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7. Author(s)
L.R. Wang, K-Man Cheng

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9. Performing Organization Name and Address
Rensselaer Polytechnic Institute
Department of Civil Engineering
Troy, New York 12181

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Overall aims of this research are to develop a systematic way of assessing the adequacy and vulnerability of water/sewer distribution systems subjected to seismic loads and also to develop future design methodologies for water/sewer systems. This paper reports pipeline damages caused by earthquake excitations in the longitudinal direction of a pipeline have been observed to be a major mode of failure. A simplified quasi-static seismic deformation analysis neglecting the dynamic terms for buried pipelines subjected to earthquake motions in the axial direction is proposed. The analysis involves the solution of a system of static equilibrium equations of a pipeline which consists of rigid pipe-segments and flexible joint springs. Using this model, parametric studies involving soil-pipe interaction parameters, time delay of the traveling seismic waves, soil variations along the pipeline, end conditions, and variation of the seismic wave form are performed. Results obtained indicate that the delay time of seismic waves and the non-uniformity of soil resistance have much greater effects on the response behavior of buried pipelines than other parameters.

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Seismic Vulnerability, Behavior and Design

of Underground Piping Systems

Seismic Response Behavior of Buried Pipelines*

by

Leon Ru-Liang Wang
and
Kwong-Man Cheng

Sponsored by National Science Foundation

Research Applied to National Needs (RANN)

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Technical Report (SVBDUPS Project) No. 5

June 1978

Department of Civil Engineering
Rensselaer Polytechnic Institute
Troy, New York 12181

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Department of Civil Engineering
Telephone — (518) 270-6360

Rensselaer Polytechnic Institute Troy, New York 12181

List of NSF SVBDUPS (Seismic, Vulnerability, Behavior and Design of Piping Systems) Project Technical Reports

No. 1 Leon Ru-Liang Wang and Michael J. O'Rourke
State of the Art of Buried Lifeline Earthquake Engineering
Jan. 1977
Also in ASCE Proceedings of Current State of Knowledge of Lifeline Earthquake Engineering Conference, Los Angeles, CA, Aug. 1977, pp. 252-266

No. 1A Leon Ru-Liang Wang and Michael J. O'Rourke
An Overview of Buried Lifeline Earthquake Engineering
Jan. 1978
Also to be published in ASCE Journal of Technical Councils

No. 2R Leon Ru-Liang Wang
Vibration Frequencies of Buried Pipelines
Jan. 1978
Also to be published in ASCE Journal of Technical Councils

No. 3 Michael J. O'Rourke and Eric Solla
Seismic Risk Analysis of Latham Water District, Albany, New York
June 1977

No. 4 Michael J. O'Rourke and Leon Ru-Liang Wang
Earthquake Response of Buried Pipelines
March 1978
Also in Proceedings of ASCE Geotechnical Division Specialty Conference on Earthquake Engineering and Soil Dynamics, Pasadena, CA, June 1978, pp. 720-731

No. 5 Leon Ru-Liang Wang and Kwong-Man Cheng
Seismic Response Behavior of Buried Pipelines
June 1978
Also in preprints of ASME Winter Conference, San Francisco, CA, Dec. 1978

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The authors wish to express their appreciation for the inputs and discussions from all members of the research team during the course of investigation.

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ABSTRACT

Pipeline damages caused by earthquake excitations in the longitudinal direction of a pipeline have been observed to be a major mode of failure. A simplified quasi-static seismic deformation analysis neglecting the dynamic terms for buried pipelines subjected to earthquake motions in the axial direction is proposed. The analysis involves the solution of a system of static equilibrium equations of a pipeline which consists of rigid pipe-segments and flexible joint springs.

Using this model, parametric studies involving soil-pipe interaction parameters, time delay of the traveling seismic waves, soil variations along the pipeline, end conditions and variation of the seismic wave form are performed.

Results obtained indicate that the delay time of seismic waves and the non-uniformity of soil resistance have much greater effects on the response behavior of buried pipelines than other parameters.

NOMENCLATURE

i	:	An index
n	:	Number of pipe segment
t	:	Time
Dt	:	Constant delay time of seismic wave between two pipe segments in constant segment length system used in the parametric study
d_i	:	Distributed soil damping coefficient along i^{th} pipe segment
f_i	:	Total soil resistant force (spring + damping) on i^{th} pipe segment
k_i	:	Distributed soil spring constant (force/length) along i^{th} pipe segment
$\ddot{x}_i, \dot{x}_i, x_i$	:	Acceleration, velocity, displacement of ith pipe segment
$\ddot{x}_{Gi}, \dot{x}_{Gi}, x_{Gi}$	:	Acceleration, velocity, displacement of ground above i^{th} pipe segment
$\ddot{x}_{G0}, \dot{x}_{G0}, x_{G0}$	:	Acceleration, velocity, displacement of ground at beginning of pipeline
$\ddot{x}_{Gn}, \dot{x}_{Gn}, x_{Gn}$	:	Acceleration, velocity, displacement of ground at end of pipeline
$f(t), g(t), h(t)$	:	Seismic acceleration, velocity, displacement time functions
A_{max}	:	Maximum acceleration of a seismic record
C_i	:	Damping coefficient of ith joint dashpot
C_0	:	Pipeline beginning restraint damping coefficient
C_n	:	Pipeline end restraint damping coefficient
F_i	:	Total restrained force (spring + dashpot) of ith joint
K_i	:	i^{th} joint spring constant
K_0	:	Pipeline beginning restraint spring constant
K_n	:	Pipeline end restraint spring constant
L_i	:	Length of ith pipe segment
M_i	:	Mass of ith pipe segment
U_i	:	Extension/contraction of ith joint spring
V_{max}	:	Maximum velocity of a seismic record
V_{si}	:	Seismic wave propagation velocity within i^{th} pipe segment
Y_i	:	Relative displacement between i^{th} pipe segment and the ground displacement above
α_i	:	Normalized i^{th} joint spring constant K_i/k_iL_i
β_i	:	Normalized soil restraint constant along i^{th} pipe segment k_i/k_1
ΔT_i	:	Delay time of seismic wave from beginning of pipeline to i^{th} pipe segment
γ_o	:	Normalized pipeline beginning restraint spring constant K_0/k_1L_1
γ_n	:	Normalized pipeline end restraint spring constant K_n/k_nL_n
$\{\ddot{\underline{x}}\}, \{\dot{\underline{x}}\}, \{\underline{x}\}$	:	Pipe segment acceleration, velocity, displacement vectors
$\{\dot{\underline{x}}_G\}, \{\underline{x}_G\}$	:	Ground velocity, displacement vectors
$[d]$	:	Damping matrix of soil
$[k]$	:	Stiffness matrix of soil
$[C]$	:	Damping matrix of joint dashpots
$[C']$	:	Equivalent damping matrix of pipeline beginning and end dashpots
$[K]$	:	Stiffness matrix of joint springs
$[K']$	:	Equivalent stiffness matrix of pipeline beginning and end restraints
$[M]$	:	Mass matrix of pipe segments

INTRODUCTION

Earthquake damage has become an increasing threat to human life in recent years due to its frequent

occurrence. The design of structures against earthquake has long been a practice in areas where earthquakes often occur. However, much effort in the past has been concentrated on the above-ground structures, such as buildings, towers and bridges. As to underground structures, which are just as vulnerable in the event of earthquakes, very little discussion in the literature has been found until recently.

