Response of Buried Structures to Aircraft Impact

I.V. Constantopoulos, B.J. Gryspeert
D'Appolonia S.A.,
100 Bd. du Souverain, B-1170 Bruxelles, Belgium

I. Attalla
Kraftwerk Union AG,
Berliner Str. 295, D-6050 Offenbach/Main, Germany

SUMMARY

For an aircraft impact at the ground surface, the response of buried concrete tunnels and the integrity of buried steel pipes were evaluated. In a first case, a three-dimensional dynamic analysis was performed for a buried tunnel which will connect the reactor and auxiliary buildings of a nuclear power plant and be protected by a concrete slab on the ground surface. The tunnel will be covered by 1.5 meters of granular backfill beneath the protective slab. The analyses were performed by decoupling the vertical-rocking and horizontal-torsional modes of response. The three-dimensional analytical model comprised plate elements for the surface slab, lumped masses, springs and dashpots representing the backfill, beam elements for the tunnel and a distributed parameter higher order Winkler model for the tunnel compliances. The vertical response was obtained by subjecting the model to the aircraft impact force-time relationship. The impact was postulated at one end of the tunnel system so that maximum vertical and rocking response would be obtained. A mode frequency analysis, followed by synthesis of the responses, was performed using the computer code "DAPSYS" to obtain the dynamic response of the system. For the horizontal response, the free-field horizontal accelerations were first obtained and a three-dimensional model of the soil and tunnel was analyzed, using these acceleration time histories as input support motion.

In a second case, the analysis pertained to buried pipes which will carry emergency cooling water from the intake structure to the main system, at a depth of seven meters below plant grade. The pipes consist of steel with internal and external concrete linings and are circular in section. No protective slab will be constructed between the pipes and the ground surface. For the calculation of bending stresses in the pipes, horizontal and vertical soil displacements were first computed at various locations in the soil, along the proposed pipe alignment. Bending stresses were then computed by equating the soil displacements to those of the pipes, since the pipe is more flexible in bending than the soil. In the longitudinal direction, where the pipe is much stiffer than the surrounding soil, axial forces cannot realistically be evaluated from soil displacements and pipe-soil interaction was, therefore, considered. The analysis showed that the pipes will also be subjected to significant ring deformation stresses.

1. Introduction

Category I structures of nuclear power plants are often required to withstand the effects of aircraft impact. Several papers have been already published presenting analyses of above ground structures to aircraft impact, however, the literature is scarce on the response of underground (buried) structures. Two such cases are presented herein. In the first case, floor response spectra were derived for a stiff concrete tunnel housing pipes and cables, while in the second, the integrity of buried emergency cooling water pipes was assessed.

2. Buried Tunnel Response to Aircraft Impact

2.1 Structural Layout and Soil Profile

The layout of the tunnel system between the reactor and the auxiliary buildings is shown in Figure 1. Displacement joints were provided at each end of the tunnel, where it is connected to the buildings. A 90-centimeter thick concrete slab, located at the ground surface above the tunnel provides protection to the tunnel from penetration of aircraft components and distributes the impact load. The tunnel will be founded on sandy gravel, at a depth of about eight meters below plant grade, its roof will be at a depth of about 2.5 meters, and the surrounding soil will be compacted granular backfill.

2.2 Development of Analytical Model

The mathematical model representing the soil-structure system must be capable of representing high frequency response, i.e. in excess of 75 to 100 Hertz. It has been shown that due to the very short duration of the aircraft impact, high frequency modes are excited and significantly contribute to the local response [1]. Therefore, the model must allow for representation of high-frequency response, in terms of discretization of the structural components and soil compliances, as well as in terms of integration time step. Separate finite element structural and lumped-parameter soil models were developed to obtain the vertical and horizontal responses as illustrated in Figures 2 and 3, respectively.

2.2.1 Structural Model

A three-dimensional analytical model was prepared comprising the tunnel itself, the protective slab, the backfill above the tunnel and the soil beneath the tunnel (Figure 2).

