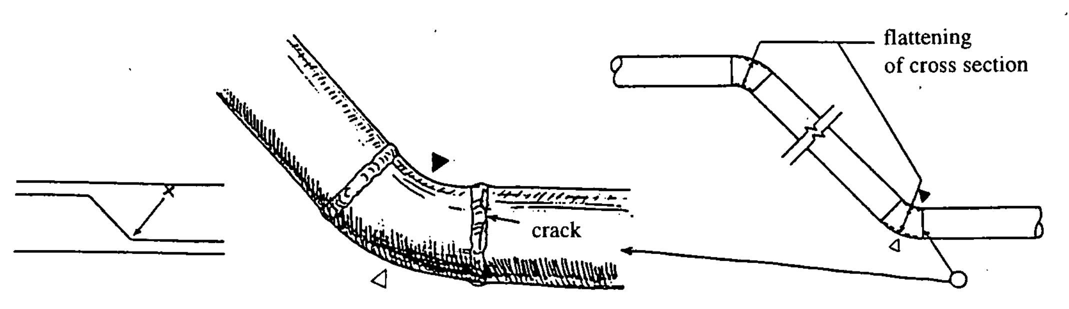


Fig. 13 Failure, Oga-No. 4

Address	Wakimoto, Oga	Nominal diameter/Thickness	100/4.5 mm
Location of break	Heat affected zone and weld bead (slightly angle-welded)		
Primary cause of failure	Repeated compression and tension		

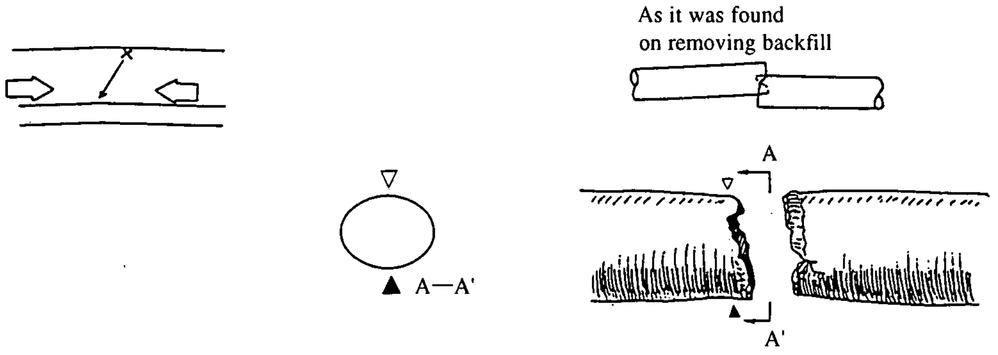

As it was found on removing backfill

Fig. 14 Failure, Oga-No. 5

fractured part of Oga-No. 5 was considerably flattened. This suggests that beam-mode buckling occurred before fracturing. (Note that fractures always occur under tensions, as explained in the preceding chapter.)

The failures at Noshiro-Nos. 3 and 4 (**Figs. 5** and **6**, respectively) show that final fracture was due to tension. They also show, however, the direction of flattening at the elbows is parallel with the plane containing the pipeline axis. This indicates the occurrence of buckling due to compressive force prior to tension. Especially, severe deformation in cross section at Noshiro-No. 4 suggests that both compression and tension occurred more than once prior to fracture. The plastic deformation (flattening) in the elbows due to compressive ground deformation is considered to have been the cause of easy fracture occurrence when subjected to the succeeding tensile force.

The failure of Wakami-No. 4 (**Fig. 8**) clearly shows the evidence of beam-mode buckling. As a result, the pipe was bent to cause the flattening of the cross-section at the fractured part. This is very similar to what has been explained schematically in **Fig. 1b**. Of course, the fracture took place during the cycle of tensile deformation in the ground, although the final (permanent) deformation was compressive.

