ANALYSIS OF EARTHQUAKE EFFECTS ON PIPELINES

by

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SYNOPSIS

A procedure for computing the seismic response of cross-country pipelines is described, with emphasis on above-ground lines. The procedure accounts for the effects of initial static loads, support nonlinearity, and out-of-phase ground motions at different points along the pipe. The idealization assumptions and theory are described, and the influence of certain parameters on the response is discussed.

INTRODUCTION

Cross-country pipelines in Artic regions are likely to be placed above ground over substantial portions of their length, because the soil deformations produced by buried lines may be unacceptably large. Analyses of earthquake effects on above-ground lines involve substantially different problems from those which arise in analyses of more conventional piping systems. In particular, the following two problems must be recognized.

(1) The pipeline must be firmly fixed to the ground by anchors at intervals along its length. Between anchors, however, it must be allowed to slide on its supports to avoid excessive restraint of movements due to thermal expansion. Hence, the pipe can also slide on its supports during an earthquake, with the result that the dynamic response is nonlinear and governed greatly by the properties of the supports. Linear dynamic analyses, of either response spectrum or time history type, are therefore not applicable.

(2) The pipeline extends long distances in plan, and hence different points on the structure will be subjected to different ground motions. In particular, the relative displacements between anchors may be substantial at any instant of time, producing a time-dependent effect similar to a thermal expansion. Hence, the analysis procedure must take account of out-of-phase support motions.

This paper describes a computational procedure and a computer program for the practical dynamic analysis of cross-country pipelines. The procedure is necessarily approximate, because of the many unknowns in the problem and because the costs for an "exact" analysis would be prohibitive. However, the important parameters affecting pipeline response are taken into account, and the procedure is believed to be of ample accuracy for use in pipeline design.

STRUCTURAL IDEALIZATION

The following assumptions are made to set up the structural model. (1) The pipe lies in a single plane (usually horizontal, but vertical if desired). (2) The pipe is elastic, but rests on inelastic supports. The pipe is idealized as a finite number of beam elements, with masses lumped at the nodes between elements. The supports are idealized as discrete nonlinear springs, to represent frictional resistance and the effects of displacement-limiting stops. (3) Displacements are assumed to be small in comparison with the plan dimensions of the system. (4) The system is prestressed by static loads

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(gravity, thermal expansion and/or pressure) before the earthquake begins. This is important because initial loads on the supports substantially affect the subsequent dynamic response. (5) The ground motion is represented as a wave moving past the system with constant velocity.

The analysis can be applied to (a) above-ground configurations subjected to combined longitudinal and transverse ground motions; (b) above-ground configurations subjected to combined longitudinal and vertical motions (in which case the pipe may lift off the supports) and also (c) below-ground configurations subjected to longitudinal and transverse motions (in which case the nonlinear springs can represent longitudinal cohesive resistance as well as transverse soil stiffness). The procedures and computer program details have been described in reports to Alyeska Pipeline Service Company [1,2]. A similar procedure has been developed independently by Anderson and Johnston [3].

THEORY

There are three degrees of freedom at each node, namely rotation plus translations in each of the X and Y coordinate directions. The mass matrix is diagonal. At any instant of time, let:

(1) $\{r_a\}$, $\{\dot{r}_a\}$ and $\{\ddot{r}_a\}$ = vectors of nodal displacement, velocity and acceleration, respectively, with respect to a fixed coordinate system (i.e. absolute quantities).

(2) $\{r_g\}$, $\{\dot{r}_g\}$ and $\{\ddot{r}_g\}$ = vectors of displacement, velocity and acceleration, respectively, of the ground immediately beneath the corresponding node.

(3) $\{r_r\}$, $\{\dot{r}_r\}$ and $\{\ddot{r}_r\}$ = vectors of nodal displacement, velocity and acceleration, respectively, relative to the ground. That is

$$\{r_r\} = \{r_a\} - \{r_g\} \tag{1}$$

with similar equations for $\{\dot{r}\}$ and $\{\ddot{r}\}$.

(4) $[M]$ = diagonal mass matrix, assumed to be constant.

(5) $\{F_m\}$ = vector of inertia forces on the nodes, given by

$$\{dF_m\} = [M]\,\{d\ddot{r}_a\} \tag{2}$$

(6) $[K_p]$ = static structure stiffness matrix for the pipe alone, which is constant because the pipe is elastic and displacements are small.

(7) $\{F_p\}$ = vector of nodal forces due to deformation of the pipe alone, given by

$$\{dF_p\} = [K_p]\,\{dr_a\} \tag{3}$$

(8) $[K_s]$ = tangent static stiffness matrix for the support elements only, which varies because the supports are nonlinear.