Past observations of actual earthquake damage to underground pipeline systems show a variety of failure modes (longitudinal, shear and bending). In particular, most literature surveys on pipeline failure due to earthquakes indicated joints being pulled out and crushed are the most common modes of failure (5,6,7, 20,21). The response behavior of buried pipelines during seismic shaking has been found to be predominant in the axial direction of the pipeline (8,10,11, 14,16,18). 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.

State of the art papers (9,20,21) on buried lifeline earthquake engineering have been published recently. Analytically, the response behavior of underground piping systems has been studied by the investigators at Weidlinger Associates (4) and at Rensselaer Polytechnic Institute (15). To aid the design of buried pipelines, both the static displacement approach (13,17) and the dynamic interference response spectra approach (12) have been proposed.

The purpose of this paper is to study 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.

Note that since the dynamic effects on the response behavior of buried pipelines have been found to be negligible (8,10,14,18), the inertia and damping terms in the dynamic equations of motion can be dropped. Thus, the equilibrium equation is essentially a static one. Since the input ground motion is a function of time, the response will also be a function of time. Therefore, the analysis is called a quasi-static analysis.

GENERAL DESCRIPTION AND ASSUMPTIONS

The buried piping system described in this paper is a long pipeline (typical of water/sewer transmission lines) buried underground. The pipeline is made up of pre-fabricated pipe segments. These pipe segments are connected at joints, which are sealed by a rubber gasket or caulked by cement/lead. Figure 1 shows a buried piping system schematically.

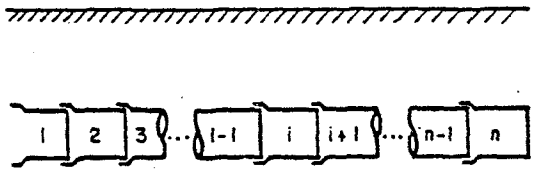

Fig. 1 Schematic of A Buried Pipeline

The earthquake damping forces to buried pipelines include seismic shaking/vibrations, fault displacements, tectonic uplifts/subsidences, landslides, soil liquefaction, etc. The modes of failure of pipelines due to tectonic uplifts/subsidences, landslides or soil liquefaction are catastropic and will not be considered. This paper limits discussions to the response behavior of buried pipelines due to seismic shaking/vibrations.

Due to the motion of the ground relative to the pipe segment during earthquakes, resistance between the pipe and the surrounding soil develops. The soil resistance to the pipe motion is assumed to be uniformly distributed and linearly proportional to the relative displacement between the pipe and the ground (Fig. 4). To model such soil resistance, a uniformly distributed soil spring, k, is proposed.

The joint resistance between two pipe segments is modeled by a joint spring, K, and a dashpot, C, as shown in Fig. 2. Note that the joint spring constant from a rubber-gasket, cement-caulked or lead-caulked joint is in general very small as compared to the stiffness of pipe itself or the resultant soil spring constant along a pipe segment.

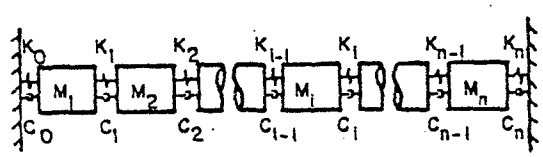

Fig. 2 A Buried Long Pipeline Model

Under seismic excitation, both pipe segments and joint springs are all subjected to the imposed ground displacements/strains. However, it is anticipated that most of the ground displacements/strains will be absorbed by the movements of joint springs and very little by straining of the pipes. For simplicity and conservatism (in estimating joint extension/contraction) purposes, all pipe segments will be assumed to be infinitely rigid.

An earthquake motion traveling along a pipeline resembles the problem of wave propagation in an elastic media. An incident earthquake at one end of a pipe segment will not simultaneously reach the other end some distance away. Thus, for wave propagation problems, a time lag is generally associated with the wave in the direction of propagation. Since the dissipation of seismic wave energy is negligible along a pipeline during the period of investigation, we assume that the wave form remains constant in the course of propagation.

Further assumptions or limitations for the simplified model will be made in later sections.

FORMULATION OF THE PROBLEM

A long buried piping model consisting of n-segments is shown in Fig. 2 where M_1, M_2, ... M_i, .. M_n are equivalent masses of each segment of underground pipes which should include the mass of the pipe and the soil that moves with the pipe; K_1, K_2, ... K_i, .. K_{n-1} and C_1, C_2, ... C_i, .. C_{n-1} are spring constants and damping coefficients at joints between pipes; K_0, K_n and C_0, C_n are spring and damping constants at the end supports.

The coordinates that define the motion of the ground and the pipe during an earthquake are shown in Fig. 3 in which x_1, x_2, .. x_i, .. x_n are longitudinal displacements of mid-sections of pipe segments; x_{G1}, x_{G2}, .. x_{Gn} are the corresponding ground displacements in the direction of the pipeline axis; x_{G0} and x_{Gn+1} are the ground movements at the ends; L_1, L_2, .. L_i, .. L_n are pipe lengths.

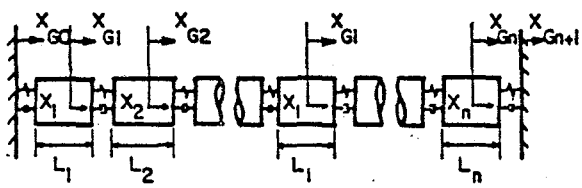

Fig. 3 Coordinates of Buried Pipeline Model

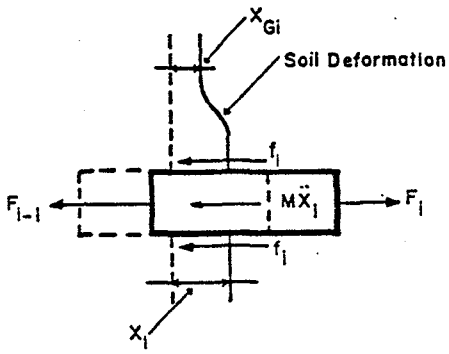

Fig. 4 Dynamic Equilibrium of A Pipe Segment

Referring to Fig. 4, the dynamic equilibrium equation (2) for pipe segment i is:

$$M_i \ddot{x}_i + F_{i-1} - F_i + f_i = 0 \tag{1}$$

in which $M_i \ddot{x}_i$ is the inertia force; F_{i-1}, F_i are joint resistant forces at both ends of the pipe and f_i is the resistance from soil surrounding the pipe.

Using the coordinates, $x_i > x_{Gi}$, $x_i > x_{i-1}$, $x_{i+1} > x_i$, the above resistant forces can be expressed as:

$$\left.\begin{aligned} F_i &= C_i(\dot{x}_{i+1}-\dot{x}_i) + K_i(x_{i+1}-x_i) \\ F_{i-1} &= C_{i-1}(\dot{x}_i-\dot{x}_{i-1}) + K_{i-1}(x_i-x_{i-1}) \\ f_i &= d_iL_i(\dot{x}_i-\dot{x}_{Gi}) + k_iL_i(x_i-x_{Gi}) \end{aligned}\right\} \tag{2}$$

where d_i and k_i are damping and spring constants per unit length of surrounding soil.