The three-branch tunnel was idealized by means of beam elements, coincident with the axis of each branch, with their section properties computed from their corresponding geometry. Since deformations due to shear had to be accounted for in the analysis, appropriate effective shear areas in the vertical and horizontal directions were computed. Structural damping was taken equal to four percent of critical, which is a typical value for concrete in the non-plastic region.

Plane shell elements, with bending capability, were employed to model the protective slab in sufficient detail for proper representation of its high frequency modes. For the vertical response analysis, the area of the slab where the aircraft impact is postulated was modeled with a finer mesh so that unrealistic concentrated force effects would be avoided (Figure 2). Structural damping of the slab was taken equal to seven percent of critical because of the large strains expected to develop during the aircraft impact.

2.2.2 Soil-Structure Interaction Model

Lumped springs and dashpots were derived to model the backfill and foundation soil compliances. These were distributed beneath the slab and tunnel to simulate the continuous support provided by the soil.

The maximum shear modulus in the soil, calculated from in-situ shear wave velocity measurements, corresponds to practically "zero strain" and must, therefore, be reduced to account for larger strain levels. Thus for computation of shear strains in the backfill and foundation soils, an iterative procedure was used. The static strains under the impact load were first computed for the backfill and foundation soil and were then adjusted to account for the dynamic nature of the load, by applying a correction factor. The ratio of the vertical displacement due to a harmonic concentrated load [2], to the static vertical displacement on the surface of a half-space due to a concentrated load [3] of equal magnitude, was defined as the correction factor, and was applied at the predominant frequencies of the impact history. The differences in phase and amplitude of the harmonics were also accounted for in this process; thus maximum shear strains in the soil were obtained and used for derivation of the soil and backfill shear moduli. The procedure was repeated until the shear moduli became compatible with the shear strains obtained. It is noted that a reduction on the order of 80 percent in shear modulus was obtained in the vicinity of the impact.

The protective slab which extends beyond the width of the tunnel, was supported by the free-field soil compliances, i.e. stiffness and damping (radiation and material), except where underlain by the tunnel, at which place the model of the backfill was introduced. The soil between the slab and tunnel was represented by columns, modeled as one-dimensional three-lumped mass, spring and dashpot systems having the actual mass of the soil, and spring constants adjusted to reproduce the vertical frequencies of the backfill layer. Radiation damping was neglected in the backfill, because of its confinement between the protective slabs and tunnel which will prohibit radiation of energy.

Finally, the tunnel compliance was modeled with distributed springs and dashpots, including distributed rotational springs so that both translational and rotational modes were simultaneously represented. After obtaining strain-compatible shear modulus and damping values, lumped spring constants and damping coefficients were computed for all modes of vibration [4]. These soil compliances were subsequently corrected for frequency and embedment effects. For the horizontal response analysis, the same methodology was followed, except that the model (Figure 3) included only the tunnel and its compliances, as the input excitation already incorporated the effects of the slab and backfill.

The magnitude, duration and frequency content of the impact load are such that, an a priori assumption of a rigid tunnel is not warranted, and therefore, the soil compliances had to be distributed below the base of the tunnel. Furthermore, since coupled translational and rotational modes were anticipated to participate in the response of the tunnel, a higher order Winkler model [5] was developed and the protective slab and tunnel base were represented by an assemblage of independent rigid disks (Figure 4). Thus distribution coefficients were derived and applied under each node of the tunnel model, to obtain the three-dimensional soil-structure interaction model.

The soil radiation damping is viscous while the material damping of structural components and soil are hysteretic in nature. Because damping varies in magnitude and nature, a classical modal analysis is not strictly applicable. However, the motion of the structure can be computed using modal analysis by assuming normal modes and assigning a percentage of critical damping (modal damping) to each mode. Modal damping values, representing composite damping of the interaction system are a function of the vibrational mode and can be computed as described in [6]. This method is incorporated in the computer code "DAPSYS" [7] which was used for the dynamic analyses.

