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# FIELD INVESTIGATION AND ANALYSIS OF BURIED PIPELINES UNDER VARIOUS SEISMIC ENVIRONMENTS

by

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**16. Abstract (Limit: 200 words)**

A research project is proposed in which the behavior of oil, water, sewer, and gas pipelines under various seismic environments, including seismic shaking and large ground deformation would be investigated. It is suggested that the investigation be conducted in the Beijing and Tangshan areas. Three major hazards to underground pipelines are identified: (1) the effect of wave propagation; (2) ground rupture and differential movement along fault lines; and (3) soil liquefaction induced by ground shaking. Ruptures or severe distortions of the pipe are most often associated with fault movements, landslides, or ground squeeze associated with fault zones. A model is presented to evaluate the general longitudinal responses of buried pipelines, both segmented and continuous, subjected to ground shakings and vibrations. The results of these tests will be used to develop aseismic codes for buried lifelines.

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# FIELD INVESTIGATION AND ANALYSIS OF BURIED PIPELINES UNDER VARIOUS SEISMIC ENVIRONMENTS

Leon Ru-Liang Wang(I)

## SUMMARY

The overall objective of the proposed cooperative research project is to critically investigate the behavior of buried pipelines such as water, sewer, gas and oil pipelines under various seismic environments including seismic shaking and large ground deformation effects. Specifically it is proposed to investigate the responses through field investigations in Beijing and Tangshan areas. Such responses will also be correlated with different geotechnical, geological and seismological parameters. Ultimately, this project will verify and improve the analytical models and seismic resistant design methodology of buried pipelines already developed.

## INTRODUCTION

This project is proposed to carry out a cooperative research on "Field Investigation and Analysis of Buried Pipelines Under Various Seismic Environments" between the United States and the People's Republic of China (PRC). The proposed project will be jointly carried out by the University of Oklahoma (P.I. Dr. Leon R.L. Wang) and the University of Tulsa (P.I. Dr. Teoman Ariman) in the United States in cooperation with the Municipal Engineering Research Institute of Beijing (P.I. Mr. Sun Shaoping) and the Pipeline Design and Research Institute of the Petroleum Ministry (P.I. Ms. Chen Guanging) of the People's Republic of China.

The overall objective of the proposed cooperative research is to critically investigate the response behavior of buried lifelines such as water, sewer, gas and oil pipelines under various seismic environments including seismic shaking and large ground displacement effects. Specifically, it is proposed to investigate the responses through field investigations in Beijing and Tangshan areas. Such responses will also be correlated with different geotechnical, geological and seismological parameters. Ultimately, this project will verify and improve the analytical model and seismic resistant design methodology of buried pipelines already developed (4,7,18,31,32,34).

## PROBLEM STATEMENT AND BACKGROUND

Recent studies have shown that buried water, sewer, gas and oil pipelines have been damaged heavily by earthquakes.(10,15,35) Because of the importance of lifelines vis-a-vis the health, safety and

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supplies to the populace, lifeline earthquake engineering has become one of the most important areas of the earthquake engineering researchers and practicing engineers.

In general, there are three major causes of seismic hazards to underground pipelines namely, (a) the effect of wave propagation, (b) ground rupture and differential movement along fault zone and (c) soil liquefaction induced by ground shaking.

According to the damage reports of buried pipelines due to earthquakes, ruptures of severe distortions of the pipe are most often associated with fault movements, landslides, or ground squeeze associated with fault zones. Ruptures or severe distortions (including pullout for segmented pipe) might also result from the relative pipe movements in liquefied soils and from the relative movements at abrupt interfaces between rock or stiff soils and much softer soils.

However, the damage mechanisms of lifeline systems due to earthquakes have not been fully analyzed. In order to develop an effective and realistic analytical model for future design applications, it is necessary first to study thoroughly the failure mechanisms of lifeline systems subjected to direct and indirect effects of destructive earthquakes.

At the present time, researchers in the United States, China, Japan and Canada are now actively engaged in research on buried pipelines under seismic environments(2,5,16,17,21,22,27,30). Among them, only Japanese investigations have conducted preliminary field observations and laboratory experiments on the seismic response of submerged tunnels and pipes. Although quite recently, preliminary experimental projects were initiated in the United States(8,25). Further research needs in lifeline earthquake engineering have been outlined by the Technical Council on Lifeline Earthquake Engineering (TCLEE) of ASCE and the investigators(3,29,33). It is clear that more comprehensive and realistic experiments and field investigations are absolutely necessary before seismic resistant design guidelines can be developed.

