Seismic Vulnerability, Behavior and Design

of Underground Piping Systems

Seismic Analysis and

Design of Buried Pipelines*

by

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by

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ABSTRACT

This paper describes an analysis procedures and design criteria for buried piping systems to resist earthquakes. The paper is centered on the 'Simplified Analysis' and 'Quasi-static Analysis' approaches for analyzing the axial strains and relative joint displacements due to seismic ground shaking. To fulfill the analysis requirements, the related parameters are discussed. Failure criteria and design considerations are recommended. In addition, this paper also presents some passive and active design considerations to reduce damage of buried pipelines due to seismic effects.

INTRODUCTION

The earthquake damage of buried pipelines has recently been receiving more attention because of the impact of these systems upon the populus during and after a major earthquake due to the loss of fire fighting capability (water pipelines), disruption of energy transportation (oil or gas pipelines) and possibility of disease (sewer pipelines) [1,2,3,4]. The pipeline performance and damage characteristics have been discussed by several authors elsewhere [4,5,6,7,8,9] and thus will not be repeated.

The analysis and design of buried pipelines, which by their nature have both temporal and spatial variations, are much different from those of buildings. Presently, there are no codified provisions for the design of buried pipelines to resist seismic loads in the United States. Aside from the effects of large fault displacements, landslide and soil liquefaction, this paper discusses some aspects of the analysis and design of buried pipelines under seismic ground shaking environments.

To evaluate the adequacy of the existing pipelines and to aid the design of future systems, this paper presents the analysis approaches from which the pipe strains and relative joint displacements are calculated. As to seismic design of buried pipelines, both passive and active design considerations will be discussed in this paper.

SIMPLIFIED ANALYSIS APPROACH

Although there are currently no codified provisions to design underground pipelines for earthquake effects, a 'Simplified Analysis' procedure [10] to estimate the underground pipe strains and curvatures due to seismic shaking

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has existed for some time. Basically, the analysis assumes no relative motion between the pipe and the ground. Thus, as upper bounds, one can take the seismic ground strains as the pipe strains and the seismic ground curvature as the pipe curvatures. This is equivalent to assuming that the pipe has no stiffness, and therefore follows the ground exactly.

For the analysis and design of continuous pipelines, the upper bound of the axial strain of the pipe, $\varepsilon_{p,max}$, will be the maximum ground strain, ε_{max}, due to the earthquake:

$$\varepsilon_p = \varepsilon_{max} = V_{max}/C_p \tag{1}$$

The upper bound for the maximum curvature of the pipeline, $\chi_{p,max}$, will be the maximum ground curvature, χ_{max}:

$$\chi_{p,max} = \chi_{max} = A_{max}/C_s^{\,2} \tag{2}$$

where V_{max} is the maximum ground velocity and A_{max} is the maximum ground acceleration during a seismic event at the site; C_p and C_s are the longitudinal (compressive) and transverse (shear) wave propagation velocities respectively of the controlling environments with respect to the pipeline.

If a continuous piping system can meet both sets of upper bound criteria (strain and curvature), the pipeline will be adequate against earthquakes producing ground velocities and accelerations less than the V_{max} and A_{max} used in the analysis. In comparing the two criteria, Weidlinger [11] indicated that the free-field ground strain due to intensive shaking is more likely to exceed the failure strain of the pipe, whereas the free field ground curvature is less likely to exceed the pipe failure curvature. From Eqns. (1) and (2) it is noted that the strain is inversely proportional to the wave propagation velocity, whereas the curvature is inversely proportional to the square of the wave velocity. For larger propagation velocities, the above observations can be easily verified. Numerically, the free field strain may be in the order of 10^{-2} to 10^{-3} and the free field curvature in the order of 3.3×10^{-5} to 3.3×10^{-6} m^{-1} (10^{-5} to 10^{-6} ft^{-1}) for moderate to strong earthquakes [11].

For segmented pipelines (Fig. 1), the maximum relative joint displacements and maximum joint rotations become important design parameters in addition to the pipe strains and curvatures. If we assume that the pipeline consists of rigid segments which have their mid points move with the ground exactly, then the maximum relative motion/rotation between two points on the ground will be entirely taken up by the relative displacements and rotations of segments at the joints. Hence, the upper bounds of maximum joint displacement, $U_{p,max}$ and maximum joint rotation, $\theta_{p,max}$, shown in Fig. 2 can be expressed as:

$$U_{p,max} = \varepsilon_{max} L \tag{3}$$

$$\theta_{p,max} = \chi_{max} L \tag{4}$$

where L is the length of the pipe segment; ε_{max} and χ_{max} are the maximum free field ground strain and curvature defined in Eqns. (1) and (2) respectively.