2.2.3 Loading Function

The loading time history describing the aircraft impact is the standard loading function of a military fighter aircraft impacting on structures (Figure 5) [8]. This was digitized at 0.5 millisecond intervals and extended, by adding zeros, to a total duration of 200 milliseconds, for the vertical analysis, in order to represent in the response the free vibration of the system. For the horizontal analysis, the time history was extended, by adding zeros, to 400 milliseconds so that travel times under the tunnel and the longer natural periods could be accounted for.

2.3 Dynamic Analyses and Results

The dynamic analysis consisted of a modal superposition in the time domain to obtain the overall (vertical or horizontal) response of the soil-structure system with "DAPSYS" [7]. The modal analysis included 100 modes of vibration for the vertical response, and 23 for the horizontal response, with frequencies up to 150 Hertz. For effective inclusion of the higher modes in the solution, integration time steps of 0.25 and 0.50 milliseconds were selected for vertical and horizontal analyses, respectively.

2.3.1 Vertical Response Analysis

The response to aircraft impact over the reactor building end of the tunnel, was examined, as this loading would be the most unfavorable. Indeed, mode shapes and participation factors indicated coupled vertical and rocking response about both horizontal axes. Figures 6 and 7 present the vertical response spectra for Nodes 101 and 127 (See Figure 2). The maximum response at Node 101 occured during the time of forced vibration, while at Node 127 it occured during the free vibration shortly after the end of the impact.

2.3.2 Horizontal Response Analysis

When subjected to the aircraft impact, the soil undergoes three-dimensional deformation and waves will propagate radially from the impact point, leading to horizontal and torsional motions which have to be considered simultaneously for the computation of horizontal response spectra. The horizontal response of the tunnel was obtained by calculating the free-field horizontal motion, due to the aircraft impact, and then applying this motion as multiple support excitation to the tunnel model.

The analytical methodology utilized is as follows:

- The three-dimensional model used for the vertical analysis was used for computation of the vertical load time histories in the soil beneath the protective slab.
- The radial displacement time history of a point within the half-space was obtained for a vertical Heaviside load function [9].

- The above load time histories were decomposed to a large number of Heaviside functions and the displacement time histories at the points under the tunnel structure were obtained in the time domain, by superposition for both X and Y directions. Arrival times and delays between the wave components were accounted for at each point.

- The displacement time histories thus obtained were transformed in the frequency domain and smoothed to eliminate discontinuities inherent in the use of the Heaviside functions. Accelerations were then computed in the frequency domain and inverted to the time domain to obtain acceleration time histories.

- Finally, the three-dimensional model for horizontal response (Figure 3) was analyzed using the acceleration time histories, derived as explained above, as travelling wave input motion. It is noted that each free-field nodal point was subjected to two time histories in X and Y directions, and different wave arrival times at each nodal point were incorporated in the analysis.

The above procedure was repeated several times for different impact points until the controlling case was defined. The impact point for the controlling case for this study is shown in Figure 1. Figures 8 through 11 present the horizontal response spectra at Nodes 101 and 127, for the X and Y directions. It was found that maximum response occured after the loading had ended.

3. Integrity of Buried Pipes Subjected to Aircraft Impact

The subject pipes will carry the emergency cooling water of a nuclear power plant and must, therefore, retain their functional integrity following an aircraft impact on the overlying soil. The pipes are circular, 87 centimeters in diameter, and consist of a central steel ring, covered internally and externally by three centimeters of concrete. The pipes will be located seven meters below the plant grade and surrounded by granular backfill having an estimated shear wave velocity equal to 320 meters per second. It is not envisaged to construct a protective slab above the pipes.

When subjected to aircraft impact, the soil will undergo vertical and horizontal deformations, which will decrease with distance from the impact area. Because of the non-uniform displacements imposed on the soil by the impact, the pipes will be subjected to bending and longitudinal forces. In addition, the soil will impose ring deformations on the pipe cross section. The stresses in the pipes obtained from bending, longitudinal forces and ring deformations need to be combined to an equivalent stress for comparison to the allowable stress in the steel.