In general, most earthquake engineering experiments may be done either in a laboratory or in the field. However, for lifeline earthquake engineering, the experimental verification on the seismic response of lifelines, which cover a large area is very difficult, if not impossible, although laboratory studies on the influencing parameters, such as soil-structure interaction parameter, joint resistant characteristics, have been successfully done. Field verification of seismic response of buried lifelines due to seismic shaking and large ground deformations will then be the effective and accurate method of investigation.

Field verification on seismic response of buried lifelines may be done either by active (explosion)(1,6) or passive (actual) earthquakes. Earthquakes simulation by explosion in the field is somewhat expensive, but results can readily be obtained. However, due to high cost, the experiments do usually fall short of the failure stage of the pipeline. Passive verification by actual earthquakes and fault movements on the other hand would be more accurate providing that the seismicity of the site selected is high enough to produce meaningful results.

Tangshan and its neighboring cities Beijing and Tianjin are known to be in a highly seismic zone. The Tangshan earthquake in 1976 destroyed 90% of the buildings and lifelines in Tangshan and also caused heavy damages in Beijing and Tianjin cities. It would be reasonable to expect that fruitful results can be obtained within a reasonable length of time, if field observations are done in these cities.

## RESPONSE BEHAVIOR OF BURIED PIPELINES DUE TO SEISMIC GROUND SHAKING

Although the effects of wave propagation alone to the damages of buried pipelines located under uniform firm soil have been observed to be relatively minor(12), the affected area is rather large. In attempting to explain some of the failure mechanisms, this section describes the response behavior of buried pipelines due to seismic ground shaking.

Under ground shaking environments, the response behavior of buried pipelines during seismic shaking has been found to be predominant in the axial direction of the pipelines(15,19). From these observations, it is logical to believe that the failure mode or response behavior of buried pipeline due to longitudinal earthquake motion is, if not the most important, certainly one of the most important characteristics deserving close attention and thorough investigation.

Since the dynamic effects on the response behavior of buried pipelines have been found to be negligible(16,19), this section is to present the response behavior of long buried pipelines due to seismic excitations in the direction of the pipeline axis by a simplified quasi-static analysis model(32).

The detailed derivations for the quasi-static analysis of buried pipelines are given in Ref. 32. The formulation for the soil-structure interaction system is based on the variational principle of energy neglecting dynamic (inertia) terms. This paper briefly describes the formulation.

A long buried piping system model consisting of n-segments is shown in Fig. 1. A pipe segment has axial stiffness (Ea/L) and a node at each end. The joints are represented by linearly elastic springs. The resistance forces that develop between the soil and the pipe segments are represented by linearly elastic soil resistance springs.

The equation of static equilibrium, obtained from the variation of the total strain energy in the soil-structure interaction system, are as follows:

$$\underset{2n \times 2n}{[K_{system}]}\ \underset{2n\text{x}1}{\{X\}} = \underset{2n \times 2n}{[K_{soil}]}\ \underset{2n\text{x}1}{\{X_G\}} \tag{1}$$

where $[K_{system}]$ and $[K_{soil}]$ are the symmetrical tridiagonal structural system and soil resistance matrices respectively, $\{X\}$ is the nodal axial displacement vector and $\{X_G\}$ is the ground displacement vector which varies with time. Note that this general model has 2n degrees of freedom.

The solution of static pipe motion $\{X\}$ shown in Eqn. (1) depends on the inputs of the ground motion $\{X_G\}$. Since $\{X_G\}$ is a function of time, the solution of $\{X\}$ is also a function of time. Thus, the analysis is quasi-static.

Assuming that the wave form of the traveling seismic excitation remains constant over the entire length of the pipeline which consists of n-segments, the inputs of the time-space varying ground motions starting from the first support are:

$$X_{GO} = \begin{cases} 0 & t < 0 \\ \Delta_{max}\ h(t) & t \geq 0 \end{cases}$$

$$X_{G1} = \begin{cases} 0 & t-\eta_1 < 0 \\ \Delta_{max}\ h(t-\eta_1) & t-\eta_1 \geq 0 \end{cases} \tag{2}$$

$$X_{Gi} = \begin{cases} 0 & t-\eta_i < 0 \\ \Delta_{max}\ h(t-\eta_i) & t-\eta_i \geq 0 \end{cases}$$

where $\Delta_{max}$ is maximum ground displacement input; h(t) is the displacement time function; $\eta_i$ is the delay time of the seismic wave traveling from the first support to the end node of the $i^{th}$ pipe segment considered as:

$$\eta_i = \sum_{j=1}^{i} L_j/C_j \tag{3}$$

and $C_j$ is the traveling wave propagation velocity of soil surrounding the pipe segment j.

