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# Buried pipeline system in a liquefaction environment

L.R.L.Wang
*Old Dominion University, Norfolk, Va., USA*
H.Zhang
*Bridge Division of WSDOT, Olympia, Wash., USA*

ABSTRACT: A parametric study on the general seismic response behavior of buried pipeline systems during a soil liquefaction process has been initiated at Old Dominion University, Virginia, USA. The purpose of this research is to study the effects of several important parameters including pipe diameter, buried depth, additional mass and the size of liquefied soil zone during a soil liquefaction process. Pipeline systems could be cross-type, T-type, Y-type or straight pipelines, with or without a manhole, and are buried in a soil liquefiable zone. Time varying soil's spring constants during the liquefaction process are used. The nonlinear damping of the soil surrounding the pipe includes geometric damping and material damping. The pipe body is assumed to be elastic.

A computer program based on finite element method has been developed. Modal superposition method is used to solve the equations of motion of the pipeline. The required eigenvalues and eigenvectors are calculated by subspace interactions. A few uncoupled modal equations of motion are solved by step-by-step numerical integration method. This paper presents the formulation, background, verifications and results of simple systems.

## *Introduction*

Buried pipelines have been damaged heavily by recent earthquakes including the 1989 Loma Prieta earthquake. Field observations showed that there are three major causes of damage to buried pipelines during earthquakes: soil liquefaction, fault movement and seismic ground shaking. Soil liquefaction has been one of the major causes to the damage of buried pipelines. The damage investigations have revealed that a damage ratio of pipelines (Number of breaks/per km) has much larger values in liquefied grounds compared with one in shaking ground without liquefaction according to damage statistics during past severe earthquakes as report by Takada and Tanabe (1984), and particularly at pipeline intersections with a heavy structure.

In 1986, the response behavior of buried pipelines under a soil liquefaction environment induced by seismic shaking has been studied experimentally by Kuribayashi et al.(1986) and earlier analytically by Yeh and Wang (1985). However, only preliminary results for a straight pipeline have been obtained.

The exact response of a buried pipeline system including manholes during a soil liquefaction process is complex and the complete solution for such complex system has not been found. To verify analytically the experimental study of buried pipeline with and without a manhole under a soil liquefaction environment by Kuribayashi et al.(1986), Wang et al. (1990) published a paper on dynamic responses of buried pipelines during a liquefaction process using simple Rayleigh-Ritz method. Although the results for verification purposes were considered satisfactory, the paper recommended that a finite element analysis including soil-structure-fluid interaction effects and a more realistic damping value be carried out.

As currently reported by Miyajima and Kitaura (1991),Yeh and Wang (1991), several papers on the similar subject can be found in Japanese literatures. However, most of them discussed the performance and behavior from observations or from static analysis involving a complete soil liquefaction environment, but not during liquefaction process.

Since there is no general dynamic solution for buried pipeline systems during a soil liquefaction process, this paper focuses on the development of a rigorous analysis coupled with a computer program based on finite element method to study the seismic response of buried pipeline system during soil liquefaction process. Pipeline systems could be straight pipeline or "T", "Y", Cross-type, with or without manhole. Both geometric and material damping of surrounding soils are included.

## System Model and Assumptions

The system model, as shown in Figure 1, is essentially the same as the model without soil liquefaction previously proposed by Wang and Lau (1989) except that there is a soil liquefiable zone within the studied area and the pipeline systems may include manholes. It consists of mains and branches of the buried pipeline system. For each pipe element, it is bonded by the continuous axial ($K_{sa}$) and lateral ($K_{sl}$) soil springs, which may vary with time during soil liquefaction process.