3.1 Bending Stresses

Due to the small bending stiffness of the pipes, in comparison to the surrounding soil, it was conservatively assumed that the pipes will follow the soil displacements and bend due to differential displacements along their axes. The bending stresses were thus obtained by computing the free-field motion due to aircraft impact and then imposing this motion as deformation to the pipe. The free-field motion was computed making use of data available in the literature [9] for a Heaviside vertical load, in a similar manner as for the horizontal response of the buried tunnel analysis described in Section 2.3.2 of this paper.

The methodology adopted to compute the bending stresses in the pipes is as follows:

- The aircraft impact loading function was decomposed to a large number of Heaviside functions.
- At various distances from the impact point and at the depth of the pipes, the horizontal and vertical displacement time histories in the soil were computed. This was done by superimposing the displacement time histories due to each of the Heaviside functions.
- The displacement time histories were thus obtained for different points along the pipe, accounting for time delays of the various waves as well as for first arrivals at different points.
- The displacement time histories, for the different points along the pipe, were compared and the maximum relative displacement between various points in the pipe determined, in the vertical and horizontal directions.
- These maximum relative displacements were assigned, as prescribed support displacements, to a beam representing the pipe and the corresponding stresses were computed in the pipe section.

3.2 Longitudinal Stresses

The radial soil movement due to the impact loading will cause tension in the pipe. The stiffness of the pipe in the axial direction is greater than that of the soil; therefore, the pipe will undergo smaller strains than the soil. The maximum shear stress that can be transmitted to the pipe is limited by the friction capacity of the soil-pipe interface. The distribution of the shear stresses along the pipe was computed from static solutions for the circular pressure load at the surface corresponding to the maximum value of the impact loading [3]. The shear stresses obtained were checked against the maximum shear stress that can be transmitted, and the resulting distribution of transmittible shear stresses was integrated over the circumference of the pipe and for a length of 13 meters (ten times the radius of the impact area), after which the transmittible shear stress becomes negligible. The total axial force acting on the pipe was thus computed, and the resulting longitudinal stress was obtained.

3.3 Ring Deformation Stresses

The stresses induced in the soil by the impact will also deform the pipe section (ring deformation), generating stresses perpendicular to the pipe axis. The vertical and horizontal stresses, due to the static pressure corresponding to the aircraft impact loading were evaluated at the depth of the pipe for the most severe condition, i.e. for an impact immediately above the pipe. To account for the pipe stiffness, the soil stresses were considered as two uniform stress fields, one horizontal and one vertical, at a large distance from the pipe. Static solutions for the internal stresses in the pipe [3] were then superimposed and the maximum pipe stresses due to ring deformation were computed.

3.4 Design Stresses

The bending, axial and ring deformation stresses in the pipe section were combined to obtain a two-dimensional stress state, for which an equivalent one-dimensional stress was computed, and compared to the allowable stress in the steel. A steel thickness of 12 millimeters was found to be satisfactory for sustaining a postulated aircraft impact.

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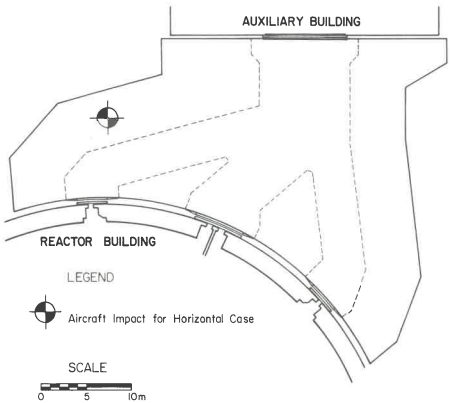
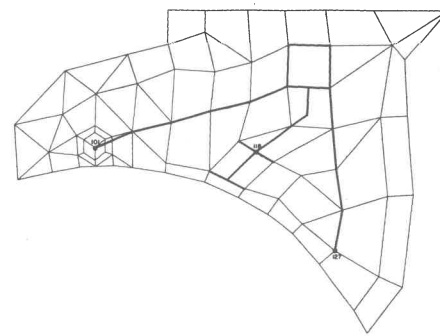