The system of governing equations requires the input of ground displacement at an instant of time. The response of nodal displacements, $X_i$, are calculated by a modified Gauss-elimination procedure (9) at each time step for the entire time-history of the earthquake input record. The resulting pipeline nodal displacements, X's, are used to determine two design parameters:

$$\varepsilon_i = (X_{2i} - X_{2i-1})/L_i \tag{4}$$

and

$$U_i = X_{2i+1} - X_{2i} \tag{5}$$

where

$\varepsilon_i$ = average strain in $i^{th}$ pipe segment
$U_i$ = relative displacement, extension/contraction, of $i^{th}$ joint spring between two adjacent pipe segments

By comparing these parameters within the earthquake time domain, the maximum values of average pipe strains, $\varepsilon_{p,max}$; relative joint displacement, $U_{p,max}$; and their corresponding occurrence time and location are determined. As an example, the effects of pipe segment length on pipe strain and relative joint displacement for three pipe segment lengths of 3.05 m (10 ft.), 6.10 m (20 ft.), and 12.20 m (40 ft.) are shown in Figs. 2a and 2b respectively. From these figures, one can easily see that the longer the pipe segment is, the larger the pipe strain, and also the larger the relative joint displacement will be. Since the pipe segment length is proportional to the delay time from one end of the pipe to the other end, the longer delay time directly affects the seismic response behavior.

The upper bounds of pipe strain and relative joint displacement estimated by the "Simplified Approach" are also shown in the figures. One can easily see that actural pipe strains and relative joint displacements are always below these two upper bounds.

The effects of a number of other parameters on the response of buried pipelines, such as pipe size (diameter), non-uniform resistance along the pipeline route, and wave forms, duration and magnitude, have been investigated and reported in detail in Reference 32.

In conclusion, this analysis model is capable of evaluating the general longitudinal responses of buried pipelines (segmented or continuous) subjected to seismic ground shakings/vibrations.

## ANALYSIS OF BURIED PIPELINES UNDER FAULT MOVEMENTS AND SOIL LIQUEFACTIONS ENVIRONMENTS

Although damages of pipelines are frequently associated with fault movements, only simple analysis for continuous buried pipelines subjected to tensive strike slips has been studied by Newmark and Hall(20) and later extended by Kennedy et al.(13,14). Similar analysis for segmented pipeline has been proposed by O'Rourke and Trautman(23,24).

Except mentioning by Kennedy et al.(14) that the proposed analysis for large fault movements might be used for soil liquefactions, there is no analysis method for pipeline under soil liquefaction environment. This section is to briefly describe the simple analysis proposed by Newmark and Hall(20) and Kennedy et al.(13,14). In general, the problem is to specify the largest amount of movement a pipeline can tolerate before failure.

Fig. 3 shows a schematic diagram of Newmark-Hall-Kennedy's model for shallow buried pipeline deflection resulting from a tensive horizontal strike-slip fault movement. The analysis assumes that the deflection is a single curvature curve antisymmetrically with respect to the mid-point of the fault movement and ends at an 'anchored point' of the straight portions of the pipeline.

As shown in Fig. 4, the vertical and horizontal equilibrum equations are obtained by considering half of the deformed pipeline plus its image as:

$$2F_a \sin\theta_L = 2\int_0^{\theta_L} (p_p \cos\theta + f_p \sin\theta)\, R_{CL}\, d\theta \qquad (6)$$

$$F_a \cos\theta_L = \int_0^{\theta_L} (f_p \cos\theta - p_p \sin\theta)\, R_{CL}\, d\theta + f_s L_s \qquad (7)$$

where

$f_p$ = frictional force on deformed pipe with passive soil pressure = $p_p \tan\theta_p$

$f_s$ = frictional force on undeformed pipe with static pressure = $p_s \tan\theta_s$