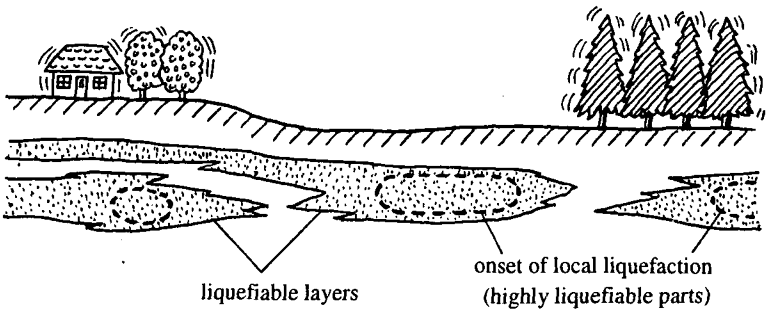
The failure of Oga-No. 2 (**Fig. 11**) also suggests that deformation in the bend, due to buckling, preceded the fracture caused by tension. The complex shape of the fractured part also suggests that severe compression and tension occurred more than once before and after the fracture.

The remaining failures, i.e., Wakami-No. 5, Oga-No. 1, and Oga-No. 4 (**Figs. 9**, **10**, and **13**, respectively), all took place at the weld beads. These failures may be due primarily to poor welding. A poorly-welded joint may sustain failure due to static deformation if the degree of deformation is great. The failure of Wakami-No. 5 may not have occurred were the welding of better quality. The failures of Oga-Nos. 1 and 4 are difficult to account for by static ground compression, although the flattening at the elbows shows the action of compressive force. It will be more natural to assume that the cracks in the weld beads were due to tension preceded by compression.

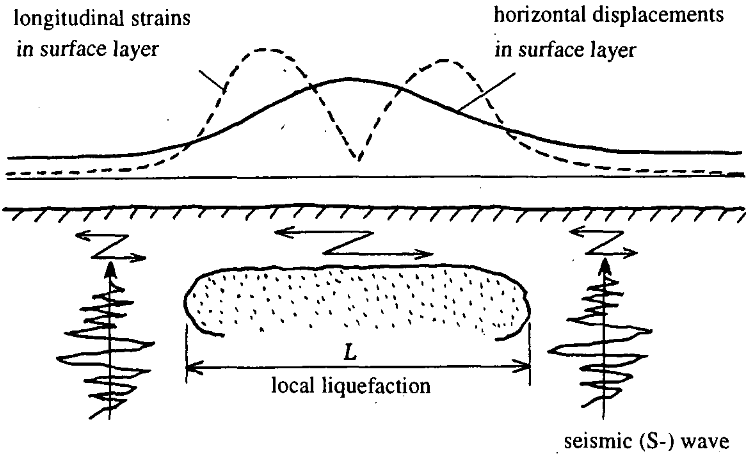
4. DISCUSSIONS

(1) Ground motion as the cause of failures

Of the twelve failures in welded steel pipelines, seven failures showed evidence of repeated compressive and tensile deformation in the ground as well as in the pipeline (Noshiro-Nos. 2, 3, and 4; Wakami-No. 4; and Oga-Nos. 2, 3, and 5). Two more failures (Oga-Nos. 1 and 4) are likely to indicate the occurrence of repeated



a. Schematic soil profile with respect to liquefiable-soil distribution



b. Response of surface layer over the liquefied soil

Fig. 15 *Schematic mechanism for longitudinal (horizontal) dynamic-ground-strain due to local soil liquefaction*

compression and tension.

The most remarkable fact is that six failures took place where the final (permanent) deformation in the ground was compressive (Noshiro-Nos. 2 and 3; Wakami-No. 4; and Oga-Nos. 2, 3, and 5). The fact is also remarkable that a great compressive force acted probably more than once even at a location where great permanent tensile deformation was observed (Noshiro-No. 4).

On the contrary, two failures can be attributed to static tensile deformation in the ground. They do not, however, necessarily deny the possibility of the contribution to the failure, of the repeated compression and tension that may have occurred prior to the final failure.