FIGURE 1
GENERAL LAYOUT OF TUNNELS



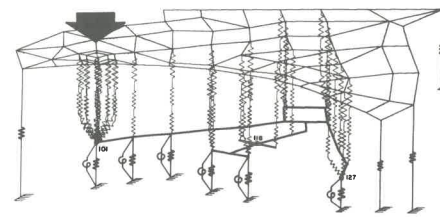
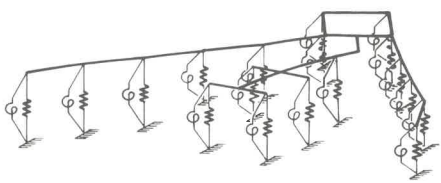


FIGURE 2
SOIL-STRUCTURE INTERACTION MODEL
FOR VERTICAL ANALYSIS



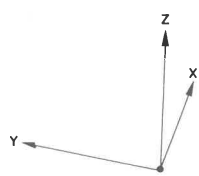


FIGURE 3
SOIL-STRUCTURE INTERACTION MODEL
FOR HORIZONTAL ANALYSIS

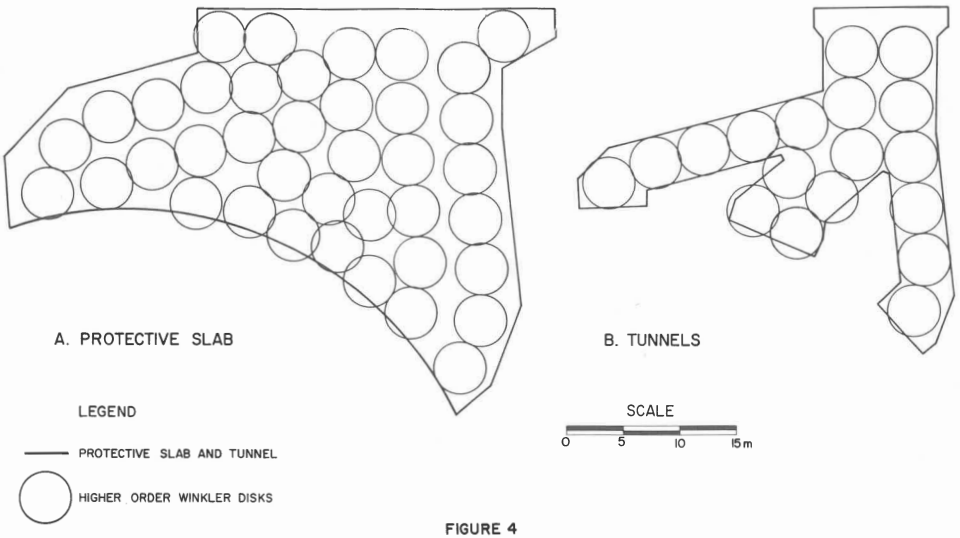


FIGURE 4
HIGHER ORDER WINKLER MODEL

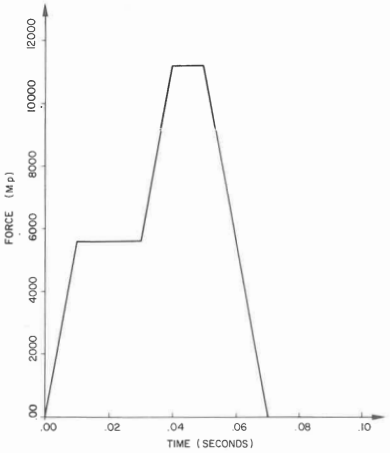


FIGURE 5
IMPACT LOAD TIME HISTORY

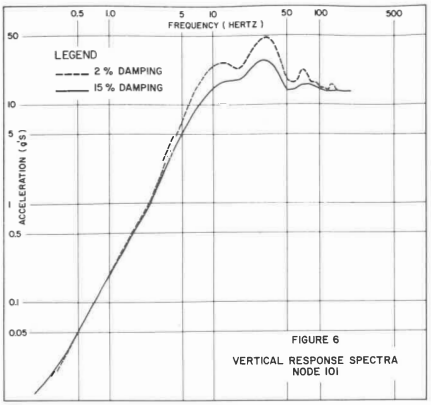


FIGURE 6