Substituting Eqn. (2) into Eqn. (1), the equation of motion is obtained:

$$\begin{aligned} &M_i\ddot{x}_i+C_{i-1}(\dot{x}_i-\dot{x}_{i-1}) + K_{i-1}(x_i-x_{i-1}) \\ &- C_i(\dot{x}_{i+1}-\dot{x}_i) - K_i(x_{i+1}-x_i) \\ &+ d_iL_i(\dot{x}_i-\dot{x}_{Gi}) + k_iL_i(x_i-x_{Gi}) \\ &= 0 \end{aligned} \tag{3}$$

After rearranging, Eqn. (3) becomes

$$\begin{aligned} &M_i\ddot{x}_i-C_{i-1}\dot{x}_{i-1} + (C_{i-1}+C_i+d_iL_i)\dot{x}_i \\ &-C_i\dot{x}_{i+1}-K_{i-1}x_{i-1} + (K_{i-1}+K_i+k_iL_i)x_i-K_ix_{i+1} \\ &= d_iL_i\dot{x}_{Gi} + k_i\,L_ix_{Gi} \end{aligned} \tag{4}$$

Let us define

$$\begin{aligned} \bar{C}_i &= C_{i-1} + C_i + d_iL_i \\ \bar{K}_i &= K_{i-1} + K_i + k_iL_i \end{aligned} \tag{5}$$

Eqn. (4) is simplified to:

$$\begin{aligned} &M_i\ddot{x}_i - C_{i-1}\dot{x}_{i-1} + \bar{C}_i\dot{x}_i - C_i\dot{x}_{i+1} \\ &- K_{i-1}x_{i-1} + \bar{K}_ix_i - K_ix_{i+1} \\ &= d_iL_i\dot{x}_{Gi} + k_iL_ix_{Gi} \end{aligned} \tag{6}$$

Note that Eqn. (6) is valid for any i-values except $i = 1$ and $i = n$ in which case the end-restraint springs are involved.

When $i = 1$, $\dot{x}_0$ and x_0, which do not exist, are replaced by $\dot{x}_{G0}$ and x_{G0} to obtain the equation of motion for the beginning pipe segment as:

$$\begin{aligned} &M_1\ddot{x}_1+(C_0+C_1+d_1L_1)\dot{x}_1-C_1\dot{x}_2+(K_0+K_1+k_1L_1)x_1-K_1x_2 \\ &= C_0\dot{x}_{G0}+d_1L_1\dot{x}_{G1}+K_0x_{G0}+k_1L_1x_{G1} \end{aligned} \tag{7}$$

Similarly, when $i = n$, $\dot{x}_{n+1}$ and x_{n+1}, which are not defined, will be replaced by $\dot{x}_{Gn+1}$ and x_{Gn+1}, and the equation of motion for the end pipe segment becomes:

$$\begin{aligned} &M_n\ddot{x}_n - C_{n-1}\dot{x}_{n-1} + (C_{n-1} + C_n + d_nL_n)\dot{x}_n \\ &- K_{n-1}x_{n-1} + (K_{n-1} + K_n + k_nL_n)x_n \\ &= C_n\dot{x}_{Gn+1} + d_nL_n\dot{x}_{Gn} + K_nx_{Gn+1} + k_nL_nx_{Gn} \end{aligned} \tag{8}$$

Combining Eqns. (6) to (8), the system of equations of motion for a pipeline of n-segments in matrix form will become:

$$\begin{aligned} &[M]\,\{\ddot{\underline{x}}\} + [C]\,\{\underline{x}\} + [K]\,\{\underline{x}\} \\ &= [d]\,\{\dot{\underline{x}}_G\}+[k]\{\underline{x}_G\}+[C']\{\dot{\underline{x}}_G'\}+[K']\{\underline{x}_G'\} \end{aligned} \tag{9}$$

where

$$\{\ddot{\underline{x}}\}=\underset{n\times 1}{\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \vdots \\ \ddot{x}_i \\ \vdots \\ \ddot{x}_n \end{Bmatrix}}; \quad \{\dot{\underline{x}}\}=\underset{n\times 1}{\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \vdots \\ \dot{x}_i \\ \vdots \\ \dot{x}_n \end{Bmatrix}}; \quad \{\underline{x}\}=\underset{n\times 1}{\begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_i \\ \vdots \\ x_n \end{Bmatrix}} \tag{10}$$

are the acceleration, velocity and displacement vectors of the pipeline system respectively. The system mass matrix is:

$$[M]=\underset{n\times n}{\begin{bmatrix} M_1 & & & & & \\ & M_2 & & & & \\ & & M_3 & & & \\ & & & \ddots & & \\ & & & & M_i & \\ & & & & & \ddots \\ & & & & & & M_n \end{bmatrix}} \tag{11}$$

the system damping matrix is:

$$[C]=\begin{bmatrix} \bar{C}_1 & -C_1 & & & & & \\ -C_1 & \bar{C}_2 & -C_2 & & & & \\ & -C_2 & \bar{C}_3 & -C_3 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & -C_{i-1} & \bar{C}_i & -C_i & \\ & & & & \ddots & \ddots & \ddots \\ & & & & & -C_{n-1} & \bar{C}_n \end{bmatrix}_{n \times n} \tag{12}$$

the system stiffness matrix is:

$$[K]=\begin{bmatrix} \bar{K}_1 & -K_1 & & & & & \\ -K_1 & \bar{K}_2 & -K_2 & & & & \\ & -K_2 & \bar{K}_3 & -K_3 & & & \\ & & \ddots & \ddots & \ddots & & \\ & & & -K_{i-1} & \bar{K}_i & -K_i & \\ & & & & \ddots & \ddots & \ddots \\ & & & & & -K_{n-1} & \bar{K}_n \end{bmatrix}_{n \times n} \tag{13}$$

and the ground velocity and displacement vectors are:

$$\{\dot{\underline{x}}_G\}=\begin{Bmatrix} \dot{x}_{G1} \\ \dot{x}_{G2} \\ \vdots \\ \dot{x}_{Gi} \\ \vdots \\ \dot{x}_{Gn} \end{Bmatrix}_{n \times 1}; \quad \{\dot{\underline{x}}'_G\}=\begin{Bmatrix} \dot{x}_{G0} \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ \dot{x}_{Gn+1} \end{Bmatrix}_{n \times 1}; \quad \{\underline{x}_G\}=\begin{Bmatrix} x_{G1} \\ x_{G2} \\ \vdots \\ x_{Gi} \\ \vdots \\ x_{Gn} \end{Bmatrix}_{n \times 1}; \quad \{\underline{x}'_G\}=\begin{Bmatrix} x_{G0} \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ x_{Gn+1} \end{Bmatrix}_{n \times 1} \tag{14}$$

the soil damping and spring matrices are:

$$[d]=\begin{bmatrix} d_1L_1 & & & & & \\ & d_2L_2 & & & & \\ & & d_3L_3 & & & \\ & & & \ddots & & \\ & & & & d_iL_i & \\ & & & & & \ddots \\ & & & & & & d_nL_n \end{bmatrix}_{n \times n}; \quad [k]=\begin{bmatrix} k_1L_1 & & & & & \\ & k_2L_2 & & & & \\ & & k_3L_3 & & & \\ & & & \ddots & & \\ & & & & k_iL_i & \\ & & & & & \ddots \\ & & & & & & k_nL_n \end{bmatrix}_{n \times n}$$

and

$$[C']=\begin{bmatrix} C_0 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ & & & \ddots & & \\ & & & & 1 & \\ & & & & & C_n \end{bmatrix}_{n \times n}; \quad [K']=\begin{bmatrix} K_0 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ & & & \ddots & & \\ & & & & 1 & \\ & & & & & K_n \end{bmatrix}_{n \times n} \tag{15}$$

