DYNAMIC ANALYSIS OF BURIED STRUCTURES SUBJECTED TO SHOCK LOADS

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A systematic method of computing the dynamic structural response of buried structures to shock load, including interaction between the structure and surrounding soil medium, is presented. The complexity of the problem increases because of the high frequency content of the shock load. The purpose of this paper is to describe how the finite element method is sucessfully used to compute structural responses due to schock loads of high frequency content. The method of selecting the various critical parameters (e.g., element size, time step of integration, frequency content, etc.) used in the analysis is also described in detail. Finally, a full-scale practical problem is solved to demonstrate the effectiveness of the proposed method.

1. Introduction

The finite element method (1) is successfully used to compute structural response of underground nuclear power plant structures due to shock load containing high frequency. Axisymmetric finite elements are used to represent the geometry of the system: conical thin shell elements represent the concrete structure, and the axisymmetric quadrilateral and triangular solid elements are used to model the soil continuum (2). The method of modal superposition is usually considered to be quite efficient to perform a dynamic analysis. However, for the type of problem considered here, the frequency up to which the structure may respond may be high due to the high frequency content of the load. This may require extracting a large number of eigenvalues, resulting in an inefficient analysis. The method of direct integration appears to solve this type of problem more efficiently. To use this method successfully, the parameters (time step of integration and the size of the finite element) should be selected very carefully.

The maximum element size to be used in the finite element model determines the highest frequency content of the model. An approximate rule to determine element size ($\Delta \ell$) is to make it equal to or less than c/4f, where $\Delta \ell$ is the maximum size of the element, c is the wave speed, and f is the highest desired frequency content of the model. The above criteria are verified by solving the simple example of a long cylinder subjected to shock load.

The time step of integration, Δ t, usually depends on the type of numerical integration scheme used in the program and the type of problem under consideration. These methods of integration are approximate and the accuracy of the solution depends on the size of the time step used in the analysis. A large time step induces the erroneous effect of period elongation and amplitude deamplification in the responses of the system (4). An appropriate time step is usally taken to be a fraction of the minimum period of interest, i.e., T/N or 1/Nf, where T is the minimum period of interest, f is the frequency corresponding to the period T, and N is a constant. To estimate the desired value of N, a simple one-dimensional cylinder model subjected to shock load is analyzed. A convergence study is made by anlayzing the cylinder model with different Δ t. The response spectra obtained from these analyses were compared. The spectrum for N equal to 25 is very close to the desired spectrum, and those for lower values of N show significant error. Therefore, a value of N equal to or greater than 25 is considered adequate for the analysis.

Finally, a finite element model of an underground nuclear power plant structure with surrounding soil was prepared and analyzed. The maximum element size, $\Delta \ell$, of the finite element model and the time step of integration, Δ t, are obtained from the parametric study mentioned earlier. To further verify the accuracy of determining Δ t and $\Delta \ell$, the same problem was analyzed again with refined Δ t. The responses obtained from both analyses were close. Therefore, it can be concluded that the method of calculating the parameters Δ t and $\Delta \ell$ is adequate for the present analysis.

2. Description of the Problem

Figure 1 shows the sectional elevation of the axisymmetric reinforced concrete nuclear power plant structure with the surrounding soil, and the location of the shock load generated from a nuclear blast. Material properties for concrete and soil in each of the four zones shown in Fig. 1 are given in Table 1. The shock load consists of a peak pressure of 50 psi acting on the surface of a sphere 60 feet in diameter. The triangular pressure time history of the shock load is shown in Fig. 3. The magnitude of the peak pressure is arbitrarily chosen. The purpose of this study is to compute responses at various locations in the containment structure.

3. Method of Analysis

A finite element method of analysis is used to calculate the response of the soil-structure system due to the propagation of waves generated in the medium by the shock load. Axisymmetric finite elements are used to represent the geometry of the system: conical thin shell elements represent the concrete structure, and the axisymmetric, quadrilateral and triangular solid elements (2) are used to model the soil continuum.