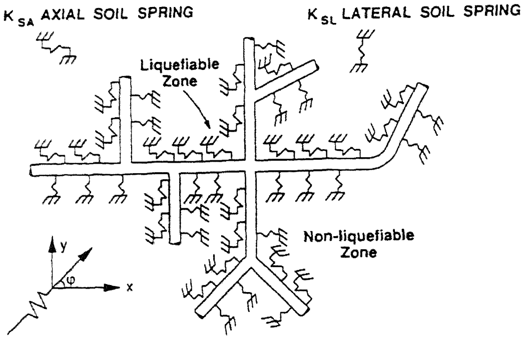

Figure 1. Buried Pipeline System

Since buoyancy force in soil liquefaction process can be treated as a static force and separated from the response in the horizontal plan, the system is subject to a horizontal ground shear wave, with a traveling speed $V_s$, at an incident angle $\phi$, with respect to the x-axis. With this simplification, the system may be considered as a plane frame with members surrounded by time varying elastic springs from the structural analysis point of view. In the finite element model, lumped mass and lumped damping are used, however, commonly known consistent stiffness are used for soil and pipe elements. Another assumption is that the pipe body is considered elastic at all time.

## Finite Element Formulation

Using energy method, the equations of motion can be established as follows:

$$\begin{aligned}&[M_t]_{nxn}\{\ddot{v}(x,t)\}_{nx1}+[C_t]_{nxn}\{\dot{v}(x,t)\}_{nx1}+\\&[K_t]_{nxn}\{v(x,t)\}_{nx1}=-[M_t]_{nxn}\{\ddot{v}_g(x,t)\}_{nx1}\\&\qquad -[K_p]_{nxn}\{v_g(x,t)\}_{nx1}\end{aligned} \qquad (1)$$

Where $[M_t]$, $[C_t]$, $[K_t]$ are total mass, damping and stiffness matrices of pipeline system: $v(x,t)$, $\dot{v}(x,t)$, $\ddot{v}(x,t)$ are the relative displacement, velocity and acceleration of pipeline system with respective to the ground, and $v_g(x,t)$, $\ddot{v}_g(x,t)$ are ground displacement and acceleration. Please note that the total mass, damping and stiffness are defined as follows:

$$[M_t]=[M_p]+[M_a] \qquad (2)$$

$$[C_t]=[C_g]+[C_m] \qquad (3)$$

$$[K_t]=[K_p]+[K_s] \qquad (4)$$

Where $[M_p]$, $[M_a]$ are mass matrices of pipeline and added soil mass that moved with the pipe; $[C_g]$, $[C_m]$ are geometric and material damping matrices of the soil and $[K_p]$, $[K_s]$ are pipe and soil stiffness matrices. These matrices are discussed below:

(1) **Mass Matrix** - The mass matrix is composed of pipe mass and additional soil mass. Pipe mass includes the mass of pipe body and water inside. During an earthquake, some amount of soil surrounding pipeline system will move with the pipeline together. This amount of soil is called added or effective soil mass. Parmelee et al. (1975) pointed out that the added soil mass increases rapidly from low buried depth to radius ratio, but approaches almost constant when the ratio is greater than 18. The formula given by Parmelee et al. (1975) is:

$$M_a=\xi(\alpha)\rho_{soil} \qquad (5)$$

where $\alpha$ is ratio of depth/radius; $\rho$, density of the soil medium; $\xi$, non-dimensional function of $\alpha$

In this paper, added soil mass is defined as:

$$[M_a]=\beta[M_p] \qquad (6)$$

and $\beta$ will be used for parametric study.

(2) **Damping Matrix** — As discussed earlier, damping matrix of soil can be divided into geometric damping and material damping. Gazata et al. (1987) studied the geometric damping of embedded foundations and derived a series of formulations to calculate the value of geometric damping. Buried pipelines are similar to embedded foundations, except having more contact surface with the soil for given base dimension. With a little revision, Gazata's formulations are used in this study.