(9) $\{dF_s\}$ = increment of nodal forces due to support deformations, given by

$$\{dF_s\} = [K_s]\,\{dr_r\} \tag{4}$$

(10) $[K]$ = tangent static stiffness matrix for complete structure, given by

$$[K] = [K_p] + [K_s] \tag{5}$$

(11) $[C]$ = tangent viscous damping matrix, assumed to be given by

$$[C] = \alpha\,[M] + \beta\,[K] \tag{6}$$

(12) $\{dF_c\}$ = increment of nodal forces due to viscous damping effects, assumed to be given by

$$\{dF_c\} = [C]\,\{d\dot{r}_r\} \tag{7}$$

Over a time interval dt, the following dynamic equilibrium equation must be satisfied.

$$\{dF_m\} + \{dF_c\} + \{dF_p\} + \{dF_s\} = \{0\} \tag{8}$$

Hence, from Eqs. 2, 3, 4 and 7

$$[M]\,\{d\ddot{r}_a\} + [C]\,\{d\dot{r}_r\} + [K_p]\,\{dr_a\} + [K_s]\,\{dr_r\} = \{0\} \tag{9}$$

and hence from Eqs. 1 and 5

$$[M]\,\{d\ddot{r}_r\} + [C]\,\{d\dot{r}_r\} + [K]\,\{dr_r\} = -[M]\,\{d\ddot{r}_g\} - [K_p]\,\{dr_g\} \tag{10}$$

Eq. 10 can be integrated by step-by-step methods. Equilibrium violations produced in any step because of the finite step size are compensated for by applying an out-of-balance force correction in the succeeding step. The procedure is identical to that used in the DRAIN-2D general purpose computer program for earthquake response of plane inelastic structures [4,5], and is not repeated here.

Two different ground acceleration records may be specified, one representing longitudinal motion of the ground and the second representing transverse motion. The ground displacement records are obtained by double integration within the computer program. Each ground motion is assumed to propagate past the pipeline as a wave with straight wavefront and constant velocity. Any two points on the ground therefore experience the same motions, but these motions are out of phase by the length of time required for the wave to travel between the points.

FACTORS AFFECTING RESPONSE

A typical segment of a large diameter cross-country pipeline will extend approximately 600m between points of "rigid" anchorage to the ground, and will have shallow bends in plan to prevent excessive stresses developing due to restraint of thermal expansion. The pipe will rest on supports at intervals, and will be free to slide laterally on the supports. The amount of lateral movement will be restricted by stops at certain supports, to prevent excessive displacements during an earthquake. Because the operating temperature of the pipe will exceed the construction temperature, the pipe will typically be tending to move outwards at the bends, while being restrained by friction forces. These initial stress effects in the structure have a substantial effect on the subsequent dynamic dynamic response.

Because the anchors are substantial distances apart in plan, it can be expected that the ground displacements will differ at adjacent anchors during an earthquake, possibly by substantial amounts. This relative anchor movement may have a substantial influence on the earthquake response. In particular, if the anchors are assumed to be rigid and infinitely strong, then the computed anchor reactions may be very high, and anchors designed to resist these reactions may have to be massive structures. In fact, however, no anchor can be completely rigid. Also, it may be a sound design procedure to design the anchors to have limited strength, sufficiently large to prevent movement under thermal and pressure loadings, but such as to allow slip during an earthquake. Analyses have shown that substantial reductions in pipe stresses and forces on the pipe stops can be produced by allowing anchor slip, with required slip distances of the order of 15 cm for severe earthquakes.

In order to understand the computed response, it is important to recognize that the X and Y ground motions exert substantially different influences on on the structure, as follows.

For the case of zero initial stresses in the structure, the Y motions (i.e. transverse to the pipe) exert a relatively small effect on the pipe. This is because the pipe is flexible transversely, and is supported at close intervals on supports which can transmit only small forces to the pipe and which absorb substantial amounts of energy. The effects of Y motion alone in this situation are therefore small. Also, these effects do not change much as the wave propagation velocity changes, because the pipe is flexible and is insensitive to relative support displacements.

For the case with initial stresses, the effect of Y direction shaking is primarily to relieve the stresses produced by frictional restraint of thermal expansion. That is, the pipe tends to move outward, to the position it would adopt if there were no friction. In this case, there is a tendency for the pipe to contact the stops, and the stress changes may be more substantial than for the case with zero initial forces. However, these stress changes tend to relieve the initial stresses.

The effects of X ground motions (i.e. along the pipe) are quite different from those of Y motions. If the pipe were rigidly anchored and the supports all were to move in phase, the stresses produced by the X motions would be small. However, if there are differences between the X displacements at the anchors, then effects similar to those of thermal expansion are produced (except that they are dynamic). The anchor movements in this case tend to produce substantial outward and inward movements of the pipe at the bends, and may produce substantial stop loads and pipe stresses. The effect is more severe for anchors which are rigid than for anchors in which some of the relative ground displacement can be accommodated by anchor slip.

Space does not allow a more detailed discussion of results in this paper.

CONCLUSION

The procedure described in this paper is believed to provide a sound approach for determining the effects of earthquakes on cross-country pipelines. The procedure takes account of the most important parameters affecting the pipeline response, yet is sufficiently simple and efficient for practical use. In the author's opinion, it is doubtful whether any significantly greater accuracy would be obtained for design purposes by using a more refined analysis (for example, accounting for three dimensional effects, inelastic behavior of the pipe, etc.).

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