The modal superposition method is usually considered quite efficient in performing a dynamic analysis. However, for the type of problem considered here, the frequency up to which the structure may respond may be high due to the high frequency content of the load. This may mean extracting a large number of eigenvalues, resulting in an inefficient analysis. The direct integration method appears to solve this type of problem more efficiently. To use the direct intergration method successfully, the parameters of the analysis (time step of integration and the size of the finite elements) should be selected very carefully. The selection of these parameters is described in Section 5.

The equations of motion are integrated using a step-by-step direct integration method, the Wilson's averaging method (2). The present study uses an implicit method in which the equations of motion at any time step are replaced by a set of simultaneous equations. These equations are then solved for the displacement vector. The velocity and acceleration for the same time step are obtained in terms of the existing displacement velocity and acceleration vectors. The DYNAX (2) computer program, which is based on the theory discussed above, is used in the analysis.

4. Description of Mathematical Model

The components of a typical underground nuclear power plant structure are illustrated in Fig. 1. The finite element model for this system is shown in Fig. 2. The concrete structure is subdivided into a number of conical or cylindrical shell elements (2) and the soil medium is modeled by axisymmetric, quadrilateral and triangular solid elements (2).

When a shock load is applied to a finite element model, spurious oscillations always occur (3). Such oscillations are spurious because they do not represent the physical motion of the continuum. They are generally caused by the disperion and the filtering effect of the discrete elements. Such oscillations may be minimized by selecting a nearly uniform finite element grid (3).

The criteria for selecting element size and time step of integration used in the analysis are described in the following section. To model an infinite medium by a finite medium and to eliminate the reflected waves from the boundary, a special type of viscous boundary (5) is assumed at the base and the side of the finite element model. The damping constants α and β are computed by matching the critical damping ratio of 2 percent at frequencies of 10 Hz and 40 Hz.

5. Parametric Study on Element Size and Time Step

The element size of the finite element model and the lengths of the time step used in the analysis have considerable effect on the final results. This study was made to assist us in choosing these parameters for our problem.

5.1 Element Size

In solving the problem of wave propagation using the finite element method, the element size determines the highest frequency content of the model. An approximate rule to determine element size is to make it equal to or less than c/4f, where $\Delta \ell$ is the maximum size of the elements, c is the wave speed, and f is the highest desired frequency content of the model.

To verify the above criteria, a simple example was solved. A long cylinder, as shown in Fig. 3, was subjected to a triangular shock load. Two different models with element sizes of 6 ft. and 3 ft. were considered. According to the criteria stated above, the highest frequency content of these models should be approximately 40 and 80 Hz, respectively. Response spectra were generated for the point of application of the load using the time histories from the finite element analysis. These spectra are plotted in Fig. 4. It can be seen from this plot that the peak accelerations of these spectra are very close to the theoretical solution (one degree freedom system) for up to about 40 and 80 Hz, respectively. This verifies the frequency content criteria for the finite element model.

5.2 Time Step

The DYNAX program used in this study employs Wilson's averaging method in the integration scheme. It is an approximate method of integration and the accuracy of the solution depends on the time step size used. A large time step size induces the erroneous effects of period elongation and amplitude deamplificantion (4) in the system's response. An appropriate time step is usually taken to be a fraction of the minimum period of interest, i.e., T/N or 1/Nf, where T is the minimum period of interest, f is the frequency corresponding to the period T, and N is a constant. To estimate the desired value of N, the one-dimensional cylinder with $\Delta \ell$= 6 ft. used in Section 5.1 was again analyzed with N = 4, 8 , 16 and 25 (t = 0.006, 0.003, 0.0015 and 0.001 sec., respectively). The response spectra generated for the time histories from those runs for a section 18 ft. below the loaded section are shown in Fig. 5. A time step of 0.001 (for N = 25) can integrate the frequency 40 Hz, which is the frequency content of the model. Therefore, it can be concluded that the spectrum for N = 25 is very close to the theoretical (one degree freedom system) spectrum, and that those for lower values of N show significant errors. The lower the value of N, the greater the error. Therefore, a value of N equal to or greater than 25 is considered adequate for the present study.

The results of the parametric study are used to determine the sizes of the finite element of the model shown in Fig. 2 and the length of the time step to be used in the direct integration scheme. The element size is determined based on a 40 Hz. frequency content of the model. A time step of 0.0006 sec. is assumed to be adequate to integrate the response up to 40 Hz. frequency.