The axial geometric damping, $C_a$ and lateral geometric damping $C_l$ can be calculated as following. If x is the axial direction of pipeline and y is lateral direction in horizontal plane, then the axial geometric damping $C_a = C_x$ and the lateral geometric damping $C_l = C_y$ can be expressed in a single equation below:

$$C_{x,(y)} = [\rho_{soil} \cdot V_s \cdot (A_T + A_B)] \cdot \tilde{C}_{x,(y)} + (\rho_{soil} \cdot V_s \cdot A_s) + (\rho_{soil} \cdot V_{ce} \cdot A_{ce}) \tag{7}$$

where $\tilde{C}_{x,(y)}$ are function of $A_o$, $\frac{L}{B}$, ν and

$$A_o = \frac{\omega B}{V_s} \tag{8}$$

where, L is half length of pipeline; B, radius of pipeline; ω, dominate frequency of earthquake; ν, Poissions ratio; $\rho_{soil}$, density of soil; $V_s$, velocity of shear wave; $A_T$, top area of pipeline; $A_B$, bottom area of pipeline; $A_s$, one side area of pipeline perpendicular to x(y); $A_{ce}$, one side area of pipeline parallel to x(y); $V_{ce}$, "Lysmer's analog" velocity as is defined as $V_{ce} = 3.4 \times V_s/\pi(1-\nu)$. For $C_x$ calculation, $A_{ce} = 0$ while for $C_y$, $A_s = 0$.

Since the velocity of S-wave can be calculated as proposed by Bolt (1988) as $\sqrt{\frac{\mu}{\rho}}$, (where $\mu$ is the modules of rigidity of soil and $\rho$ is the density of the surrounding soil), at full soil liquefaction stage $\mu = 0$, $V_s = 0$ therefore the geometric damping of the soil is zero at the liquefied zone.

Material damping of soil is a function of shear strain but is frequency independent practically. Ishibashi (1981) proposed a formulas for calculating the material damping ratio $\xi_m$ for sands as follows:

$$\xi_m = 0.195\left(\frac{G_{eq}}{G_{max}}\right)^2 - 0.515\frac{G_{eq}}{G_{max}} + 0.333 \tag{9}$$

$G_{eq}$ is shear modules at time t during liquefaction process; $G_{max}$, maximum shear modules before earthquake; $\xi_m$, material damping ratio of an element. When t = o, $G_{eq} = G_{max}$, $\xi_m = 0.013$; and $t = t_L$ $G_{eq} = o$, $\xi_m = 0.333$. Where t is time after seismic wave reaches pipeline; $t_L$ is total time of earthquake to cause liquefaction, then,

$$C_m = \xi_m x C_c, \quad and \quad C_c = 2M\omega \tag{10}$$

Where ω = natural frequency of pipeline calculated from mass and stiffness matrices. The total damping matrix becomes $[C_t] = [C_g] + [C_c] \times \xi_m$. Where; $[C_t]$, $[C_g]$, $[C_c]$ are the total damping matrix, geometric damping and material damping of an element. When soil is fully liquefied, $[C_g] = 0$ and $\xi_m$ = 0333, therefore $[C_t] = 0.333[C_c]$.

(3) **Stiffness Matrix** - To develop the stiffness matrix for a buried pipe element, a beam on an elastic foundation is assumed by Wang (1978). The stiffness matrix of a pipe element can be obtained from the commonly used beam stiffness.

If we define $k_a$ the axial spring constant, and $k_L$, lateral spring constant of soil, the stiffness matrices of soil corresponding to a pipe element length can be obtained from Wang's paper(1978). Note that $k_a$ is the friction type spring constant which depends on shear modules G, while $k_L$ is the compression type spring depending on Young's modules E. There are many suggestions to calculate $k_a$ with G as described by Trautmann et al. (1983). In this study $k_a = 1.65$ G is used. Using Parmelee's formulation and elastic theory (1975), and considering that $k_L$ related to diameter while $k_a$ to circumference, the following relationship is used:

$$k_L = 0.544\ k_a \tag{11}$$

During an earthquake, $k_L$ is a function of time t in soil liquefaction process. According to Seed et al. (1976), the pore water pressure build-up is a function of time t during soil liquefaction process, therefore the effective pressure of soil $\bar{\sigma}$ is also a function of time t and can be approximately determined as follows:

$$\bar{\sigma}(t) = \bar{\sigma}_o \left\{\frac{1}{2} - \frac{1}{\pi}\arcsin[2(\frac{t}{t_L})^{\frac{1}{\beta}} - 1]\right\} \tag{12}$$