EARTHQUAKE MOTION INPUTS

In order to study the seismic response of buried pipelines (governed by the equation of motion shown in Eqn. 9), the ground velocity and ground displacement time histories for every station must be known. As indicated earlier, the wave form is assumed to remain constant during the course of investigation, the earthquake motion vectors $\{\dot{\underline{x}}_G\}$ and $\{\underline{x}_G\}$ can be more realistically represented by incorporating a delay time, which is the time required for the seismic wave to travel from one segment to another. Accordingly, just one earthquake time history data is needed for the analysis.

The inputs of the time-space varying ground motions starting from the first end restraint are:

$$\left.\begin{aligned} \ddot{x}_{G0} &= A_{max}f(t) \\ \dot{x}_{G0} &= V_{max}g(t) \\ x_{G0} &= \Delta_{max}h(t) \end{aligned}\right\} \text{ for all } t \geq 0 \tag{16a}$$

$$\left.\begin{aligned} \ddot{x}_{G1} &= 0 \\ \dot{x}_{G1} &= 0 \\ x_{G1} &= 0 \end{aligned}\right\} \text{ for } t < t_{d,1} = \Delta T_1/2 \tag{16b}$$

$$\left.\begin{aligned} \ddot{x}_{G1} &= A_{max}f(t-t_{d,1}) \\ \dot{x}_{G1} &= V_{max}g(t-t_{d,1}) \\ x_{G1} &= \Delta_{max}h(t-t_{d,1}) \end{aligned}\right\} \text{ for all } t \geq t_{d,1}=\Delta T_1/2 \tag{16c}$$

$$\left.\begin{aligned} \ddot{x}_{Gi} &= 0 \\ \dot{x}_{Gi} &= 0 \\ x_{Gi} &= 0 \end{aligned}\right\} \text{ for } t < t_{d,i}=\sum_{j=1}^{i-1} \Delta T_j+\Delta T_i/2 \tag{16d}$$

$$\left.\begin{aligned} \ddot{x}_{Gi} &= A_{max}f(t-t_{d,i}) \\ \dot{x}_{Gi} &= V_{max}g(t-t_{d,i}) \\ x_{Gi} &= \Delta_{max}h(t-d_{d,i}) \end{aligned}\right\} \text{ for } t \geq t_{d,i}=\sum_{j=1}^{i-1} \Delta T_j+\Delta T_i/2 \tag{16e}$$

$$\left.\begin{aligned} \ddot{x}_{Gn+1} &= 0 \\ \dot{x}_{Gn+1} &= 0 \\ \dot{x}_{G_{n+1}} &= 0 \end{aligned}\right\} \text{ for } t<t_{d,n+1}=\sum_{j=1}^{n} \Delta T_j \tag{16f}$$

$$\left.\begin{aligned} \ddot{x}_{Gn+1} &= A_{max} f(t-t_{d,n+1}) \\ \dot{x}_{Gn+1} &= V_{max} g(t-t_{d,n+1}) \\ x_{Gn+1} &= \Delta_{max} h(t-t_{d,n+1}) \end{aligned}\right\} \text{for } t \geq t_{d,n+1} = \sum_{j=1}^{n} \Delta T_j \qquad (16g)$$

where A_{max}, V_{max}, Δ_{max} are expected maximum values of acceleration, velocity and displacement of seismic data. $\Delta T_i = L_i/V_{Si}$ is the delay time for a seismic wave traveling L_i-distance of pipe, V_{Si} = wave velocity of soil surrounding i^{th} segment of the pipeline.

SIMPLIFIED QUASI-STATIC ANALYSIS MODEL

The system of dynamic equations developed in the previous sections involved inertia and damping effects, which, together with the time delay effect in ground excitations, become an extremely tedious problem to solve. In terms of computing time, it is a very expensive task. Furthermore, it is very difficult, if not impossible, at this time to obtain reasonably accurate values for the equivalent mass and damping coefficients for the system.

For general design purposes, it is desirable that the design procedure be simple and the analysis be economically feasible, yet reasonably correct. For this reason, we need a simple model which will provide results similar to the exact model for the same problem.

In recent years, several investigations (8,10, 11, 16) done in Japan, indicated that dynamic effects are not significant in the behavior of underground piping systems. In view of this information, we will convert the dynamic model into a simple quasi-static problem by neglecting the $\{\ddot{\underline{x}}\}$, $\{\dot{\underline{x}}\}$ and $\{\underline{x}_G\}$ terms. For simplicity, we assume equal pipe segment length in the analysis model. The system of equations becomes:

$$[K]\ \{\underline{x}\} = [k]\ \{\underline{x}_G\} + [K']\ \{\underline{x}'_G\} \qquad (17)$$

in which [K] is a tridiagonal-symmetrical matrix, [k] and [K'] are diagonal matrices. Or in extended form, the governing equations of equilibrium are as follows:

$$\underset{n \times n}{\begin{bmatrix} \bar{K}_1 & -K_1 & & & \\ -K_1 & \bar{K}_2 & -K_2 & & \\ & \ddots & \ddots & \ddots & \\ & -K_{i-1} & \bar{K}_i & -K_i & \\ & & \ddots & \ddots & \\ & & -K_{n-1} & & \bar{K}_n \end{bmatrix}} \underset{n \times 1}{\begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_i \\ \vdots \\ x_n \end{Bmatrix}} = \underset{n \times n}{\begin{bmatrix} k_1L & & & \\ & k_2L & & \\ & & \ddots & \\ & & k_iL & \\ & & & \ddots \\ & & & & k_nL \end{bmatrix}} \underset{n \times 1}{\begin{Bmatrix} x_{G1} \\ x_{G2} \\ \vdots \\ x_{Gi} \\ \vdots \\ x_{Gn} \end{Bmatrix}}$$

$$+ \underset{n \times n}{\begin{bmatrix} K_0 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ & & & \ddots & & \\ & & & & 1 & \\ & & & & & 1 \\ & & & & & & K_n \end{bmatrix}} \underset{n \times 1}{\begin{Bmatrix} x_{G0} \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ x_{Gn+1} \end{Bmatrix}} \qquad (18)$$

Note that the ground displacement vectors, $\{x_G\}$ and $\{x'_G\}$ are constantly changing from one instant to another due to the delay time effect although the wave form remains unchanged.

