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Seismic Analysis of Underground Nuclear Power Plant Piping Systems

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ABSTRACT

An analytical procedure for carrying out the seismic analysis of underground piping systems for nuclear power plants is presented in this paper. Although the method is specifically applicable to nuclear power plants, its general principles are equally applicable to the analysis of buried piping systems carrying service water and fuel oil as well. The technique described performs the dynamic stress analysis, based on the flexibility method, of the piping system for earthquake loads incorporating: (a) piping system data, (b) geotechnical data, and (c) seismic strain data. To facilitate the analysis, the piping system is classified into various components, i.e., pipe bends, elbows, tees, and straight elements. The main items resulting from this analysis are: (1) forces and moments, (2) stresses, (3) soil resistance to ovalization, (4) loads induced at anchors, and (5) displacements. The piping system can thus be designed to satisfy the dynamic criteria as well as the static one. An additional and attractive feature of this procedure is that it can be easily programmed by using a scientific language, e.g., FORTRAN 77.

INTRODUCTION

The survival of modern man is dependent upon the existence of a complex system of subterranean pipelines within his environment, e.g., pipelines carrying water, slurry, and oil. The construction of these systems must be planned and completed before a thriving community could be established, as was realised by the early civilizations. The Romans and other advanced early societies devoted considerable effort for solving problems of transporting water by gravity aqueducts and pipelines to their settlements and for ensuring that waste water and sewerage were properly removed to remote areas for disposal.

Underground pipelines are an integral part of a nuclear power plant as they facilitate the conveyance of cooling water and fuel oil from one part of the plant to the other. In addition to being exposed to static loads: internal and external pressure, dead weight, thermal expansion, and settlement; they are also subjected to dynamic, e.g., seismic loads if they are located in an earthquake-prone area. In order to safeguard the safety of these pipelines, it is imperative that their analysis and design be based on the static as well as the seismic criteria.

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METHOD OF ANALYSIS

The technique described in the following sections - based on the flexibility method - performs the stress analysis of the piping system for earthquake loads by incorporating the following information:

Requisite Data for Dynamic Analysis

Piping System Data: mean diameter, wall thickness, contents, insulation thickness, design pressure and temperature, normal operating pressure and temperature, and penetration details at the anchors.

Geotechnical Data: ground velocity and acceleration, Rayleigh waves velocity, angle of internal friction for soil, soil density, coefficient of subgrade reaction, constrained modulus, and static and dynamic settlements for buildings and adjoining areas.

Seismic Strains Data: strain values corresponding to the OBE (Operating Basis Earthquake) and SSE (Safe Shutdown Earthquake) for the entire project area of nuclear power plants.

Seismic Wave Effects

Various seismic waves develop during an earthquake. There are compression waves (P waves), shear waves (S waves), and different kinds of surface waves such as Rayleigh waves (R waves). When the seismic waves propagate through the soil, the relative motion between two points can be calculated by using References (Newmark & Rosenblueth 1971, Newmark 1972, Christian 1973, and Yeh, G.C.K. 1974). In the case of a long straight pipe, its middle section is located far from the ends and is free from the influence of external supports other than the surrounding soil, and it is evident that this part of the pipe will move with the soil when seismic waves propagate though it. Since Rayleigh waves, as evidenced by experience, induce the highest axial strains in buried pipelines, only these waves will be considered in this analysis. The piping strains in the middle section of the pipe mentioned above or the strains of the soil have been conservatively established as follows (Goodling 1978):

[1] Axial strain $\epsilon_m = \frac{V_m}{C_R}$

[2] Bending curvature $\kappa = \frac{a_m}{C_R^2}$

where V_m = peak ground velocity, a_m = peak ground acceleration, and C_R = Rayleigh waves velocity.

The stresses on such a section of the pipe can be calculated from the strains shown above:

[3] Axial stress $\sigma_a = \frac{EV_m}{C_R} = \frac{F_{max}}{A_m} = \epsilon_m E$

[4] Bending stress $\sigma_b = \frac{ED_o a_m}{2C_R^2} = \frac{ED_o \kappa}{2}$

where E = modulus of elasticity, F_{max} = maximum axial force, A_m = cross sectional area of pipe, D_o = outside diameter of pipe, and a_m = peak ground acceleration. The sum of these axial and bending stresses shall be considered as the earthquake stress for the straight sections of the pipe.

