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SEISMIC VULNERABILITY STUDY OF SIMULATED UNDERGROUND STRUCTURES USING NUMERICAL APPROACH

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ABSTRACT: Solution to the complex phenomenon involving seismic action like accidental explosion could not be easily and accurately achieved except through the use of numerical tool. Various accidental explosion scenarios involving underground structures will require the interaction of quite a number of parameters such as the structures, blast loads, blast duration, ground media, contact definition between the components under consideration, material definition, boundary condition, etc. The numerical tool that is capable of analyzing all these variables to yield the required observed parameters should be examined. This tool should be able to incorporate one or more numerical methods of analysis in its program formulation with a view to simplifying and widening research horizon as well as expanding the application of the numerical tool to other field of research. In the case of modeled underground structures, the required observed parameters after analysis are displacement, pressure, stress and strain which could still be subjected to further analysis.

Keywords: Analysis, Seismic, Numerical, Structures, Underground

1. INTRODUCTION

There are many methods available to determine the dynamic or seismic responses of underground structures due to loads from accidental explosions. These are the analytical methods and the numerical methods. The analytic method is deterministic such as empirical phenomenological and computational fluid mechanics models which are used for explosion load prediction. They are used for elastic response or limited plastic response, and it does not allow for large deflection and unstable responses [6]. There are several numerical methods for assessing the response of underground structures due to dynamic loadings. These are iteration, series methods, weighted residuals, finite increment techniques usually referred to as finite difference, Newmark, Wilson, Newton, Houbolt, Eular, Runge-Kuta and Theta methods. The finite difference is popularly used to solve ordinary and partial differential equations, in particular, dynamic problems [8]; [4].

2. BACKGROUND STUDY

The ground media that could be considered in the study of the dynamic response of underground structures due to loads arising from accidental explosions are loose sand, dense sand and undrained clay. The geotechnical properties of these ground media as revealed by several researchers could be used. For accidental explosions to have taken place outside the vicinity of the underground structures, elastic scenario could be considered. Since the two elastic constants are enough to study the mechanics of such scenarios. These constants are the modulus of elasticity, E, Poisson's ratio and density [8]. Peradventure the blast (i. e. accidental explosion) takes place within the nearby region or proximity of the underground structures, then, more constitutive relations and parameters are required. Therefore, detailed soil test results are required for the study [7].

Load parameters from accidental explosions are also determined experimentally or by means of technical manuals [15] which supersede other technical manuals like TM 5-1300 (1990) could be used to predict positive phase at various stand-off points. Pressure is the determining factor in the design and dynamic response of underground structures due to surface accidental explosions. In order to evaluate ground shock parameters due to underground accidental explosions, parameters such as peak particle displacement, peak particle velocity, loading wave velocity etc. could be determined. Soil test results are required in the final design to accurately determine the density and loading wave velocity of the particular soil at the exact site location [12].

3. PROBLEM DEFINITION

Underground structures are basically structures constructed below the ground surface consisting of many different elements and various forms as the case may be depending on the functions cost as well as the applications as detailed in Figure 1.

4. ANALYSIS OF THE CONSTITUENTS OF SEISMIC ACTION OF ACCIDENTAL EXPLOSIONS

In this study, the numerical approach for studying the dynamic response of modeled underground structures due to loads from accidental explosions will be examined. This is with a view to examining its application and incorporation into available numerical tool(s) or code(s).

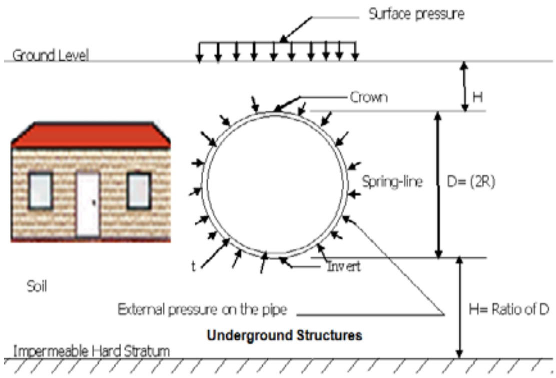


Fig. 1: Cross-section of buried/underground structures [10]; [12]; [16]

4.1 Finite Difference Method

Finite Difference Method is the former name for Finite Element Method, which allows the incorporation of certain features that makes it possible to be used in the ABAQUS software package for studying the response of underground structures due to various accidental explosions. Finite difference methods can be implicit method where the partial differential equation could be solved indirectly by solving a system of simultaneous linear equations. In this case, convergence is always assured. In other words, it could be explicit method where the partial differential equation could be solved directly using the appropriate boundary conditions and proceeding backward in time through small intervals until the determination of optimal path. In this case, convergence is assured for specific size of increment length of interval. The main principal reason for using implicit solution method is to allow for large time-step size, though it is more complex to program and require more computational effort in each solution step.

