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SEISMIC DESIGN OF LONG UNDERGROUND STRUCTURES

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SUMMARY

Portions of long underground tubular structures such as circulating water tunnels, piping systems and reinforced concrete electrical cable ducts often underlay Nuclear Power Plant facilities. They may range in cross sections from a few centimeters to a few meters and the materials are generally steel or reinforced concrete. Consequently, their relative stiffnesses with respect to the surrounding soil vary widely. Under an earthquake condition, these buried structures respond to various seismic waves propagating through the soil media. Also, the relative dynamic motions of the connecting structures further influence these buried structures. This paper addresses the underground reinforced concrete tunnels and similar structures and develops simplified seismic analysis and design procedures for these structures.

The treatment presented in this paper is primarily design orientated. Various geometry configurations and boundary conditions are possible. The effect of soil is considered by soil springs. The embedment effect can also be appropriately included. Structural design criteria are developed. They include consideration of active, dynamic and passive soil pressures, thermal loads and relative displacements of the tunnel ends. Finally, design examples, used in a nuclear power plant facility showing the application of the criteria, are presented. It is concluded that the procedure presented yields a realistic cost-effective design.

1. Introduction

Long underground tubular structures that are nuclear safety related exist at nuclear power plant facilities. Such buried structures include piping systems, electrical cable duct banks and tunnels, and circulating water tunnels. Because of their importance, these structures are designed for the effect of earthquakes.

These buried structures range in cross sectional size from a few centimeters to a few meters. The material is usually reinforced concrete, structural steel or a combination thereof. Consequently, their stiffnesses relative to the surrounding soil media vary widely. When earthquake shock waves pass through the soil media, the response of these underground structures is influenced by their stiffnesses. The determination of their response is complex because of the randomness of direction and magnitude of the seismic motion and because of the strain dependency of the deformation and damping characteristics of the soil. The relative dynamic motions of the connecting structures further influences the stresses in the buried structures.

2. Seismic Effect on Underground Structures

The seismic effects on underground structures can generally be classified as two phenomena: faulting and ground shaking. The faulting effect is limited to seismically active fault zones, and for nuclear power plant facilities is usually eliminated by proper site selection. Thus, the seismic effect on long underground structures at a nuclear power plant site is mainly concerned with the ground shaking phenomenon. It is characterized by the strains associated with the free-field vibration of the long buried structures as well as the relative seismic movements of the connecting structures.

Soil transmits energy by various types of waves. Buried piping and cable duct banks are relatively flexible with respect to the surrounding soil and essentially follow the soil motion. Newmark [1] has given a general treatment for the determination of soil strains due to the passage of a seismic wave, considering soil to be an elastic half space. He developed equations for maximum values of axial and shear strains and curvature in soil. Yeh [2] expanded the treatment to maximizing the combined effects of compressional waves (P-waves), shear waves (S-waves) and surface waves such as Raleigh waves (R-waves). Shah and Chu [3] used Newmark's treatment for the seismic analysis of buried pipe bends and T-junctions. On the other hand, for massive and deeply embedded structures, soil-structure interaction analyses, which take into consideration the strain dependent soil properties are presently in use. The importance of the structures involved have led to the development of such complex dynamic analytical procedures.

At present, however, a rigorous analytical treatment of seismic effects on long buried tunnels and pipes is beyond the state of the art [4]. A general treatment should consider simultaneous effects of free-field behavior and relative displacements of ends of the tunnels or pipes due to building motions. The methods suggested in Refs. 2, 3 and 4 yield satisfactory designs. The basic assumption governing those methods is that the soil is stiff compared to the long buried structure and, therefore, the deformation of the soil is imposed on the structure. Buried concrete tunnel structures do not necessarily conform to such an assumption. The underground reinforced concrete tunnel structures considered in this presentation, in effect, form an intermediate class of long buried structures. The design of these structures is addressed herein.