$p_p$ = passive earth pressure

$p_s$ = static earth pressure

$F_a$ = axial force of pipe at the fault crossing

$L_s$ = pipe length subjected to static soil friction

$R_{CL}$= radius of curved pipe

The compatibility required at the point of counterflexure is:

$$R_{CL}(1-\cos\theta_L) = \frac{\Delta_f}{2} \sin\beta \qquad (8)$$

where

$\beta$ = intersected angle between fault and pipeline

$\Delta_f$ = maximum fault movement

Given a ductile material with its stress strain curve shown in Fig. 5, the response of the pipeline can be classified into three zones, namely, an inelastic and an elastic zone in the deformed portion and an elastic portion in the straight portion of the pipeline. Thus, the compatibility requires that the total elongation of the three zones matches the geometrical deformation of the pipeline as shown by the following equation:

$$\Delta e_1 + \Delta e_2 + \Delta e_3 = 2\, R_{CL}(\theta_L - \sin\theta_L) + \Delta_f \cos\beta \qquad (9)$$

Note that the above four equations (Eqn. 6 to 9) contains four unknowns, $F_a$, $L_s$, $\theta_L$ and $R_{CL}$. Thus, solutions for the four unknowns can be found by giving the properties of the pipe and the surrounding soil for a given fault displacement $\Delta_f$, and its angle of attack, $\beta$.

Due to the geometry and material non-linearties, analytical solutions to the problem is very difficult, if not impossible. Iterative and numerical method, must be employed.

Using a numerical method, Kennedy et al.(13) obtained the critical fault displacement for a strike slip fault having an angle of 1 to 4 as shown in Fig. 6. The figure shows the critical displacement for depths of cover, $H_c$, equal to 3 and 10ft. The limiting tensile strain for the X-60 steel of the pipe is taken as 4.5%. For ductile response, the most favorable angle of pipeline-fault intersection is approximately 90 degrees. It is also found that the critical fault movement will be larger for lower soil resistance.

## RESEARCH PLAN

In order to verify the above discussed analytical results, the research tasks of the proposed cooperative projects are discribed below:

### Task A - Analysis of Earthquake Damage Mechanisms

Although there are extensive damage reports(10,15,17,28) from these well-publicized earthquakes available, the damages of buried pipelines from other earthquakes both in China and the United States have not been fully analyzed. Examples are Lubo, Szechwan Earthquake of February 6, 1973 (M=7.9) and Haichang Earthquake of February 4, 1975 (M7.5) in China and the Imperial County, California Earthquake of October 15, 1979 (M=6.6) and Northern Kentucky Earthquake of July 25, 1980 (M=5.1 to 5.8) in the United States.

To enhance the understanding of the seismic responses and failure mechanisms of buried pipelines due to earthquakes, this task is to systematically analyze damage data from Haicheng, Lubo and Tangshan Earthquakes in China, San Fernando, Imperial County, Northern Kentucky Earthquakes in U.S.A. as well as readily available data from other earthquakes. The purpose of the analysis is to determine the various parameters (seismic, geological, physical and geotechnical) that will control the response and failure mechanism of buried pipelines.

Using various statistical models, coupled with physical information, various response characteristics and failure mechanisms will be explained.

Task B - Field Investigation Programs

The task is to establish field investigations on buried pipelines in Beijing and/or Tainjin areas, in order to observe pipeline response behavior due to natural and artificial earthquakes. The plans of research are discussed as follows:

Task B1 - Active Field Investigation by Artificial (Explosion) Earthquakes.

The set-ups for the active field investigations would be a section of actual pipelines in the Beijing/Tainjin area. The test site should be located at open field with convenient exit but less populated area.

For this task, reinforced and prestressed concrete pipelines will be studied. For broader water/sewer pipeline application, the joint characteristics and its effects to seismic response will also be investigated. It is also desirable to choose a junction (L, T or cross junction) so that the effect of bent can be studied.

The generation of artificial earthquakes will be from line source contained explosions, a technique developed by SRI International. (1,6) It is to generate strong earth motions (seismic waves) passing through a test site embedded with underground pipelines.

The instrumentation would be strain gauges and accelerometers on pipe surface. For water/sewer pipelines, additional displacement gages will be needed to study relative joint movements.

On the free field at the site, three portable three-component seismometers will be installed to study the ground motion characteristics at the site for correlation purposes.

