TABLE OF CONTENTS

Page

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ABSTRACT

This report summarizes the seismic analyses for the responses of buried pipelines subjected to seismic ground shaking. The analyses covered are upper bound analyses, static analyses and quasi-static analyses including elastic and elasto-plastic resistant behavior of the soil and joint springs. Assumptions, formulations and results of each analysis are presented for the purposes of comparison and completeness. The report is derived from a research project titled 'Seismic Vulnerability, Behavior and Design of Underground Piping Systems (SVBDUPS Project)' under the sponsorship of the National Science Foundation.

I. INTRODUCTION

Recent studies[7,8,9] have shown that buried gas, water and sewer pipelines have been damaged heavily by earthquakes. Other than the catastropic failures such as landslides and soil liquefactions, buried pipelines, damages caused by earthquake excitations (effects of ground wave propagation) have been found to be a major mode of failure[11]. Also, the axial responses of long buried pipelines has been found to be predominant during seismic ground shaking[11,14]. The dynamic effects of buried pipelines has been observed to be small[14] due to high restraints and damping from the surrounding soils and are neglected. State-of-the-art papers[12,24,25] on the subject have been reported.

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. To evaluate the adequacy of the existing pipelines and to aid the design of future systems, this paper summarizes the currently available static and quasi-static analyses for the seismic response behavior of buried pipelines (i.e., pipe strains, relative joint displacements/rotations between pipe segments and relative displacements between the pipe and the ground due to seismic ground shaking); some of which were developed by the author[19] and his students[1,5,15,17] at Rensselaer Polytechnic Institute under the NSF sponsored research project titled 'Seismic Vulnerability, Behavior and Design of Underground Piping Systems (SVBDUPS) since 1976.

The analyses reported include upper bound analyses by simplified and quasi-static approaches; static analyses based on beams on elastic foundation and beams on elastic-plastic foundation; quasi-static analyses for elastic and elasto-plastic responses for long straight (continuous or segmented) buried pipelines.

Although the discussions for some analyses have been presented and published[20 to 23], the assumptions, formulations and results of these analyses are grouped together in the report for the purposes of comparison and completeness.

II. UPPER BOUND ANALYSES

II.1 Simplified Approach

Although there are currently no codified provisions to design underground pipelines for earthquake effects, a 'Simplified procedure'[13] to estimate the underground pipe strains and curvatures due to seismic shaking 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. Details of this approach can be found in References 15 and 20.

Assuming that the seismic wave shape remains constant while traversing the pipeline, the maximum axial strain of the ground, ε_{max}*, which will be taken as the upper bound of the axial strain of the pipe, $\varepsilon_{p,max}$, due to ground shaking will be:

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

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

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

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

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* Symbols which are consistent within a section are defined when they first appear in the section.

earthquakes producing ground velocities and accelerations less than the V_{max} and A_{max} used in the analysis.

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 relative joint displacement, $U_{p,max}$ and maximum relative joint rotation, $\theta_{p,max}$, of the pipeline shown in Fig. 2 can be expressed as:

$$U_{p,max} = \varepsilon_{max} L \quad (3)$$

$$\phi_{p,max} = \chi_{max} L \quad (4)$$

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.

Since these upper bounds are unique and simple to obtain, they will be used as a basis for the normalization of results presented later.

II.2 Quasi-static Approach

II.2.1 General Description and Assumptions

In the simplified approach for the upper bounds, pipe strains and curvatures are estimated from free field conditions. For relative joint displacements and rotations, what one needs to know about the pipeline is segment length. There is no soil-structure interaction involved.

However, in reality, the pipeline (typical of water/sewer transmission lines) 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.

Due to the motion of the ground relative to the pipe segment during earthquakes, resistance between the pipe and the surrounding soil develops. To model such soil resistance, a uniformly distributed linear soil spring, k, is used.

The joint resistance between two pipe segments is modeled by a joint spring and a dashpot. 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.

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. Thus, the upper bound for the relative joint displacements of segmented pipelines can be obtained. Furthermore, such simplification would enable us to verify some observations of seismic response of buried pipelines by the Japanese[11,14] initially.

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. More assumptions will be made later in related sections.

II.2.2 Formulation of the Problem

A long buried piping model consisting of n-segments is shown in Fig. 3 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 also 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 segment lengths.

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