For simplicity, we further assume a constant delay time, DT for the seismic wave traveling from one segment to another in a given system. Using the first pipe segment as the time reference, the input ground displacement vectors can be defined as follows:

$$\{\underline{x}_G\} = \begin{Bmatrix} x_{G1} \\ x_{G2} \\ \vdots \\ x_{Gi} \\ \vdots \\ x_{Gn} \end{Bmatrix} = \Delta_{max} \begin{Bmatrix} h(t) \\ h(t-DT) \\ \vdots \\ h(t-[i-1]DT) \\ \vdots \\ h(t-[n-1]DT) \end{Bmatrix} \qquad (19a)$$

$$\{\underline{x}'_G\} = \begin{Bmatrix} x_{G0} \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ x_{Gn+1} \end{Bmatrix} = \Delta_{max} \begin{Bmatrix} h(t + \frac{1}{2} DT) \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \\ h(t-[n - \frac{1}{2}]DT) \end{Bmatrix} \qquad (19b)$$

Now, let us define the following parametric constants for the quasi-static analysis:

1) Normalized Joint Spring Parameters

$$\alpha_i = K_i/k_iL \quad ; \quad i = 1 \text{ to } n-1 \qquad (20)$$

2) Normalized End Restraint Spring Parameters

$$\gamma_0 = K_0/k_1L \qquad (21a)$$

$$\gamma_n = K_n/k_nL \qquad (21b)$$

3) Soil Resistant Spring Ratios

$$\beta_i = k_i/k_1; \quad i = 1 \text{ to } n \qquad (22)$$

Substituting these parameters [Eqns. (20) to (22)] into Eqn. (18), the system of the governing equation becomes:

$$\begin{bmatrix} (\gamma_0+\alpha_1+1) & -\alpha_1 & & & \\ -\alpha_1 & (\alpha_1+\alpha_2\beta_2+\beta_2) & -\alpha_2\beta_2 & & \\ & \ddots & \ddots & \ddots & \\ & -\alpha_{i-1}\beta_{i-1} & (\alpha_{i-1}\beta_{i-1}+\alpha_i\beta_i+\beta_i) & -\alpha_i\beta_i & \\ & & \ddots & \ddots & \\ & & -\alpha_{n-1}\beta_{n-1} & (\alpha_{n-1}\beta_{n-1}+\gamma_n\beta_n+\beta_n) & \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_i \\ \vdots \\ x_n \end{Bmatrix}$$

$$= \begin{bmatrix} 1 & & & & \\ & \beta_2 & & & \\ & & \ddots & & \\ & & & \beta_i & \\ & & & & \ddots \\ & & & & & \beta_n \end{bmatrix} \begin{Bmatrix} x_{G1} \\ x_{G2} \\ \vdots \\ x_{Gi} \\ \vdots \\ x_{Gn} \end{Bmatrix} + \begin{bmatrix} \gamma_0 & & & \\ & 1 & & \\ & & \ddots & \\ & & & 1 \\ & & & & \gamma_n\beta_n \end{bmatrix} \begin{Bmatrix} x_{G0} \\ 0 \\ 0 \\ \vdots \\ 0 \\ x_{Gn+1} \end{Bmatrix} \qquad (23)$$

in which all elements in the matrices are dimensionless quantities. It is interesting to note that this governing equation for the analysis of buried pipelines does not involve pipe segment length variable, L, since its effect has been built into the relative values of α, β, and γ. Furthermore, the effects of pipeline length can be studied by varying the number of segments and the magnitude of DT used in the analysis.

For the analysis, the following special cases of α, β and γ are studied:

1) Pipeline buried in uniform soil environment,

$$\beta_2 = \beta_3 = \ldots \beta_i = \ldots \beta_n = 1 \qquad (24)$$

2) Pipeline without end-restraints

$$\gamma_0 = 0 \quad \text{and} \quad \gamma_n = 0 \tag{25}$$

3) Pipeline with uniform joint construction

$$\alpha_1 = \alpha_2 = \ldots \alpha_i = \ldots = \alpha_{n-1} = \alpha \tag{26}$$

which is assumed to be the case in this paper. As indicated earlier, the joint resistance is much smaller than the soil resistance along a pipe segment, thus α in general will be a small quantity even though the effects of α are studied parametrically.

METHOD OF SOLUTION

Since the system of governing equations shown in Eqn. (23) for the quasi-static analysis model involves only symmetrically tridiagonal and diagonal matrices, it is more efficient and advantageous to convert [K] into an upper triangular matrix by eliminating the subdiagonal elements. The system can then be solved directly by backward substitution (3). This scheme, which eliminates matrix inversion, reduces computer storage, and has less truncation error.

The response of the pipe-segment x_i's were computed at each time step for the whole time-history of the input earthquake record. These responses were then used to determine the following two parameters:

$$Y_i = x_i - x_{Gi} = x_i(t) - x_G(t-[i-1]DT); \quad i=1 \text{ to } n$$

$$U_i = x_i - x_{i+1} \tag{27}$$

where

Y_i : is the relative displacement between the ground and the pipe-segment i.

U_i : is the extension/contraction of ith joint spring between two adjacent pipe-segments.

These two parameters enable us to deduce the general response behavior of the pipeline under a certain earthquake record and other prescribed conditions.

Note that a computer program for the simplified quasi-static analysis of buried pipelines has been written and reported by Cheng (1), this paper only presents the important results/conclusions without details. Since the seismic failure criteria of buried pipelines will be reported later (19) this paper discusses only the elastic response behavior.

Computations were made for various conditions by varying the value of different parameters, such as the time delay, the number of pipe-segments used, the soil/joint spring stiffness parameters, the end restraint coefficients, and the relative soil resistant ratios, etc. The computer program finds the maximum values of Y and U for each condition and subsequently outputs Y_{max} and U_{max} and the time and location when the maximum Y and U occur.

RESULTS/DISCUSSION

Two sets of real earthquake records, $x_G(t)$ were used. They are the El Centro May 18, 1940 S90W component and S00E component, whose displacement time history records are shown in Figs. 5 and 6 respectively.