VERTICAL RESPONSE SPECTRA
NODE 101

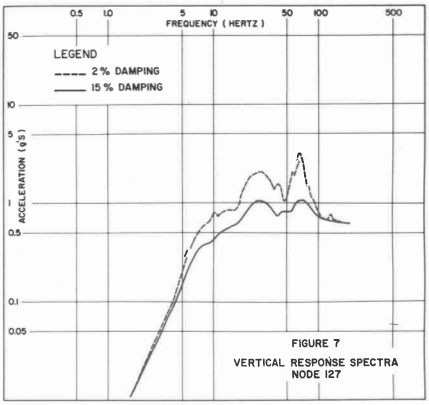


FIGURE 7
VERTICAL RESPONSE SPECTRA
NODE 127

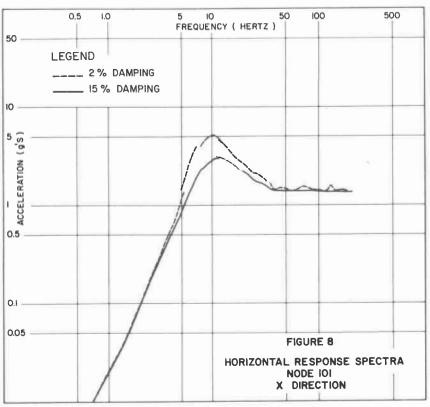


FIGURE 8
HORIZONTAL RESPONSE SPECTRA
NODE 101
X DIRECTION

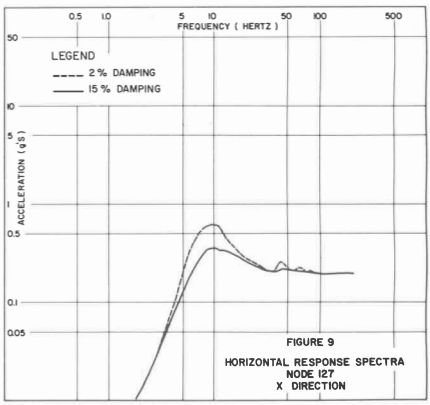


FIGURE 9
HORIZONTAL RESPONSE SPECTRA
NODE 127
X DIRECTION

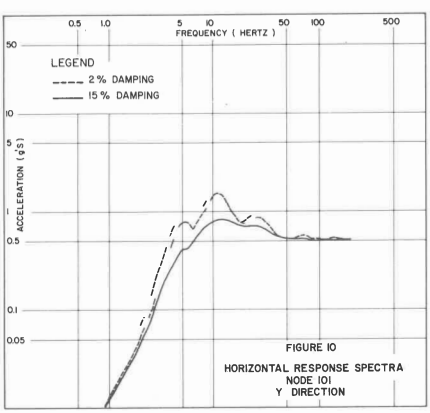


FIGURE 10
HORIZONTAL RESPONSE SPECTRA
NODE 101
Y DIRECTION

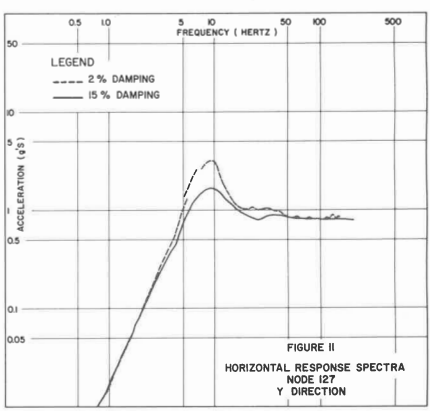


FIGURE 11
HORIZONTAL RESPONSE SPECTRA
NODE 127
Y DIRECTION