3. Structural Design Criteria

In the development of seismic structural design criteria for the long underground reinforced concrete tubular structures, it is important to recognize the following: a) The effects of seismic motions on long underground tubular structures is essentially secondary and not primary, i.e., the deformations or strains are self-limiting. For reinforced concrete tunnels, the deformations are influenced by the soil-tunnel interaction. b) Because of the relatively large cross-sections, unlike small pipes, the effect of earthquakes on lateral soil pressure is significant and is influenced by the method of construction. For braced construction, "at-rest" pressures may be assumed whereas for open cut and back fill construction, consolidation under seismic shaking should be considered. They are then combined with dynamic soil pressures. c) The seismic displacements at the junction of buried tunnels and buildings are influenced by the response of the buildings and are time dependent. In the present analysis, they are assumed completely out-of-phase and are applied at the ends of the tunnels. d) The reinforced concrete tunnel walls are not uniform in thickness. Further, the locus of the center of gravity of the cross section of the tunnel forms a nonlinear 3-dimensional curve. e) For the concrete tunnels, the ratio of length to cross-sectional dimensions is small compared to similar ratios for small pipe systems. Separation of the stresses induced by free-field behavior and the effect of relative end displacements is not possible and must be considered simultaneously.

The intent is to obtain an upper bound design of the buried tunnels. A finite element model, that considers all the geometry variations, loads and imposed displacements discussed above, is used for the analysis. This enables inclusion of other non-seismic loads such as water pressure and thermal loads. The soil is modeled as a series of horizontal and vertical springs.

4. Design Examples

Figures 1 and 2 show typical analytical models of two underground reinforced concrete tunnel structures. A typical cross-section of the tunnels in Figure 1 is given in Figure 3, which also shows the location of soil springs.

The soil was represented by a series of vertical and horizontal springs. The spring constants were based on the theory of elasticity for rigid foundations resting on elastic half space. Two models were used for each analysis. One had both vertical and horizontal springs as shown in Figure 3, whereas the second model did not have the horizontal springs on one side. The former model was used for dead, pressure and thermal loads and the latter was used for seismic and other lateral loads.

The following loads were considered along with dead loads:

A. Seismic Loads:
   - (i) Inertia of Concrete
   - (ii) Inertia of Water in the Tunnel
   - (iii) Dynamic Soil Pressure

B. Lateral Soil Pressure:
   - (i) At-Rest
   - (ii) Passive

C. Internal Water Pressure:
   (i) Positive Pressure in One Barrel
   (ii) Positive Pressure in Both Barrels
   (iii) Negative Water Pressure in Both Barrels

D. Thermal Loads:
   (i) Operating Thermal Gradient
   (ii) Transient Nonlinear Thermal Gradient

E. Local Permanent Surcharge Loads

The loads were combined in accordance with acceptable methods by treating the underground tunnels as both "other Cateogry I structures" and as "foundations".[5] The forces due to seismic wave passage, appropriately adjusting for slippage, were then combined with the loads defined below.

The following load combinations were used:

A. $1.4\,(D + F) + 1.7\,(H) + 1.9(E) + 1.9\,(\Delta)$

B. $1.05\,(D + F) + 1.28\,(H) + 1.43(E) + 1.05\,(T) + 1.43\,(\Delta)$

C. $D + F + H + E' + T + \Delta'$

where D = Dead Loads including permanent surcharge loads and hydrostatic loads
Δ, Δ' = Relative displacements due to OBE and SSE, respectively
T = Thermal effects during normal operating or shutdown conditions based on the most critical transient or operating condition.
F = Lateral Pressures from liquids, includes internal water pressures.
H = Lateral earth pressure.
E = Loads generated by Operating Basis Earthquake.
E' = Loads generated by Safe Shutdown Earthquake.

The structures were analyzed for both with and without seismic loads and were then designed in accordance with ACI-318 [6].

5. Conclusions

General seismic design criteria for the underground reinforced concrete tunnel structures are presented. Appropriate soil and seismic data is required for the design. Also, relative seismic displacemnts data of the connecting structures is necessary.

Based on the examples given, it is concluded that the criteria and procedure outlined for the seismic analysis by the equivalent static methods of long buried structures yield cost-effective designs.

6. References

[1] N. M. Newmark, "Earthquake Response Analysis of Reator Structures", *Nuclear Engineering and Design 20*, North-Holland Publishing Company, 1972, (303-322).

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[4] "Structural Analysis and Design of Nuclear Plant Facilities", Draft. Trial use and comment, Committee on Nuclear Structures and Materials of the Structural Division, American Society of Civil Engineers, 1976.

[5] US Nuclear Regulatory Commission, Standard Review Plan, Sections 3.8.4 and 3.8.5 (for other Category I structures and foundations, respectively).

[6] "Building Code Requirements for Reinforced Concrete, (ACI-318-71), American Concrete Institute, 1971.