If a buried segmented piping system can meet all four sets of upper bounds (pipe strain and curvature; joint displacement and rotation) specified in Eqn. (1) to Eqn. (4) for a design earthquake, the pipeline will be conservatively safe because in the real case, the pipe strain and relative joint displacement will jointly take-up the imposed ground strain and both the pipe curvature and joint rotation will jointly take-up the imposed ground curvature. Again, due to the difference in the order of the magnitude of free field ground strains and ground curvatures, the relative joint displacements would be more critical than the relative joint rotations as far as the design of buried segmented pipelines is concerned. More information on the subject is given by O'Rourke, et al.*

QUASI-STATIC ANALYSIS APPROACH

Preface

As indicated in Refs. 7, 8, 9, pipeline damage caused by earthquakes in the longitudinal direction has been found to be a major mode of failure. During seismic ground shaking, the response behavior of buried pipelines depends mainly on the ground displacement characteristics along the pipeline route [12,13,14]. Therefore, this investigation is limited to the axial response due to an imposed ground displacement time history neglecting dynamic terms.

In the 'Simplified Analysis' approach, upper bounds for pipe strains and relative joint displacements are obtained by assuming that the pipeline is continuous and very flexible or the pipeline consists of isolated rigid segments. In reality, a buried pipeline has elasticity and reacts to the seismic shaking through the media of the surrounding environments. Thus, the response behavior of the buried pipeline will be influenced by a number of physical, geotechnical and seismological parameters. The physical parameters are the geometrical and mechanical pipe properties such as diameter, thickness, segment length, and Young's modulus. The geotechnical parameters are the soil-structure interaction resistant constant, its variation along the pipeline and the wave propagation velocity. The seismological parameters are the form, duration, amplitude and the slope of the ground displacement time history.

In earlier investigations [15,16], a preliminary quasi-static model consisting of rigid pipe segments connected by elastic joint springs was used to study conservatively the relative joint motions of segmented pipelines due to seismic ground shaking. Based on the general formulation [17], a more rigorous quasi-static analysis model has been developed to study parametrically the response of <u>actual</u> buried pipelines, segmented or continuous, subjected to earthquake motion in the axial direction [18].

Since the inertia and damping terms in the dynamic equations of motion have been dropped and the input ground motion is a function of time, the analysis is thus called a 'Quasi-static Analysis'.

Formulation

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. 3. 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

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* O'Rourke, M.J., Singh, S. & Pikul, R., "Seismic Behavior of Buried Pipelines", Proc. of ASME Conference on Lifeline Earthquake Engineering, June 1979, pp. 49-61.

elastic soil resistance springs. Note that the soil slippage characteristics have not been taken into account.

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

$$\underset{2n \times 2n}{[K_{system}]} \; \underset{2n\text{x}1}{\{X\}} = \underset{2n \times 2n}{[K_{soil}]} \; \underset{2n\text{x}1}{\{X_G\}} \tag{5}$$

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.

The solution of pipe motion $\{X\}$ shown in Eqn. (5) 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.

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 are:

$$X_{Gi} = \begin{cases} 0 & t-\eta_i < 0 \\ \Delta_{max}\, h(t-\eta_i) & t-\eta_i \geqslant 0 \end{cases} \tag{6}$$

where Δ_{max} is maximum ground displacement input; $h(t)$ is the displacement time functipn; η_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:

$$\eta_i = \sum_{j=1}^{i} L_j/C_j \tag{7}$$

and C_j is the traveling wave propagation velocity of soil/geological environments surrounding the pipe segment j.

The solution of the system of static 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 [19] 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 i^{th} average pipe strain, ε_i and i^{th} relative joint displacement, U_i as:

$$\varepsilon_i = (X_{2i} - X_{2i-1})/L_i \quad \text{and} \quad U_i = X_{2i+1} - X_{2i} \tag{8}$$

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.

A computer program for the general 'Quasi-static Analysis' and subsequent parametric studies of buried pipelines have been reported by Fok [18]. This paper presents only representative results and conclusions of that study.