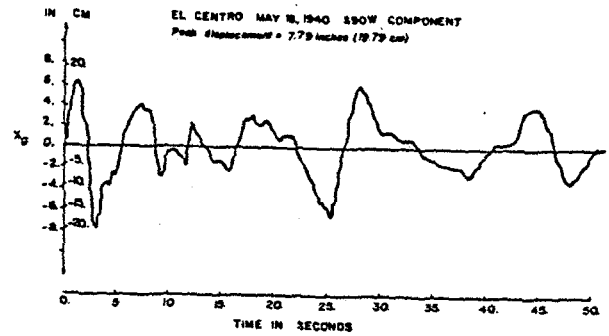

Fig. 5 Referenced Ground Displacement Input

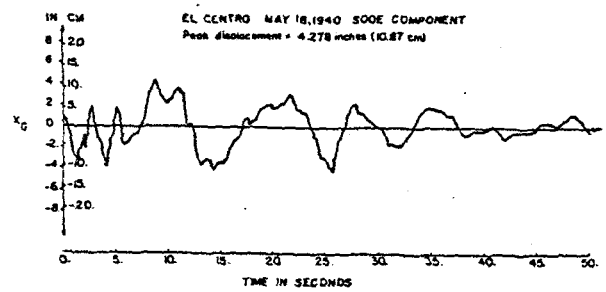

Fig. 6 Typical Ground Displacement Input

To establish a basis for comparison of the seismic response behavior of buried pipelines for various parameters, the following conditions are arbitarily set as the 'reference conditions':

Number of masses	: M = 6
End restraint conditions	: None, i.e. γ_0=0 and γ_n=0
Soil conditions	: Uniform, i.e. β = 1,1,1,1,1,1
Delay time	: DT = 0.1 Second
Seismic input	: El Centro May 18, 1940 S90W Component

Note that the seismic response behavior of buried pipelines presented in this paper are limited to the maximum relative displacements between the pipe segment and the ground, Y_{max}, and between pipe segments themselves, U_{max} (for the rigid pipe segment assumption, U_{max} represents the joint spring elongation/shortening conservatively) for various joint spring constants.

For the evaluation of the effects of a particular parameter to the response behavior, Y_{max} and U_{max}, only that parameter will be varied from the above mentioned referenced conditions.

Effect of Joint Stiffness

The results of the relative displacements between pipes, U_{max} and the relative displacements between pipes and their surrounding soil, Y_{max} against normalized joint spring stiffness, α are shown in Fig. 7 and Fig. 8 respectively.

One can see from Fig. 7 that the relative displacement between pipe segments, U_{max}, (i.e. the indication of joint extension or contraction) is about 1.4 inches (3.56 cm) for small joint stiffness (low α value) and decrease asymptotically approaching zero as α increases toward infinity. On the other hand, Fig. 8 shows that the relative displacement between the pipe segment and ground, Y_{max} is very small when α is

small and increases tremendously as α increases beyond 0.1. The low Y_{max} quantity for small α values agrees well with the observations by the investigations (8, 10,11,14,16) in Japan. Thus, for further discussions, the joint stiffness parameter has been limited to less than 0.1.

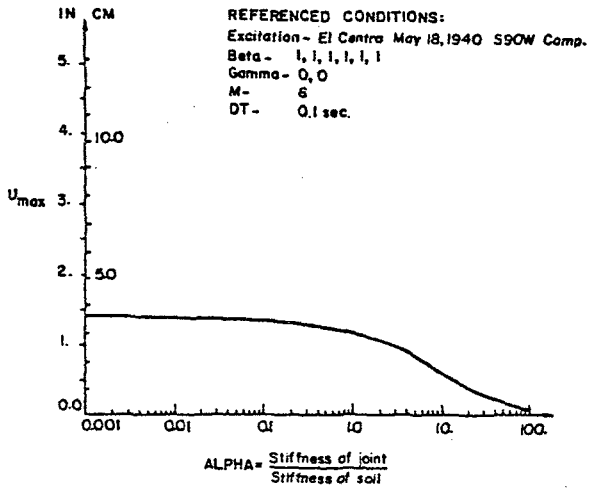

Fig. 7 U_{max} vs α Under Referenced Conditions

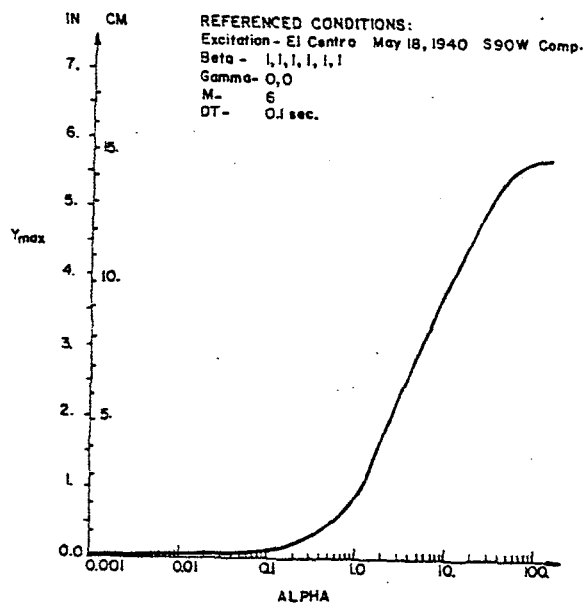

Fig. 8 Y_{max} vs α Under Referenced Conditions

Effect of Non-uniformity of Surrounding Soils

The objective of this study is to verify the statement that the earthquake damage of buried pipelines was higher in regions of transition from one soil type to another as reported by Kubo et al (9).

The effects of variation of the soil conditions for a pipeline on U_{max} and Y_{max} are shown in Figs. 9 and 10.

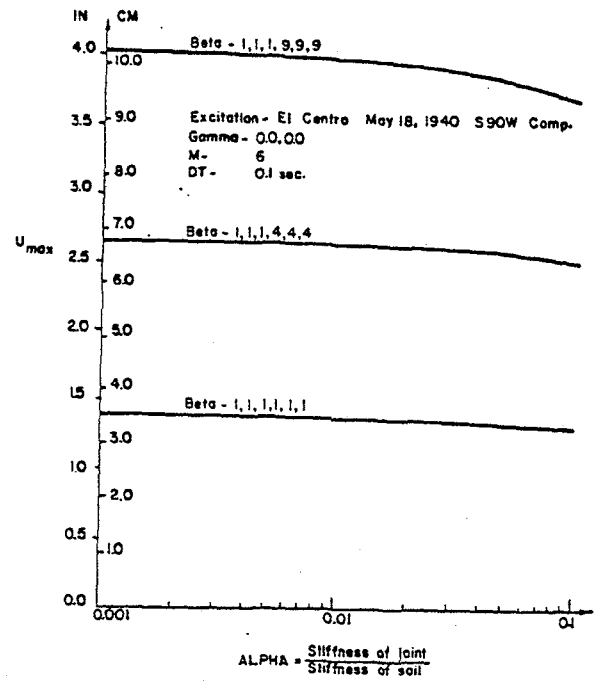

Fig. 9 Effect of Non-Uniformity of Soil on U_{max}

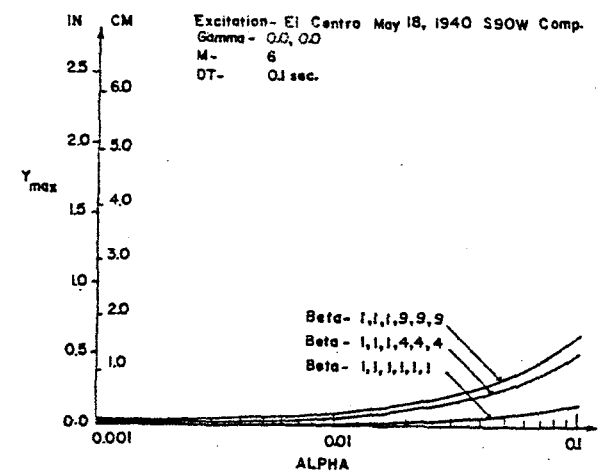

Fig. 10 Effect of Non-Uniformity of Soil on Y_{max}

In these two figures, the bottom curve, denoted by BETA = 1,1,1,1,1,1, represents the case of uniform soil condition. The middle curve denoted by BETA = 1,1,1,4,4,4 represents the effect of soil stiffness surrounding the last three pipe segments which is 4 times greater than those surrounding the first three pipe segments. The top most curve, denoted by BETA = 1,1,1,9,9,9, represents the effect for even higher relative difference in soil stiffness in two regions. These curves indicate a considerable increase in U_{max} values as the soil is changed from a uniform condition to a non-uniform condition. Thus, Kubo's observation is verified.