Calculation of Intermediate Parameters

Before proceeding with the analysis, it is necessary to calculate some pertinent soil and pipe related parameters: the soil unit spring constant k, the beam parameter λ, and the maximum friction slippage length l_m. The soil unit spring constant is found by (Goodling 1978):

$$[5] \qquad k = k_o D_o$$

where k_o = coefficient of subgrade reaction per unit length. Then λ is calculated by:

$$[6] \qquad \lambda = \sqrt[4]{\frac{k}{4EI}}$$

where I is the moment of inertia of the pipe cross-section.

The parameter λ is a factor derived by Hetenyi (Hetenyi 1946) which combines the properties of soil, pipe material, and pipe section properties and influences the shape taken by a beam (the pipe) on a continuous elastic foundation (the soil) when subjected to externally applied forces and moments.

The maximum slippage length l_m is defined as the length of pipe necessary for the friction force along the pipe axis to develop fully so that a point is reached where the pipe and soil move together in a region of zero relative motion at the soil-pipe interface. The axial load F_{max} in the pipe in this region can be expressed by fl_m and the slippage length is found by:

$$[7] \qquad l_m = \frac{\epsilon_m A_m E}{f}$$

where $f = \pi D_o p \mu$: the reaction force per unit length along the soil-pipe interface, $p = \gamma d$: the surface overpressure, γ = unit weight of soil (compacted fill condition), d = depth of overlying burden of soil, and μ = coefficient of friction at soil-pipe interface.

Classification of Pipe Elements

The configuration of a buried pipe may comprise: (1) elbows and bends, and (2) tees and straight elements. The highest moments occur in the bends and elbows of buried piping due to the differential movement, Δ between the soil and the pipe. In general, the axial and bending stresses in the straight runs will always be less critical than those experienced by the elbows or bends (Goodling 1978).

Calculation of forces and Moments

Pipe Bends and Elbows

Forces and moments in buried elbows are determined by making use of the system of equations given below -- which has been derived by incorporating the interdependence of forces, moments, soil deformation, and rotation of the pipe in the immediate vicinity of the elbow (assuming that the seismic waves propagate along the longitudinal leg of the pipe), Figures 1 and 2 (Goodling 1980 and Goodling 1979).

To determine the local deformation around a pipe bend, assume the longitudinal leg is in the direction of maximum soil strain and the transverse leg is in the perpendicular direction, Figure 3. The actual slippage length L' upon which the frictional restraint is developing can be obtained from the theory of beams on elastic foundations. The net relative displacement Δ_1 between soil and pipe, for which local deformation has to be absorbed, is the difference of soil displacement and pipe element displacement accumulated from the stretching of the actual slippage length:

[8]
$$\Delta_1 = \epsilon_m L' - \frac{fL'^2}{2A_mE} - \frac{S_1L'}{A_mE}$$

[9]
$$M = \frac{\lambda \Delta_1}{(R\phi/KEI)}$$

[10]
$$S_1 = \frac{k\Delta_1}{2\lambda} + \lambda M$$

where $\epsilon_m L'$ = theoretical unrestrained relative movement at the elbow over length L'; S_1L'/A_mE = the amount of pipe elongation due to the bearing force of soil against the transverse leg producing the shear force S_1, at the elbow and which is transformed into an axial force in the longitudinal leg; $fL'^2/2A_mE$ = the pipe elongation due to friction along the soil-pipe interface which is found from $(f/A_mE)\int_0^{L'} x\,dx$; M = bending moment, ϕ = elbow angle, L' = actual slippage length, R = radius of elbow, t = actual pipe wall thickness, a = outside radius of pipe, Δ_1 = net soil deformation at the elbow along the longitudinal leg, S_1 = axial force in the longitudinal leg, and

$$K = 1 - \frac{9}{10 + 12\,(tR/a^2)^2}$$

Equation (9) can then be used to calculate the flexible elbow bending moment M resulting from soil strain ϵ_m. The axial force S_2 in the transverse leg on a 90° bend (perpendicular to the direction of wave propagation) can then be calculated by:

[11]
$$S_2 = \lambda M$$

The bending stress can be found from the following equation:

[12]
$$\sigma_b = iM/Z$$

where i = stress intensification factor, and Z = section modulus of pipe.

Tees and Straight Elements

Expressions for forces and moments on tees and straight sections are derived by using an approach similar to the one used for bends and elbows described in the preceding section. If the stresses in the middle section of a long straight pipe due to seismic wave effects exceed their allowable values, the piping may need special design to decouple the soil strains from being transmitted to the piping, such as protective sleeves, encasements etc., or may need rearrangement of layout such that full restraint from friction will not develop. Generally, it is not expected to happen unless low strength materials are used for a soft soil site.