Most of the twelve failures thus indicate that during liquefaction, repeated compressive and tensile ground deformation preceded the final (permanent) deformation. This repeated motion, moreover, is highly responsible for the failure of the pipelines — probably even far more responsible than the permanent deformation. In most cases, the permanent deformation may play a role in dramatically exaggerating the appearance of the failed part.

(2) Model of dynamic ground motion

Actually, liquefaction does not occur all at once throughout a wide area of liquefiable ground. Liquefaction may, on the contrary, begin at separate spots where liquefaction potential is the highest of their vicinities. The area of liquefaction then spreads with time. Permanent lateral deformation will take place after the liquefied area has grown sufficiently wide. Dynamic ground motion, meanwhile, can be greater under the condition of local liquefaction than under the condition of widespread liquefaction.

The present author and his colleagues8),9),10) have proposed this local liquefaction model as the cause of dynamic deformation in the ground. The proposed model can schematically be expressed as shown in **Fig. 15**. This figure represents a state where liquefied zone has grown as wide as L in width. Shear waves that are incident from the bottom of liquefied layer cannot reach the non-liquefied surface soil layer directly through the liquefied layer, but the surface layer is excited horizontally at the both ends of the liquefied zone. As a result, great strains can be produced around the both ends of the liquefied zone where a remarkable discontinuity of ground displacement is expected. (Note that ground water tables are almost always in some depth below ground surface so that non-liquefied surface layers are left above the liquefied zones. Most gas distribution pipelines, the depth of which are usually between 1 m and 2 m, are then contained in non-liquefied surface layers).

The natural periods, T_i (i=1, 2, 3···: number of mode of vibration), for the horizontal vibration of the surface layer, under horizontal excitation at the both ends of the layer in the same phase, is given as follows assuming that the layer to be an elastic plate, and that the longitudinal-wave velocity in the plate to be c m/s:

$$T_i=\frac{2L}{(2i-1)c}$$

The above authors have shown, through model experiments, that the above proposed model applies very well, and that sufficiently great strain can be induced under the locally liquefied condition to cause plastic deformation in continuous (welded) steel pipelines.

The width L of the liquefied zone will change during an actual earthquake; it will increase with time as soil liquefaction developes. The combination of the changing values of L and the changing mode number i, then, can produce repeatedly the natural frequencies that are resonant with the predominant frequencies of earthquake motions. This fact suggests that highly strained zones in the surface layers are produced very frequently, thus increasing greatly the probability of pipeline failure.

5. CONCLUSION

The morphological study of twelve failures in arc-welded steel pipelines during the 1983 Nihonkai-chubu earthquake suggested that the major cause of failures was dynamic ground deformation, contrary to the suggestion by Hamada et al.7) that most pipeline failures can be attributed to static (or permanent) ground displacements that take place at the final stage of soil-liquefaction development.

The dynamic ground deformation can be accounted for by the horizontal vibration of non-liquefied surface soil layer at locally liquefied zones that will grow in area with time. A model for such dynamic behavior of locally liquefied ground has been proposed by the present author and his colleagues.8),9),10) This model bears the possibility of providing an effective tool for assessing the earthquake resistance of pipeline components; not only of continuous pipelines but also of pipelines that use joints of various kind.

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1983年日本海中部地震における地盤液状化に起因するパイプラインの破壊過程の考察

西尾　宣明

溶接接合により連続な構造をとる鋼管が破壊するとき，その延性のゆえに変形が残留し，その形状から荷重の種類や負荷過程を推定できることが多い．1983年の日本海中部地震では小口径の溶接接合ガスパイプラインが12箇所で被害を受けた．それらはいずれも地盤の液状化が集中した地域で生じた．それらの被害部分の形状から荷重の履歴を考察した結果，大半の被害の原因となったのは地盤の静的変位（永久変位）ではなく，引張りひずみと圧縮ひずみが交互に繰り返す動的変位であると推定された．したがって，地盤液状化時のパイプラインの耐震性を正しく評価するためには，液状化が生じたときの地盤の動的変位の発生機構を究明することが必要である．これについて，著者はすでに一つの提案を行っている．