Effect of Delay Time

The delay time of seismic waves traveling from one pipe segment to another is determined by two

variables. One is the length of the pipe segment and the other is the seismic propagation velocity which is related to the soil stiffness. Thus, one can interpret the increase of delay time as an increase in pipe segment length or by a decrease in soil stiffness.

By changing the delay time, DT, from the 'reference conditions', the effects of DT on U_{max} and Y_{max} are shown in Figs. 11 and 12. Apparently, the role of DT is to cause a magnification in both U_{max} and Y_{max}. This result is quite consistent with the observations by Kachadoorian (5) who reported that pipelines in soft soil (longer delay time) experienced more damage during an earthquake than pipelines in firm soil.

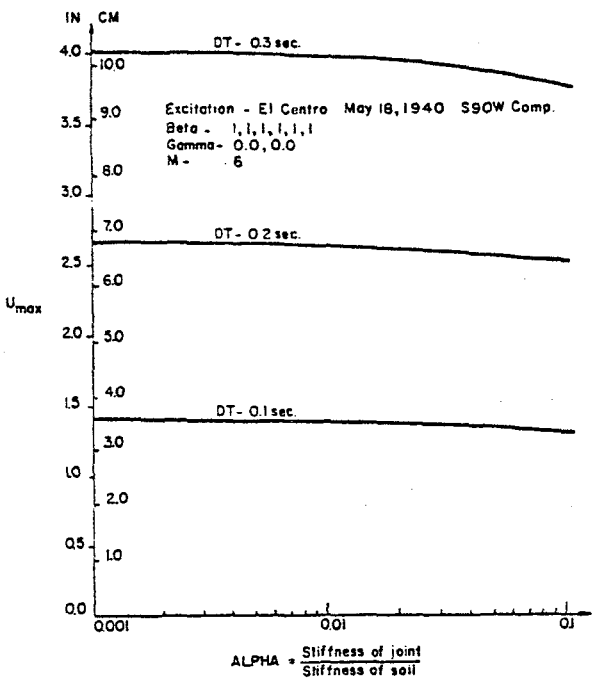

Fig. 11 Effect of Delay Time on U_{max}

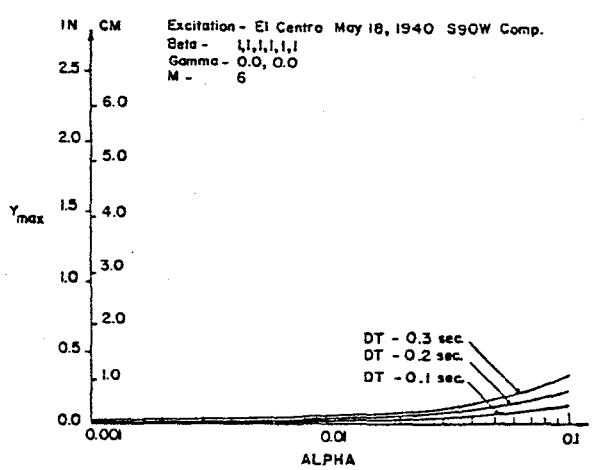

Fig. 12 Effect of Delay Time on Y_{max}

Effect of End Restraints

The effect of end restraints of a pipeline represents the effect of an intersection/junction of a pipeline with a building, a pumping station or another pipeline. They are defined by a γ quantity at ends (i.e., $\gamma_0 = K_0/k_1L$ and $\gamma_n = K_n/k_nL$). The effects of end restraints with γ-value ranging from zero (free end) to unity (equivalent to the same soil resistance along a pipe segment) on U_{max} and Y_{max} are shown in Figs. 13 and 14.

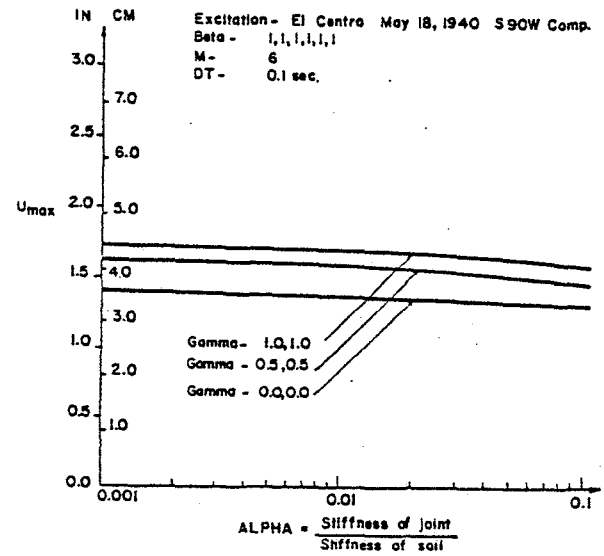

Fig. 13 Effect of End Restraints on U_{max}

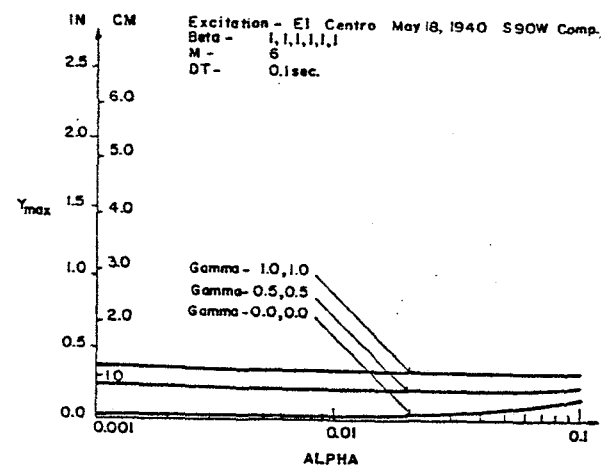

Fig. 14 Effect of End Restraints on Y_{max}

One can see from these figures that the higher the end restraints are, the larger the relative displacements, U_{max} and Y_{max}, will be. However, one can easily observe that such increases of U_{max} are not as high as those influenced by the changing of soil uniformity or delay time. On the other hand, the increase of Y_{max} is much higher than those influenced by β and DT values.

Effect of Pipeline Length

Although the effect of pipeline length may be

studied by the effect of delay time described earlier, however, for a common delay time between segments, the study of the effect of pipeline length would be more representative by varying the number of segments in the analysis model.

By varying M from 4 to 12, the results of U_{max} and Y_{max} are given in Figs. 15 and 16. From these two figures, one finds that there are almost no changes of U_{max} and Y_{max} values for $\alpha < 0.1$.