Determination of Seismic Stresses

Having determined the values of S_1, M, and F_{max}, the bending stresses due to local deformation of the pipe can be evaluated. These stresses are superimposed on the stresses caused by the curvature of the pipe given by Eq. (4). Equations giving these combined stresses for elbows as well as straight segments of the pipe are given below. To account for the higher intensity of stresses at the elbow, combined stresses at the elbow have been multiplied by an intensification factor 0.75i.

1. Stress at an elbow

[11] $\sigma_b(\text{comb}) = 0.75i \{ED_o \kappa/2 + M/z\} + S_1/A_m$

2. Stress in the longitudinal run

[12] $\sigma_b(\text{comb}) = F_{max}/A_m + ED_o \kappa/2$

Soil Resistance to Ovalization

Bending moments on thin-walled curved beams (elbows) result in intensification of the stresses computed by the ordinary flexure formula $\sigma = M/z$. This intensification is due to the ovalization or tendency of the circular cross section in the elbow to flatten as a result of the radial components of the forces at the convex and concave sides of the elbow. The ASME (American Society of Mechanical Engineers) Piping Code prescribes the use of a stress intensification factor for pipe bends and welding elbows which is found by:

[13] $i = 0.9/h^{2/3}$

in which $h = t_n R/r^2$, t_n = wall thickness, R = radius of elbow, and r = nominal radius of pipe section.

Seismic Loads at Anchors

For structures built in a seismic environment, it is reasonable to assume that the soil surrounding the structure experiences the same seismic motion as the structure itself. Therefore, for pipelines anchored to a structure, there will be no relative displacement between the pipe and the anchor. Seismic loads induced at the anchors can be determined by performing an analytical analysis of the pipelines using NUPIPE Computer Program.

Seismic Displacements

Displacements induced in the underground pipelines by seismic forces can be determined by an analytical technique, viz., method of consistent deformations -- which when used with NUPIPE Computer Programm can lead to a satisfactory numerical solution. In this approach, the pipeline is represented as a beam supported by the continuous reaction of the soil. This reaction is mathematically modelled as a series of restraints applied transversely at regular intervals to the beam. In addition, static axial forces representing soil friction may be imposed on those straight sections of the pipeline where axial displacements are anticipated. For a very long straight pipe, the axial stress, σ_a effected at a rigid anchor due to an axial displacement, Δ_a can be obtained by the analytical formula (Yeh, G.C.K. 1974):

[14] $$\sigma_a(\text{displ.}) = \sqrt{(2Ef\Delta_a)/A_m}$$

When a buried piping system is located within the influence length - which for a beam on an elastic foundation is the distance within which the deflection produced by a concentrated load diminishes to a negligible amount - of two buildings, the resultant seismic stress can be obtained by considering its out-of-phase resultant movement - that can be avoided if sufficient expansion loops are provided in the piping system.

RECOMMENDATIONS FOR STRUCTURAL PENETRATION

The presence of a nuclear power plant, along with its underground piping, in the free environment of a soil-medium disturbs its uniformity. The action of the resulting combined structure, when subjected to seismic forces, can best be determined by analysing the soil-structure interaction. In turn, the reaction of the structure becomes an external force acting on buried piping. The effect of this external force on the piping networks is strongly influenced by the design of the structural penetration. In general, it is considered to be a sound practice to use rigid-type of building penetration at the location where a pipe enters the plant building. Because of this rigid penetration, the junction of pipe and wall acts as a fixed anchor. The resulting fixity should be taken into account while considering the effects of boundary conditions: thermal expansion, seismic displacements, and differential settlements on the soil-structure interaction, because as a result of this interaction local stresses develop at plant building entry points.

For reducing these excessive local stresses, a standard buried piping structural-penetration-assembly is recommended, as shown in Figure 4. According to this assembly, a single pipe line is rigidly anchored to the wall and enclosed in a protective sleeve, which is not attached to the building so that it can move with soil rather than moving with the building. A group of pipelines may be enclosed in protective sleeves individually. Alternatively, these could be encased in either a culvert-type sleeve or a concrete box.

The purpose of a protective sleeve, which is designed to sustain the earth load on it, is to decouple the soil reaction from the piping. The waterproof mastic on the sleeve seals the joint but provides enough flexibility in it to prevent the transmission of transverse (vertical and horizontal) relative building displacements. However, it does not affect the axial displacement pattern. If the sleeve is considerably long, it should be supported at a number of intermediate supports along its span. NUPIPE Computer Program can be used to design, based on simplified boundary conditions, the sleeves for their size, length, and support locations.