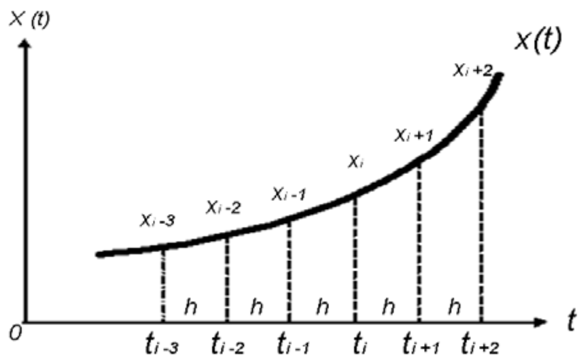


Fig. 2: Finite difference discretization

Mathematically, finite-difference methods are numerical methods for approximating the solutions to differential equations using finite difference equations to approximate derivatives. In this method, there is always a difference in the approximation and the exact solution known as error. The two main sources of error in finite difference methods are round-off error and truncation error or discretization error, that is, the difference between the exact solution of the finite difference equation and the exact quantity assuming perfect arithmetic [4]; [9]; [13].

Looking at the function x (t) shown in Figure 2 having grid points of i to be 1, 2, ... n along the coordinates t equally spaced with interval of h. Taylor's series could be used to express in terms of xi as shown below

$$f(x)= f(h_i)+(h-h_i)f'(h_i)+\frac{(h-h_i)^2}{2!}f''(h_i)+\cdots+\frac{(h-h_i)^n}{n!}f^{(n)}(h_i)+\cdots \quad 1$$

Evaluating at point t_{i+1}, we have

$$f(x_{i+1})= f(h_i)+(h_{i+1}-h_i)f'(h_i)+\frac{(h_{i+1}-h_i)^2}{2!}f''(h_i)+\cdots+\frac{(h_{i+1}-h_i)^n}{n!}f^{(n)}(h_i)+\cdots \quad 2$$

Truncating the series after the first derivative (f' = dy/dx) term, we have,

$$f(x_{i+1})\approx f(h_i)+(h_{i+1}-h_i)f'(h_i) \quad 3$$

Solving for the first derivative, i. e. $f' = \frac{dy}{dx}$ = the rate of change of a dependent variable, such as y, with respect to an independent variable, such as x gives the forward difference approximation of the first derivative

$$f'(x_i)\approx\frac{f(x_{i+1})-f(x_i)}{x_{i+1}-x_i} \text{ or better still } f'(x_i)\approx\frac{f(x_{i+1})-f(x_i)}{h} \quad 4$$

Backward difference approximation of the first derivative gives

$$f'(x_i)\approx\frac{f(x_i)-f(x_{i-1})}{x_i-x_{i-1}} \text{ or better still } f'(x_i)\approx\frac{f(x_i)-f(x_{i-1})}{h} \quad 5$$

While the central difference of the first derivative gives

$$f'(x_i)\approx\frac{f(x_{i+1})-f(x_{i-1})}{2h} \quad 6$$

Solving for the second derivative (i. e. $f'' = \frac{d^2y}{dx^2} = \frac{d}{dx}\left(\frac{dy}{dx}\right)$) gives the forward difference approximation of the second derivative

$$f''(x_i) \approx \frac{f(x_{i+2}) - 2f(x_{i+1}) + f(x_i)}{h^2} \qquad 7$$

Backward difference approximation of the second derivative gives

$$f''(x_i) \approx \frac{f(x_i) - 2f(x_{i-1}) + f(x_{i-2})}{h^2} \qquad 8$$

While central difference approximation gives

$$f''(x_i) \approx \frac{f(x_{i+1}) - 2f(x_i) + f(x_{i-1})}{h^2} \qquad 9$$

The truncation error in the centered difference approximation is of the order of h^2 while the truncation error in the forward and backward difference approximation is of the order of h. Central difference approximation is more accurate than the forward or backward difference approximation and as a result of this, it could be used in the study of the response of modelled underground structures due to loads from accidental explosions to solve the equation of motion using explicit integration scheme in any available numerical code. Most of the numerical methods in the analysis of dynamic problems are based on the finite difference approach [8]; [12]. Direct-integration dynamics of time integration in the explicit integration scheme of central difference method of numerical method could be used to solve the equations of motion (Eqs 10, 11 or 12) of the system. This is integrated through time. That is,