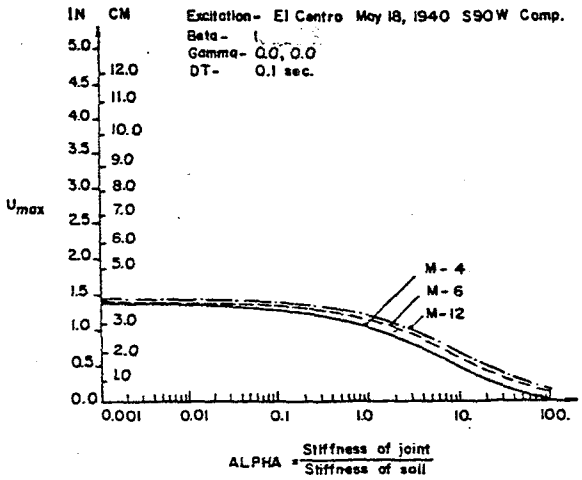

Fig. 15 Effect of Pipeline Length on U_{max}

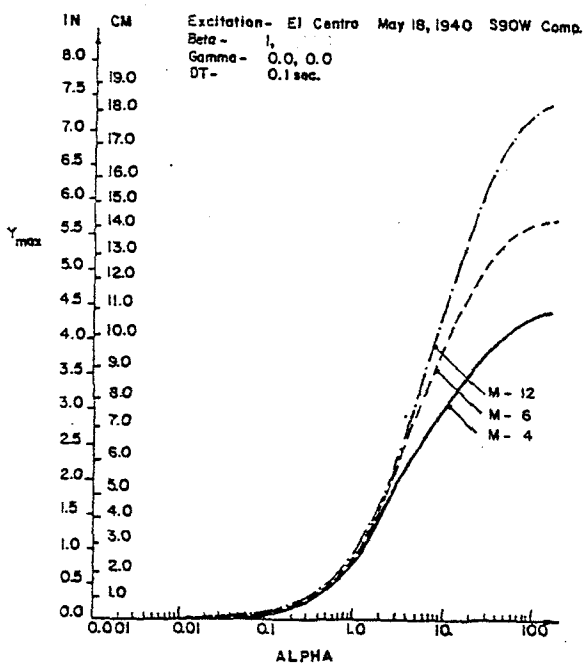

Fig. 16 Effect of Pipeline Length on Y_{max}

From these observations, one may conclude that the seismic response behavior of a long buried pipeline may be studied by a quasi-static model consisting of 4 segments or more.

Effect of Seismic Wave Forms

In this case, two El Centro May 18, 1940 records, the S90W component and S00E component were used with the maximum displacement for each case normalized to unity as shown in Fig. 17. Obviously, the response of a buried pipeline is dependent on the magnitude of the ground excitation. The purpose of the normalization of ground waves is to eliminate the absolute value comparisons. Thus, the effect of wave forms can be evaluated.

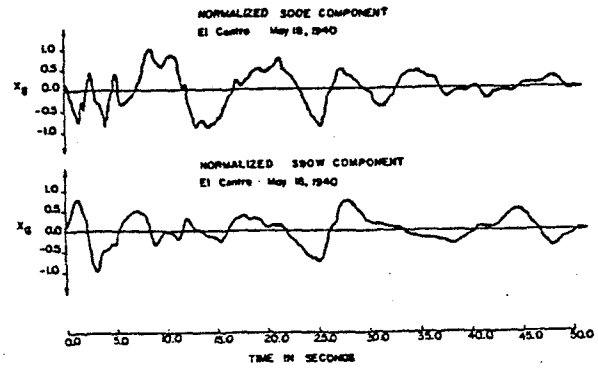

Fig. 17 Normalized Ground Displacement Input

The results of U_{max} and Y_{max} of a common 'reference' buried pipeline model subjected to two normalized ground waves are given in Fig. 18 and Fig. 19.

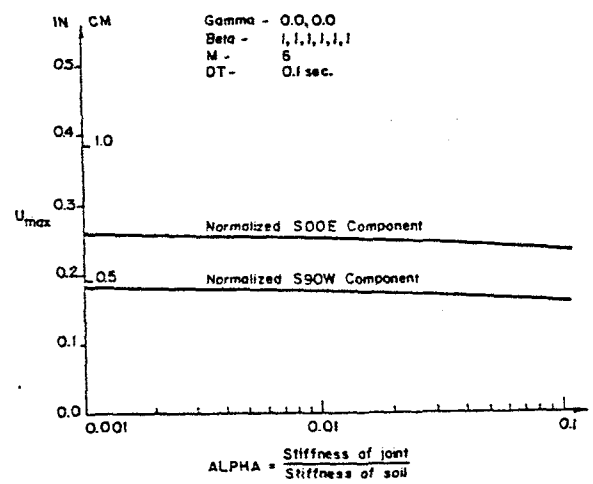

Fig. 18 Effect of Wave Form on U_{max}

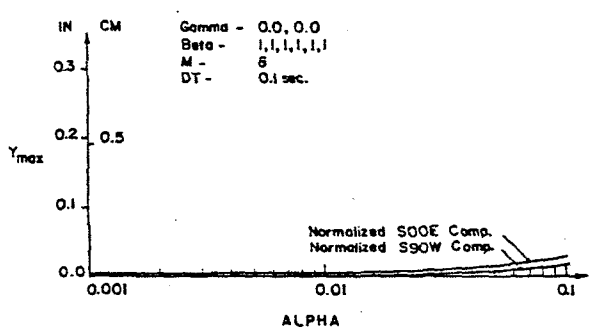

Fig. 19 Effects of Wave Form on Y_{max}

From these two figures, the response of U_{max} and Y_{max} seem to be a little higher under the S00E component than those under the S90W component. One

possible explanation is that the S00E component exhibits several cycles of peaks at $\pm$ 1 values while the S90W component experienced only one peak at the earlier stage. One may conclude that for the same maximum ground displacement, the seismic wave form with more cycles of the same peak will have higher effects on the response behavior. However, more research is required to study the true effect of wave forms.

SUMMARY AND CONCLUSIONS

The proposed simplified quasi-static analysis model seems capable of evaluating the general longitudinal response behavior of buried pipelines subjected to seismic shakings/vibrations. Parametric studies involving such important parameters as joint stiffness, uniformity of soil condition, delay time, end constraints, pipeline length and wave forms have been performed. The following general concluding remarks can be made:

1. Higher joint stiffness will produce larger relative displacements between pipe segments and between pipe segments and the ground. For low joint stiffness, the relative displacement between pipe segments and the ground is very small, which agrees with the general field observations.
2. The effects of non-uniformity of soil environments and the delay time are the two most important influential parameters on the response behavior of buried pipelines. For uniform soil, the longer the delay time or the softer the soil stiffness, the larger the differences the transition of one type of soil to another, the higher the response will be.
3. The effect of end restraints is also observed, but such an effect is not as large as those caused by non-uniformity of soil and the variation of delay time.
4. For a pipeline consisting of pre-fabricated segments, a model involving 4 or more segments will be accurate enough to determine its response behavior.
5. As to the effect of the seismic wave form, it is found that a wave form which has more cycles of maximum peaks seems to yield large response values. More research in this area is recommended.

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