Results

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. 4a and 4b 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. 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. One can also see from these figures, that as the joint stiffness increases (approaching a continuous pipe) the strains become larger and the relative joint displacements become smaller.

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 actual 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 18 and thus will not be repeated herein.

PASSIVE DESIGN CONSIDERATIONS

In the absence of seismic design codes for buried pipelines, several passive design considerations have been used [20] by engineers to reduce seismic damage and minimize hazardous effects. Following are some common engineering practices and recommendations:

1. Redundancy should be built into the distribution system. More smaller pipes should be used in lieu of a single larger pipe to minimize reduction in operation due to breakage of pipes.

2. Blow-off valves should be installed at a location where higher seismic activity is anticipated, such as along a fault line. By this technique, water is led to a nearby reservoir after a blow-off valve fails during an earthquake.

3. Ductile pipe materials such as steel, ductile iron or plastics should be used to allow larger pipeline deformations.

4. For segmented pipelines, flexible joints such as rubber gasketed connections should be used to provide for relative joint movements. For anticipated large ground movement, extra long restraining sleeves or 'Bellow Joints' should be used. When feasible, shorter segments which will experience less strain imposed by the ground motion, should be used. Also, relative joint displacements are less for shorter segments.

5. If feasible, consideration should be given to encasing the pipeline in a larger tunnel in order to isolate the pipeline from the seismic ground motion, or to lubricating the pipeline in order to increase the "slippage" between the pipe and the surrounding soil.

In summary, all these qualitative passive seismic design considerations may reduce the damage of buried pipelines. Quantitative and comprehensive design guidelines are still urgently needed to ensure the safety of future designs.

ACTIVE DESIGN PROCEDURES

Preface

Active design is a process to develop a set of physical parameters of a system capable of resisting the anticipated loads, called the design loads. In light of the fact that there is no seismic design code for buried pipelines in the United States, this paper outlines an active design procedure which may serve as a basis for future design code developments. Sequentially, the active design procedure involves three stages, namely: (1) Site Environment Evaluations, (2) Engineering Decision Making and (3) Design Analyses.

Site Environment Evaluations

In order to satisfactorily design buried pipelines to resist the anticipated seismic ground shaking, the site environment must be evaluated so that the important site-dependent design parameters can be determined. The site-dependent parameters are the seismic risks of the region, wave propagation velocities at the site and the soil resistant characteristics of the surrounding environment of the pipeline.

Seismic Risks: In this paper, seismic risk is defined as the probability of exceeding a particular ground acceleration, velocity or displacement in a given time period called the return period. Using seismic data in the region where the pipeline is to be designed, a family of curves of ground acceleration vs. probability of exceedance for a number of return periods (e.g., 50 years, 100 years, etc.) can be determined by a seismic risk analysis [21]. It should be noted that peak ground acceleration values for particular return period are available from other sources [22,23] for the United States. It is recommended that a seismic risk analysis for a particular site be undertaken only if the designer wishes to design for return period other than those available in References 22 or 23.

One technique to estimate peak ground velocity, is to first establish the probable peak ground acceleration in rock based on a seismic risk analysis [21] or from available information [22,23]. Knowing the peak acceleration in rock, the peak acceleration in soil can be determined by standard techniques [24]. Once maximum ground accelerations have been established, maximum ground velocities can be estimated through the use of published relationships such as those by Seed [24] and Newmark [25].

Note that the maximum ground acceleration and maximum ground velocity are required for the 'Simplified Analysis' approach. However, for the 'Quasi-static Analysis' approach, the ground displacement-time function is also required. Unfortunately, there is no known seismic risk analysis or relationship on ground displacement-time functions available to the author at this time. Before the advancement of seismic risk analysis to include ground displacement-time function is available, it is suggested that for design purposes, a known earthquake displacement-time record (e.g., El Centro or San Fernando) be used, with the magnitude of the displacements scaled to the level corresponding to the estimated maximum ground velocity obtained from the Seismic Risk Analysis discussed earlier.

Propagation Velocity: Another site dependent parameter is the wave propagation velocity. The wave propagation velocity pertinent to buried pipelines is a function of the epicenter distance, focal depth as well as the geological and soil properties along the transmission path of the waves to the site.