Where $\bar{\sigma}_o$, is initial soil overburden pressure, and $\bar{\sigma}$, effective confining pressure of soil at time t. Using the experimental data given by R.G. Hicks (1970).

$$\log E_s(t) = \log 9 + 0.54 \log \bar{\sigma}(t) \quad (in\ psi) \tag{13}$$

Finally, using the relationship, $K_L(t) = \tau(\alpha)\ E_s(t)$ given by Parmelee(1975), following $k_L(t)$ function has been obtained:

$$k_L(t) = 9.0 \cdot \gamma(\alpha) (\bar{\sigma}_o\{0.5 - arcSin[2.0 \cdot (\frac{t}{t_L})^{\frac{1}{\beta}} - 1.0]/\pi\})^{0.54} \tag{14}$$

when t=o, $k_L(o) = 9.0 \times \gamma(\alpha) \times \bar{\sigma}_o$ and $t = t_L$, $k_L(t_L) = 0$

In this study, when $t \geq t_L$, a residual value, $k_L(t) = k_L(o)/3000.0$ is used as suggested by Takada (1987). During soil liquefaction process, the mass matrix, damping matrix and stiffness matrix will change with time. Schematically, the time varying soil stiffness is shown in Figure 2 below:

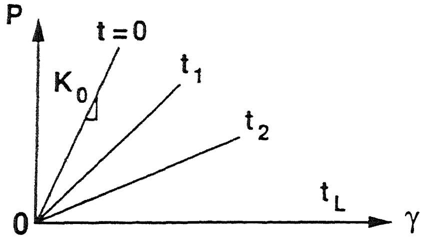

Figure 2. Time Varying Soil Stiffness

## Methods of Solution

Because of the assumptions used, the system of equations can be solved by the so-called modal superposition method. The element mass, damping and stiffness matrices will be transformed and assembled into global coordinates. With subspace iteration method, a few (say p) eigenvalues and their associated eigenvectors can be obtained. The size of the matrices in the equations of motion can be reduced to pxp. These p equations correspond-ing p modes are uncoupled because of the lumped damping. Each modal equation can be solved by step-by-step numerical integration method independently. The final solution is obtained by summing up the modal contributions. The details of the method of solution will be given in Zhang's dissertation (in progress). This paper gives only brief discussion of the methods of solution.

## Verifications

Before using the developed computer program to study the response behavior of buried pipeline systems during liquefaction process, verifications of the developed program in simple cases with known solutions would be needed to ensure its correctness and accuracy. Two cases are reported; one is on the frequencies of beams on an elastic foundation without liquefaction and the other is the comparison of the response results of a buried pipe experiment by Kuribayashi et al. (1986) and subsequent analytical study by Wang et al. (1990).

**(1) Frequencies and Mode Shapes of Beams on an Elastic Foundation.** The frequencies and mode shapes of several steel pipes, 60 cm in diameter, 1 cm thick and 100 meters long with and without buried soils under various boundary conditions (fixed, free, simply supported, etc.) have been studied using the developed program. The lateral soil resistance is 927 kg/cm$^2$ and the specific weight of 7.9g/cm$^3$ for steel is used.