All the instrumentations will be connected and controlled by a data recorder system. Strain and displacement gauges and accelerometers or seismometers will be connected to the same trigger system so that common recording time can be established.

Task B2 - Passive Field Investigation by Natural (Actual) Earthquakes

This task is for long term observations on the responses of buried lifelines due to actual earthquakes. It is to instrument an existing pipeline in the northeast part of Beijing.

Since Beijing is one of the highly seismic regions (Intensity VIII and Locally IX) in China, it is expected that within the next few years, say 1-4 years, there will be sufficiently strong earthquake records to yield meaningful results, statistically as well as physically. Also, Beijing has a strong motion network to monitor and study ground motion characteristics, it would be more effective to instrument an existing pipeline under the control of the strong motion network so that the responses can be directly correlated with the ground motion.

Note that, since the soils in the northeast of Beijing have liquefaction potential, it would be interesting to observe the pipeline response characteristics under soil liquefaction condition (indirect earthquake effect).

For this project, an important task for the passive field investigation by actual earthquake would be to design a simple and economical but effective monitoring system to record both earthquake and pipeline response data for long term observations. The system should be tied in with the strong motion network system now in Beijing so that the pipeline responses and ground motion characteristics can be directly correlated.

The instrumentations such as accelerometers, strain gauges and/or displacement transducers will be placed on an existing pipeline in the northeast region of Beijing where soil liquefaction is one of the potential hazards.

The field investigation by natural (actual) earthquakes for buried pipelines will be conducted also in Tangshan and Tianjin area because they are highly active seismically as well as the existing Quing-Jing oil pipeline crossing an active fault in Tangshan.

Task C - Aseismic Measures and Applications

This task is to study the physical parameters, such as joint resistant characteristics, soil resistant characteristics, pipe length and material properties, etc. that will affect the performance of buried pipelines during earthquakes.

Based on empirical considerations and engineering analyses, a number of protective measures for buried pipelines have been recommended by Ford(11) Steinhardt(26) Newmark and Hall(20) etc. This task intends to confirm and improve such aseismic measures by testings of joints and soil resistant characteristics in laboratories. Favorable material, joint and soil properties will be incorporated in the field testings when the results are confirmed. Ultimately, the results will be used to develop the aseismic codes for buried lifelines.

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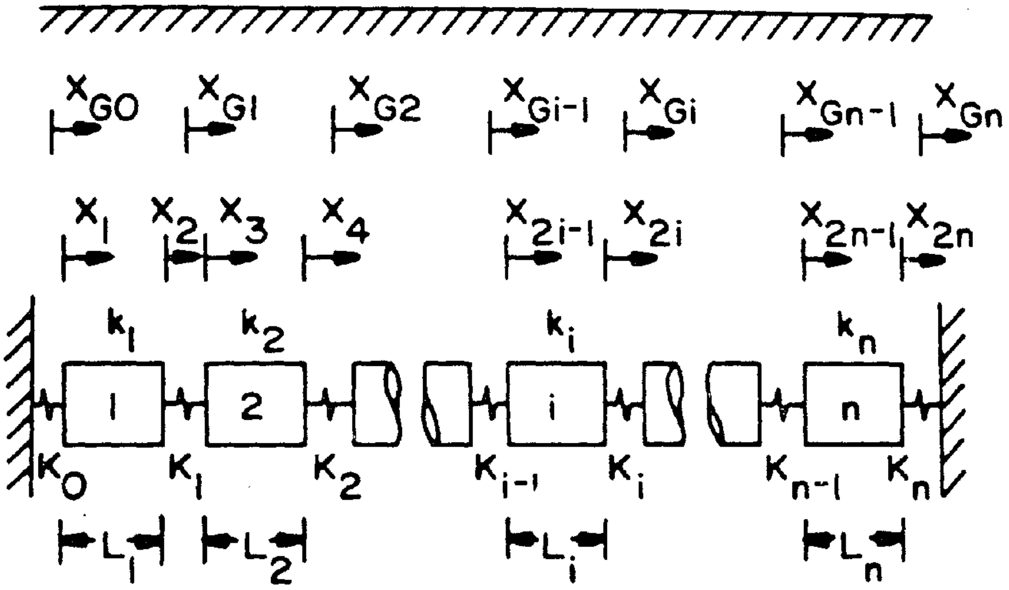