6. Results and Conclusion

After determining the basic parameters needed to compute the responses, the time history analysis is performed for a duration of .16 sec. The time histories and response spectra for 5% damping computed for various locations in the containment structure are shown in Fig. 6-9. To check the accuracy of the results, the same analysis is performed by reducing the length of the time step of integration to 0.0003 sec. The results of this analysis, match almost exactly with those obtained from the analysis with Δ t = .0006 sec. Therefore, for the given element size with a maximum representative frequency of about 40 Hz, a time step of .0006 sec. is adequate. However, if the frequency of interest is more than 40 Hz, the parameters involved in the calculation of responses must be computed again by a method similar to the one described in Section 5.

It can be concluded from the results of this analysis that the finite element method is capable of computing structural responses of buried structures subjected to shock loads of high frequency.

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TABLE 1: MATERIAL PROPERTIES FOR DIFFERENT ZONES

ZONES	MATERIAL	MODULUS OF ELASTICITY, E psf	POISSON'S RATIO, ν	WEIGHT DENSITY, ρ pcf	COMPRESSION WAVE VELOCITY C* ft/sec
1	Crushed Stones	1.1×10^8	0.35	128.8	6643.0
2	Soil above Water Table	1.7×10^7	.4	112.7	3226.
3	Soil below Water Table	4.4×10^7	.4	125.6	4916.
4	Concrete	5.86×10^8	.17	150.	11628.

$$C^* = \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)} \frac{E}{\rho}}$$