The first four modes (flexural modes) of beams with and without soil stiffness have been verified with known results. The comparisons of frequencies for the present study for beams with and without soil with known solutions by Clough and Penzien (1975) and Wang(1978) are given Table 1 below:

**Table 1 Comparison of Frequencies of Beams**

| Mode | | 1st | 2nd | 3rd | 4th |
|---|---|---|---|---|---|
| with -out soil | This Study | 0.222 | 0.612 | 1.200 | 1.983 |
| | Clough [2] | 0.225 | 0.625 | 1.2241 | 2.024 |
| | Diff. % | -1.26 | -2.06 | -2.04 | -2.04 |
| with soil | This Study | 73.014 | 73.0170 | 73.0244 | 73.042 |
| | Wang[14] | 73.014 | 73.0168 | 73.0241 | 73.041 |
| | Diff. % | 0 | +0.0002 | 0.0003 | 0.0007 |

One can see from the above table that the calculated frequencies are very close to the known solutions for both with soil and without soil cases. It is interesting to note that the mode shapes for cases with and/or without soil are almost identical because of the elastic Winkler's soil spring assumption made by Vallabhan & Das (1989).

**(2) Comparison to a Buried Pipeline Experiment** - An experimental shaking table research on the responses of buried pipeline including a manhole was carried out in saturated sand by Kuribayashi et al. A simple analytical solution based on Rayleigh-Ritz method has been reported by Wang et al.(1990) for comparisons. Using the computer program developed, an analysis for the buried pipe with and without a manhole has been performed for comparison purposes. The time responses of the buried pipe with and without a manhole match previous results very well. The maximum displacement responses for the two cases are given in Table 2 below.

**Table 2 Comparison of Pipeline Responses during Liquefaction**

| | Experi-ment by Kuribaya-shi | Ray-leigh-Ritz Meth | This Finite Element Study |
|---|---|---|---|
| With-out Man-hole | 0.5cm | 0.79cm | 0.47cm |
| With Man-hole | 0.75cm | .80cm | 0.72cm |

Again, from the above comparison of results, the current finite element solutions verify with the experimental data much better than the Rayleigh-Ritz method done by Wang et al (1990). It is confident that the developed program is correct with accuracy.

## Preliminary Study Results

Although the objective of the project is to study the response behavior of pipeline system (Figure 1) under a soil liquefaction process, only preliminary results for a single continuous pipeline are available at this time. The system results will be incorporated into Zhang's dissertation.

The preliminary study example is a continuous steel pipeline, 100 m long, 20cm, 40cm, 60cm or 80cm in diameter and 0.6cm, 0.8cm, 1cm, or 1.2cm thick, with or without manhole, buried 6ft to 10ft in depth. The length of pipeline in liquefaction zone varies from 40m to 80m. It is assumed that the pipeline subjected to a shear wave with a magnitude corresponding to the recorded data from Tarzana station of the 1987 Whittier California earthquake at a 45° angle. These earthquake data had high ground accelerations but small ground displacements. The peak ground accelerations in the East-West direction occurred in the first 10 seconds as shown in Figure 3. In this study, it is assumed that full liquefaction stage is reached at $t_L$=8 sec. and remained liquefied for the remaining period of the earthquake.

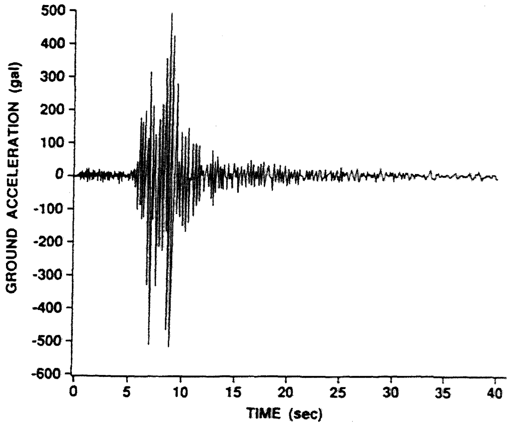

Figure 3. Earthquake Acceleration

The time displacement responses at the mid-span of a fixed ends pipeline with different diameters are shown in Figure 4 and in Table 3. all these pipelines are under a soil liquefaction zone of 40 meters. One can see from this figure and the table that the response increases as the diameter of the pipeline increases. Also, the pipeline with manholes has larger responses than that without manholes.

Further study indicated that lateral displacement responses increases rapidly when the length of pipeline in soil liquefaction zone changes from 40m to 80m. Figure 5 shows the response for a pipeline under a 80m liquefaction zone. One may note that this response is much large than those from pipelines under 40m liquefaction zone as shown in Figure 4 or Table 3.