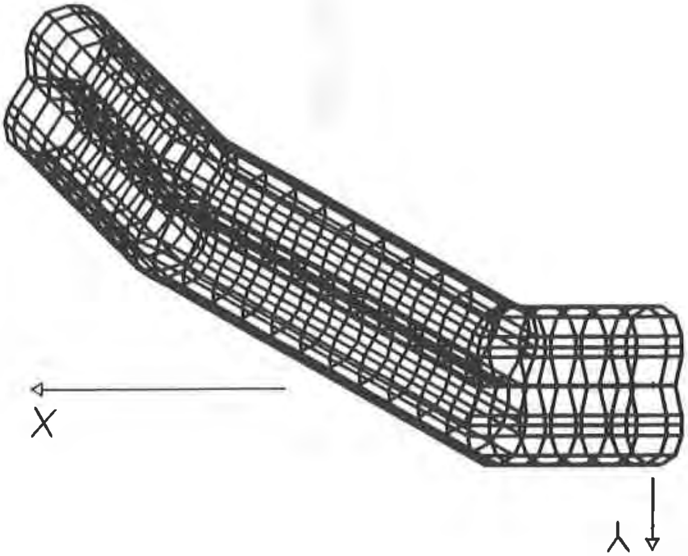

FIGURE 1: PERSPECTIVE VIEW OF AN UNDERGROUND TUNNEL (EXAMPLE 1)

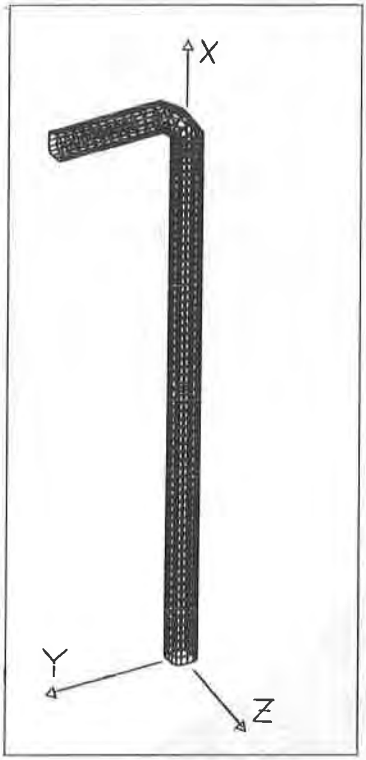

FIGURE 2: PERSPECTIVE VIEW OF AN UNDERGROUND TUNNEL (EXAMPLE 2)

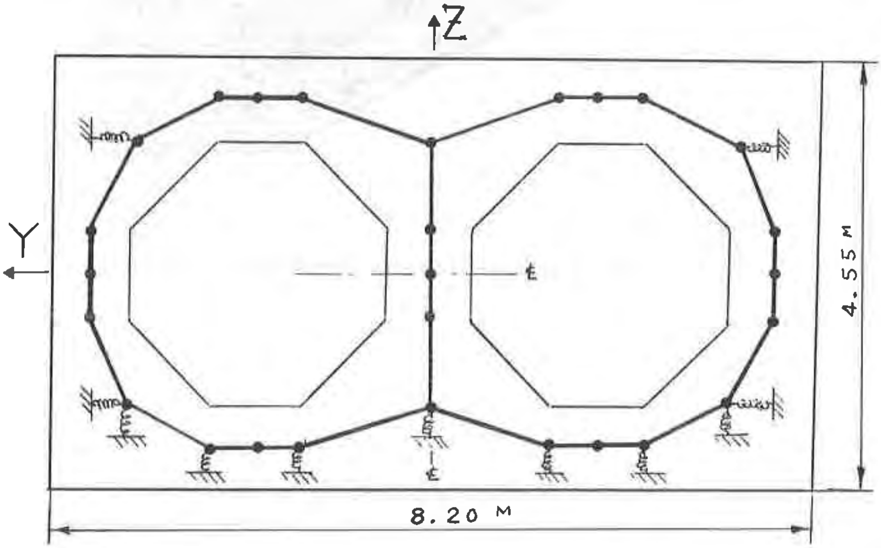

FIGURE 3: TYPICAL CROSS-SECTION SHOWING THE LOCATIONS OF SOIL SPRINGS FOR THE TUNNEL IN FIGURE 1 (EXAMPLE 1)