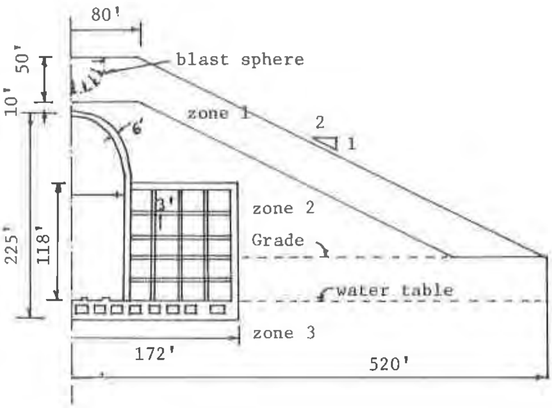

Fig. 1 Sectional Elevation of the Axisymmetric Plant Structures

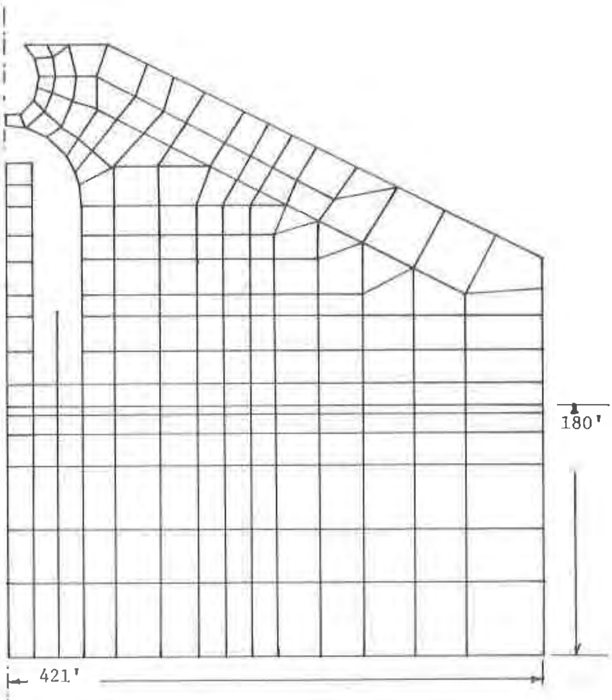

Fig. 2 Finite Element Model

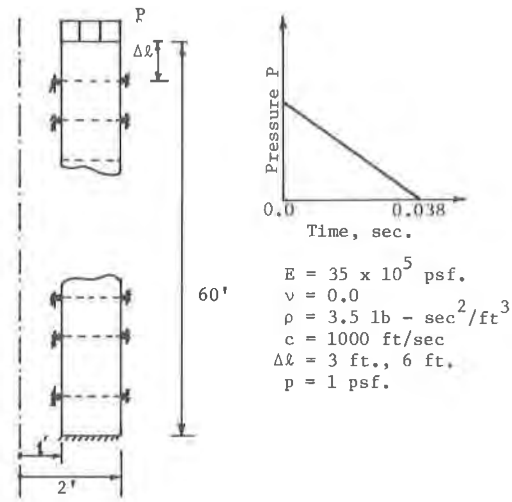

Fig. 3 One-Dimensional Cylinder For Mesh Size and Time Step Study

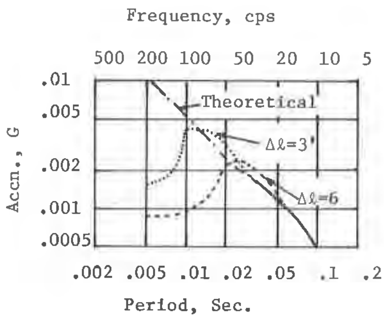

Fig. 4: Response Spectra for Different Mesh Sizes

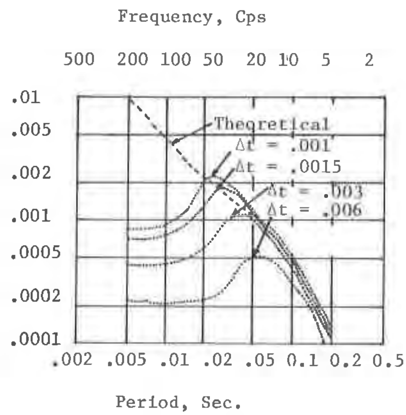

Fig. 5: Response Spectra for Different Time Steps

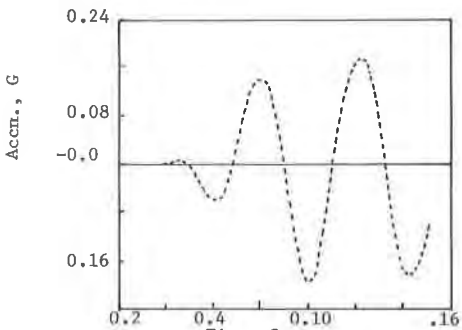

Fig. 6 Time History at the Centre of the Base Slab

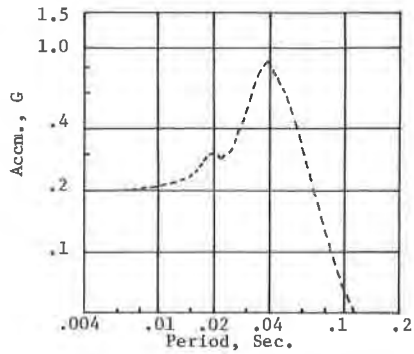

Fig. 7 Response Spectra at the Centre of the Base Slab

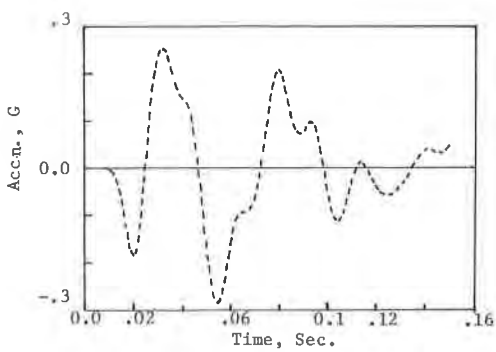

Fig. 8 Time History at the Junction of Containment and the top of Aux. building.

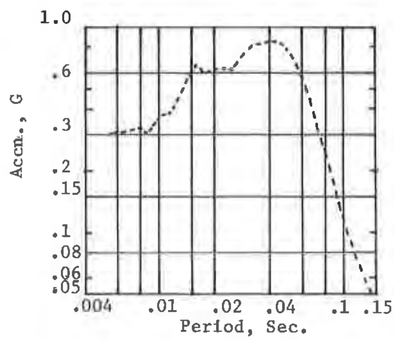

Fig. 9 Response Spectra at the Junction of Containment and the top of Aux. Building.