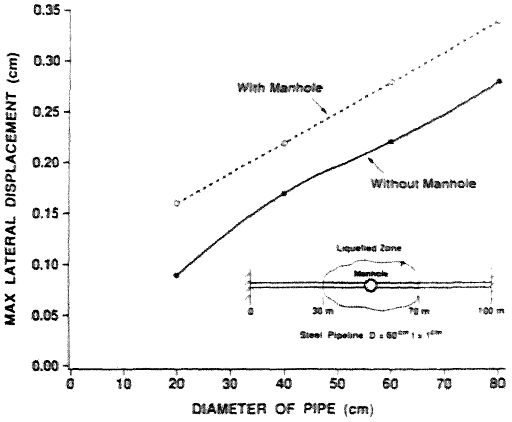

Figure.4 Mid-Span Time Response

**Table 3 Maximum deflections (cm) of pipelines**

| Φ(cm) | 20 cm | 40 cm | 60 cm | 80 cm |
|---|---|---|---|---|
| With Manhole | 0.16 | 0.22 | 0.28 | 0.34 |
| Without manhole | 0.09 | 0.17 | 0.22 | 0.28 |

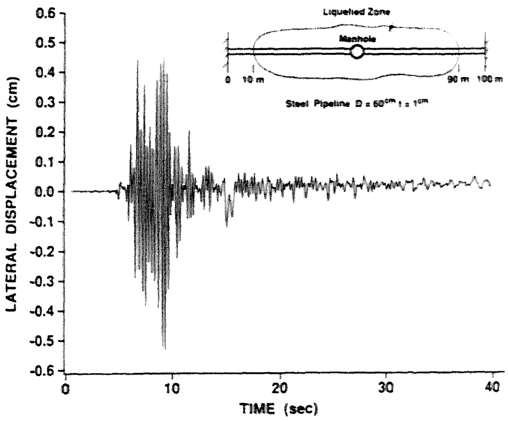

Figure 5. Response in 80m Zone

The general conclusions are as follows: (a) the response will increase when the diameter of pipeline increases; (b) the response will increase when the liquefaction zone increases; (c) the buried depth which determines the initial soil spring constant affects the response only slightly, because under full liquefaction stage, soil stiffness becomes zero for all cases; (d) additional mass also affects the response slightly at the fully liquefaction stage even setting the added mass coefficient $\beta = 370$ at the inertial time.

This study also found that the damping value plays an important role in soil liquefaction process. When zero damping was used to calculate the response from Kuribayashi's experiment with a manhole, the lateral deflection increases two to three times more than that with damping as shown Figures 6.

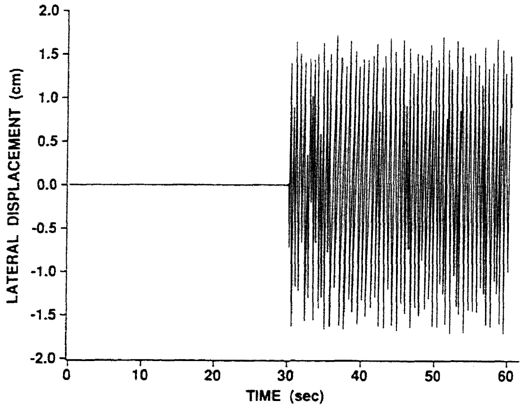

Figure 6 - Pipeline With Manhole but Without damping

## Summary and Conclusion

In this paper, a general method has been developed to study the dynamic responses of buried pipeline systems during a soil liquefaction process. A computer program based on finite element method including all influential parameters has been written, tested and verified with some known results. Preliminary study for a single continuous steel pipeline subjected to the 1987 Whittier California earthquake have been carried out and results have been reported.

It is found that the response increases with the presence of a manhole, with higher diameter pipe and larger liquefaction zone. The buried depth only affects the response slightly.

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