Because of a lack of advanced research results and as a conservative approximation, the wave propagation velocity resulting in pipeline curvature may be represented by the shear wave velocity, C_s, and the velocity resulting in axial strain may be represented by the pressure wave velocity with respect to the pipeline at the site as follows [25]:

$$C_s = \sqrt{\frac{G}{\rho}} \qquad \text{and} \qquad C_p = \sqrt{3}\, C_s \tag{9}$$

where G is the soil shear modulus and ρ is the soil mass density.

In lieu of a detailed soil analysis, an approximate value for G can be obtained using published relationships [25,26] relating Standard Penetration Resistance N to shear modulus G.

Note that if the 'Simplified Approach' is used for the analysis, the above mentioned parameters will be sufficient. However, if the 'Quasi-static Approach' is used, then the soil resistant characteristics must be obtained. Additional site investigation is then needed.

Soil Resistant Characteristics: In the 'Quasi-static Analysis' approach, the axial soil resistant characteristics are needed to study the soil-structure interaction effects. For elastic analysis, it is only necessary to determine the axial soil resistant springs constants, K_a, which are influenced by the soil properties surrounding the pipes [6]. Unfortunately, values for the longitudinal soil-structure resistant spring constants are not readily available in the literature and must be obtained from experimental studies.

Recently, Wang et al. [6] and Novak et al. [27], through analytical studies, have proposed the axial resistant spring constant, K_a, in the form:

$$K_a = 2\pi\, G\, \alpha \tag{10}$$

where α is a constant depending on soil and pipe properties and buried depth. For design purposes, it is recommended that $K_a = 2\pi G$ be used.

Engineering Decision Making

Engineering decisions for the seismic design of buried pipelines that should be made are (1) a determination of the 'Design Earthquake' for the site and (2) a choice of material or joint ductility or the combination of the two in order to resist the imposed ground strains/curvatures resulting from the selected 'Design Earthquake'. Both aspects have great economic implications and are briefly discussed below.

Design Earthquake: The probability of failure of a system is directly related to the magnitude of the 'Design Earthquake' used. It is obvious that the larger the earthquake used for the design, the less the risk of failure of the system. In reality, there is no absolute earthquake-proof design without some risk. It is more costly to design the system to resist stronger 'Design Earthquakes'. At the present time, there is no explicit criteria, from an economical point of view, to select a satisfactory 'Design Earthquake'. In most cases, it is a matter of engineering and administrative judgement.

Based on discussions with various utility personnel, a 100 year economic lifetime for buried pipelines and an acceptable probability of exceedance of 20% corresponding approximately to a 450 year design earthquake seems to be reasonable and acceptable at this time.

Pipe Materials and Joint Construction: Note that for the design of continuous pipelines to resist earthquakes, once the 'Design Earthquake' is chosen, it is only necessary to select the proper material and check the thickness of the pipeline through one of the two analysis approaches discussed. However, for segmented pipelines, both pipe materials and joints share the resistance to the imposed ground excitations. The choice of pipe material and joint construction again involves both economic considerations and engineering judgement. Overall sizing of the pipeline will generally be controlled by hydraulic or other fluid flow considerations.

Note that choosing more ductile materials and more flexible joints will increase the ability of buried pipelines to absorb higher imposed ground disturbances due to earthquakes. Thus, the safety of the system will be increased by increasing ductility. From an economic point of view, the designer should investigate the proper choice of material(s) and joint construction(s) unless functional requirements control (e.g., continuous pipelines are used for gas and oil transportation in order to prevent leakage). In this regards, the 'Quasi-static Analysis' approach must be used to determine the pipe strains and relative joint displacement for a given seismic input.

Design Analyses

After engineering decisions have been made to select a 'Design Earthquake', pipe materials and joint constructions thus establishing a set of physical parameters for the pipeline, the next step will be the design analysis to determine the adequacy of the trial design. The design analyses include Seismic Design Criteria Analysis to establish the reserve strength/ductility available beyond non-seismic loadings followed by the Simplified Response Analysis and/or Quasi-static Response Analysis to establish strain and displacement rotation magnitudes due to seismic loading.

Seismic Design Criteria Analysis: For a given material (e.g., cast iron, ductile iron and concrete, steel pipes) and use (water, sewer, gas and oil pipelines), a Seismic Design Criteria Analysis [28] is required to determine the reserve strength/ductility of buried pipes beyond normal non-seismic stress/strain conditions. This reserve strength/ductility is the capacity available in buried pipes to resist seismic loads.