Figure 1. A buired segmented piping system model

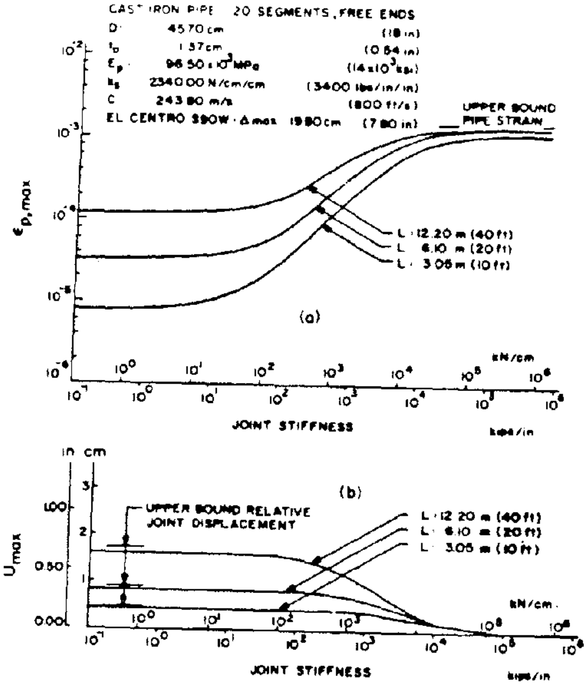

Figure 2. Effect of pipe segment length

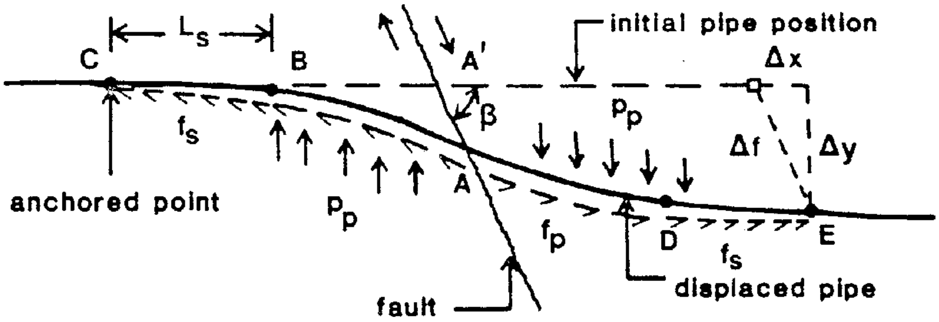

Figure 3. Pipeline Response to Strike-Slip Fault Movement

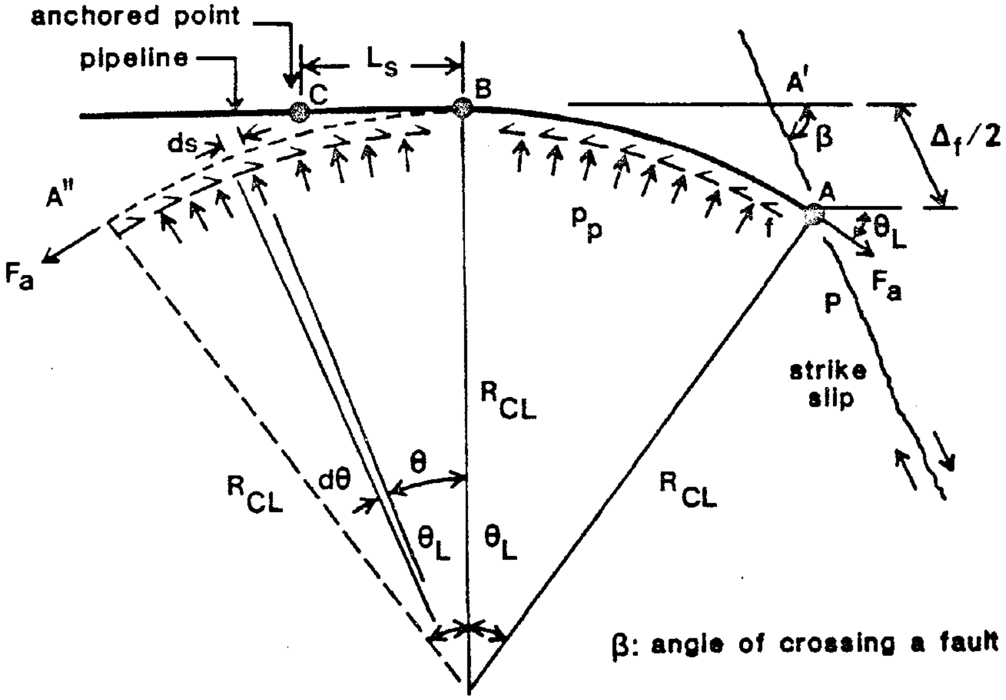

Figure 4. Force Equilibrium Model