CONCLUSIONS

The static analysis of underground pipelines in the past has been fairly standardized by the analysts and is routinely carried out for applied dead loads. However, if the pipelines are located in an earthquake-prone area, they are invariably subjected to seismic (dynamic) loads in addition to carrying static loads. Under these circumstances, it is imperative that the analysis and design of these pipelines be based upon the combined effects of static and dynamic loads. Up until recently, there has been a paucity of literature available dealing with the seismic analysis of buried pipelines. However, in the past decade, several excellent analytical and empirical studies dealing with this subject have appeared in engineering journals; and, the methodology presented in this paper highlights some of the salient features of these publications.

This seismic analysis technique essentially determines: (i) strains, stresses, displacements, forces, and moments in piping system components; (ii) soil resistance to ovalization and, (iii) dynamic loads induced at anchorages. Thus the design of the piping system can be based on the dynamic as well as the static analysis. The approach has already been successfully applied to several nuclear power plants in North America, e.g., the Beaver Valley Nuclear Power Station in Pennsylvania, USA.

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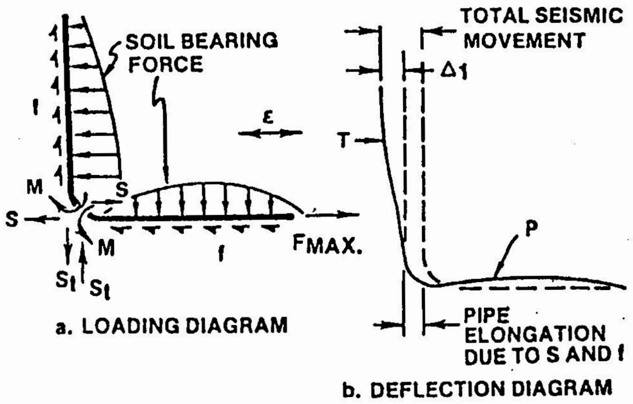


a. LOADING DIAGRAM

b. DEFLECTION DIAGRAM

Fig.1. Soil effects on buried elbows

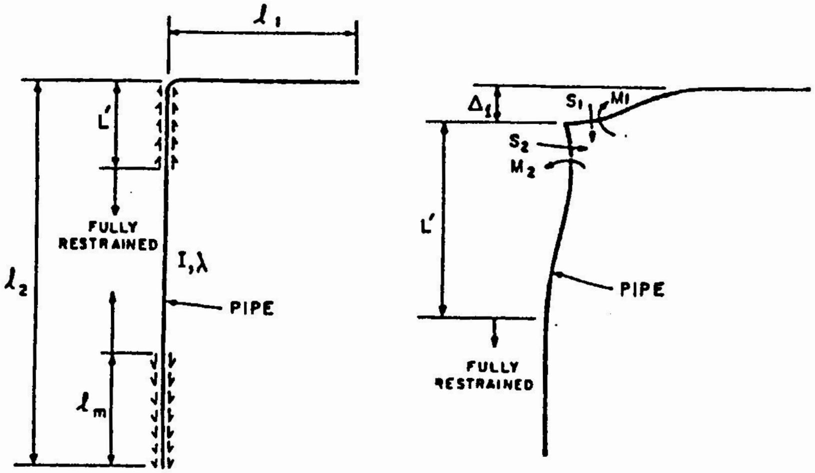
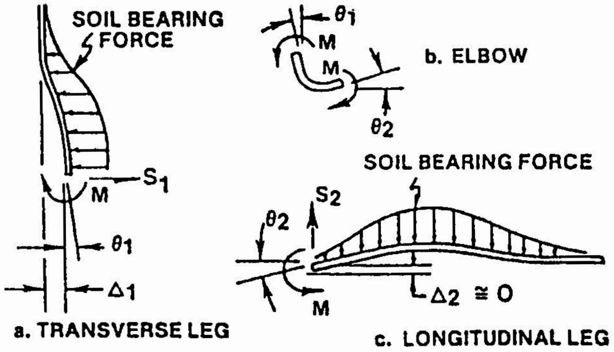


Fig.3. Effects of soil strain at buried pipe bends



a. TRANSVERSE LEG

b. ELBOW

c. LONGITUDINAL LEG

Fig.2. (above) Free body diagrams of elbows
Fig.4. (right) Structural penetration assembly