To evaluate the failure of buried pipelines consisting of materials with different tensile and compressive strengths such as cast iron and concrete under a bi-axial stress state, a modified Von Mises failure criteria has been proposed [28].

Response Analysis in Design Process: As a first check on the trial design, the 'Simplified Anabysis' approach should be used since this approach is simple but conservative. It requires only inputs of maximum ground accelerations and velocities and seismic wave propagation velocities at the site. If the analysis results are within the seismic design criteria limits, no additional analysis is required.

A more refined analysis may be required for technical or economic reasons. If so, the 'Quasi-static Analysis' approach should be used since this approach will output pipeline responses in more detailed and concise terms. However, the analysis requires more inputs such as joint and soil resistant characteristics, displacement-time function as well as some other physical piping parameters.

By comparing the results from one or both of the response analyses to the seismic design criteria, the adequacy of a design can be evaluated.

SUMMARY AND CONCLUSIONS

To aid in the design of buried pipelines for earthquake loads, this paper has proposed active/passive seismic analysis/design procedures for buried pipelines subjected to seismic ground shaking.

In conclusion, it is important to note that the behavior of buried lifelines is governed by the relative displacements of the ground along the route and not the ground acceleration. Ductility or flexibility to allow buried lifeline movement with the ground is the most important factor for the seismic design of such structures.

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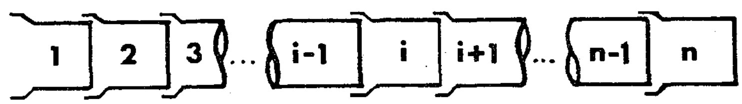