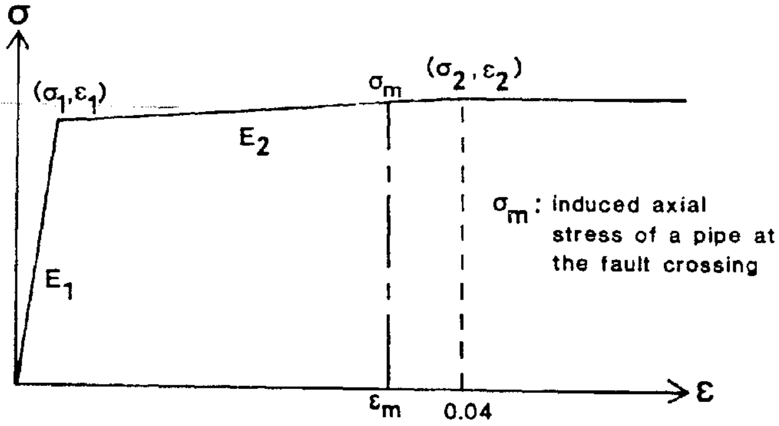

Figure 5. Stress-Strain Diagram of Pipeline Material

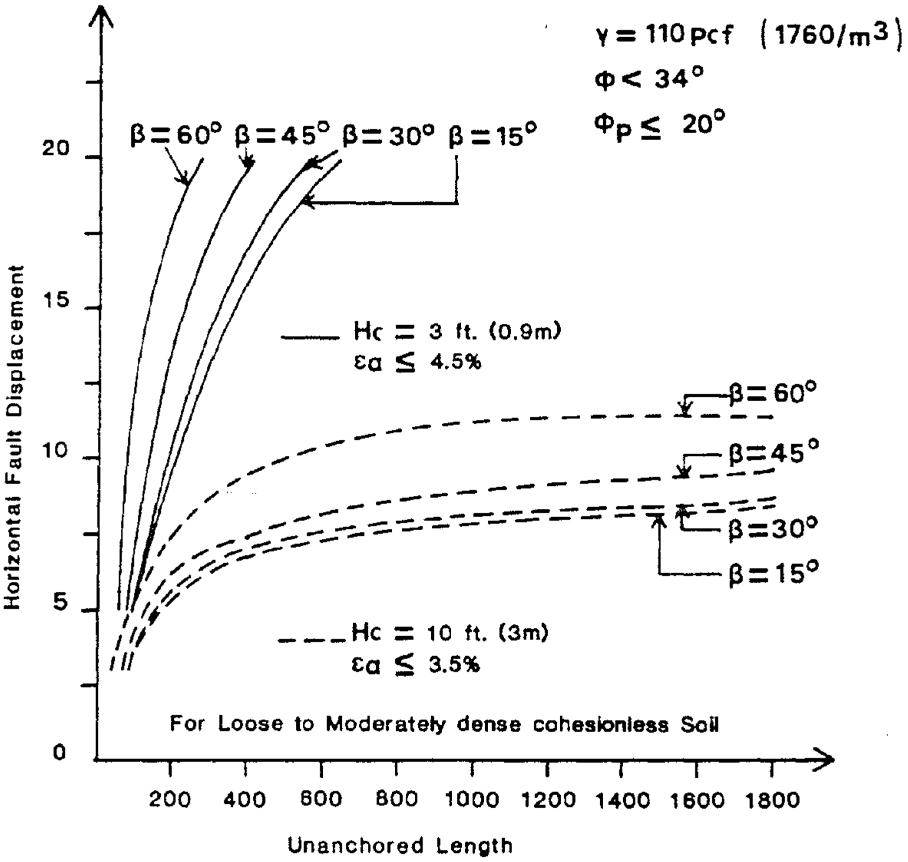

Figure 6. Fault Movement Capacity for 42-in. diam, 0.562-in. Wall Thickness, X-60 Pipe

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