Fig. 1 Schematic of a buried segmented pipeline

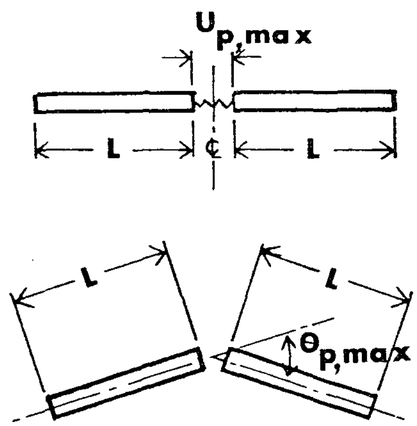

Fig. 2 Maximum relative joint displacement/rotation of segmented pipeline

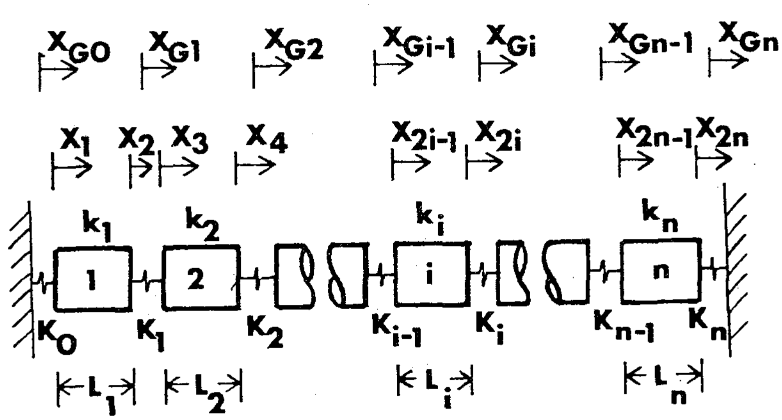

Fig 3. A buried segmented piping system model

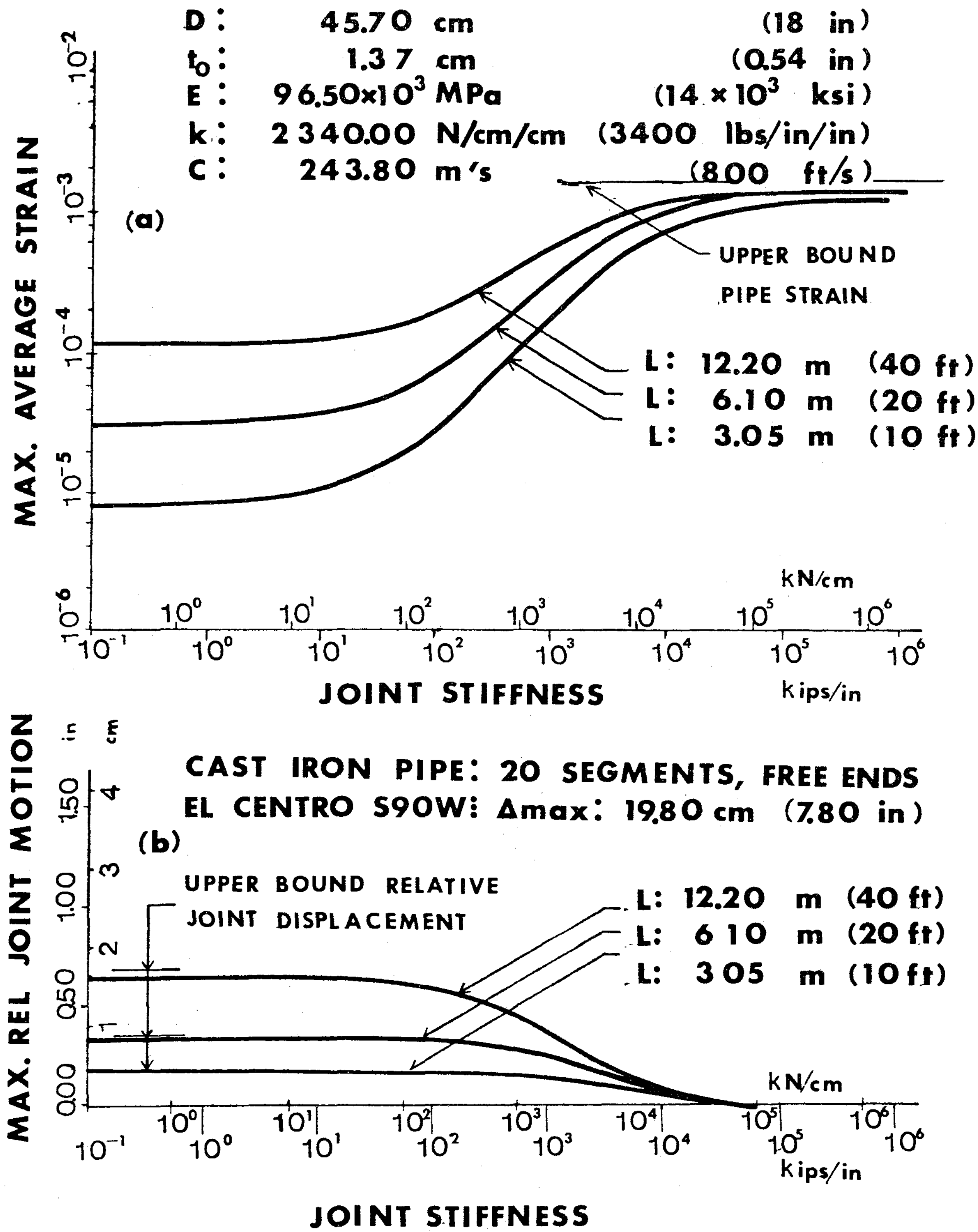

Fig. 4 - Effects of Segment Length on Pipe Strains and Relative Joint Displacements

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16. Abstract (Limit: 200 words)

Analysis procedures and design criteria for buried pipeline systems to resist earthquakes are described. Increasing attention is being devoted to the earthquake damage of buried pipelines because of the impact of disturbed conveyor systems on the citizenry during and after major earthquakes. These involve loss of fire fighting capability, disruption of energy transportation, and disease hazard resulting from damage to water, oil or gas, and sewer/pipelines respectively. To evaluate the adequacy of existing systems and improve the design of future systems, "Simplified Analysis" and "Quasi-static Analysis" approaches are presented for use in computing pipe strains and relative joint displacements due to seismic ground shaking. Related parameters to fulfill analysis requirements are described. Both active and passive design procedures and considerations to reduce seismic damage of buried pipelines are presented. The most important factor in designing buried pipelines is ductility or flexibility which permits buried pipelines movement with ground displacement.

17. Document Analysis a. Descriptors

Earthquakes
Design
Ductility
Dynamic structural analysis
Pipelines
Pipes (tubes)

b. Identifiers/Open-Ended Terms

Buried pipelines
Pipe strains
Seismic analysis

c. COSATI Field/Group

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