$$[m][\dot{U}] + [c'][\dot{U}] + [k][U] = [P] \qquad 10$$

This could be rewritten as

$$[m]\frac{d^2x}{dt^2} + [c']\frac{dx}{dt} + [k][x] = F(t) \qquad 11$$

This could also be rewritten as

$$[m]f'' + [c']f' + [k]f = F(t) \qquad 12$$

for $U_{(t=0)} = U_0$ and $\dot{U}_{(t=0)} = \dot{U} = V_0$ 13

$$P = m\frac{x_{(1+1)} - 2x_i + x_{(i-1)}}{(\Delta t)^2} + c\frac{x_{(1+1)} - x_{(1-1)}}{2\Delta t}kx_i = Pi \qquad 14$$

where $Ui = U(t)$ and U_{+1} can be written as

$$U_{(i+1)} = \frac{1}{\frac{m}{h^2} + \frac{c'}{2h}}[\{\frac{2m}{h^2} - k\}Ui + \{\frac{c'}{2h} - \frac{m}{h^2}\}U_{(i-1)} + Pi \qquad 15$$

where m, c, and k are element mass, damping and stiffness matrices and t is the time. U and P are displacement and load vectors while dot indicate their time derivatives. $\ddot{U}_o$ is known from the given initial conditions while i is the increment number of an explicit dynamic step. The terms $_{i+1}$ and $_{i-1}$ refers to mid-increment values. The time duration (period) for the numerical solution could be divided into intervals of time Δt (h). It should be noted that with no damping

$$\Delta t \le \frac{2}{\omega \max} \qquad 16$$

for stable and satisfactory solution or with damping

$$\Delta t \le \frac{2}{\omega \max}(\sqrt{1 + \xi \max^2} - \xi \max) \qquad 17$$

$$\ddot{U}o = (m)^{-1}(Po - c\dot{U}o - kUo) \qquad 18$$

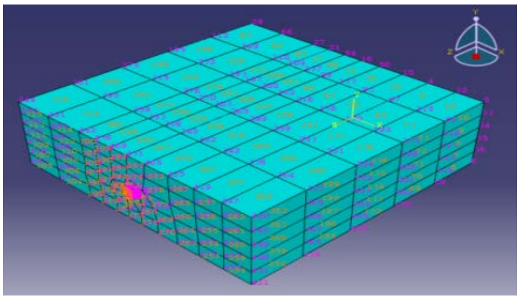
$$U_{-1} = Uo - h\ddot{U}o + \frac{h^2}{2}\ddot{U}o \qquad 19$$

$\omega \max$ is the maximum natural frequency, $\xi \max$ is the critical damping factor. Stability limit is the largest time increment that can be taken without the method generating large rapid growing errors. The accuracy of the solution depends on the time step Δt = h. However, there are some conditionally stable methods where any time step can be chosen on consideration of accuracy only and need not consider stability aspect [2]; [8]; [10].

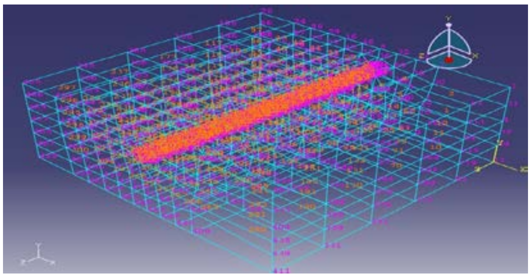
4.2 Bulk Viscosity

Bulk viscosity introduces damping associated with the volumetric straining. Its purpose is to improve the modeling of high-speed dynamic events like accidental explosions, crash, etc. Basically there are two forms of viscosity in explicit that could be used in the study. The first is found in all elements and is introduced to damp the oscillation in the highest element frequency. This damping is sometimes referred to as truncation frequency damping. It generates a bulk viscosity pressure, which is linear in the volumetric strain. The second form of bulk viscosity is found only in solid continuum element. This form is quadratic in the volumetric strain rate. The bulk viscosity pressure is not included in the material point stresses in the simulation because it is intended as a numerical effect only; it is not considered to be part of the material's constitutive response. Linear bulk viscosity is always included in explicit with default values of 0.06 and 1.2 for linear and quadratic viscosity respectively to control oscillations in the model during analysis failure of which would result to termination of the analysis [2].

Using the explicit integration scheme in ABAQUS CAE (Complete ABAQUS Environment) to solve equation of motion (i. e. eq. 10, 11, or 12) makes it unnecessary for the formation and inversion of the global mass and stiffness matrices [M], [K]. It also simplifies the treatment of contact illustrated in Figures 3 (a, b & c) between the constituents of blast and requires no iteration. This means that each increment is relatively inexpensive compared to the increments in an implicit integration scheme. It also performs a large number of small increments efficiently. Explicit integration scheme are used for the analysis of large models with relative short dynamic response times and extremely discontinuous events or processes. This makes it relevant and justifiable to be used for the analysis of the study of the response of underground structures due to loads arising from accidental explosions because blast is a short discontinuous event, or better still, it is an artificial earthquake [14].



a



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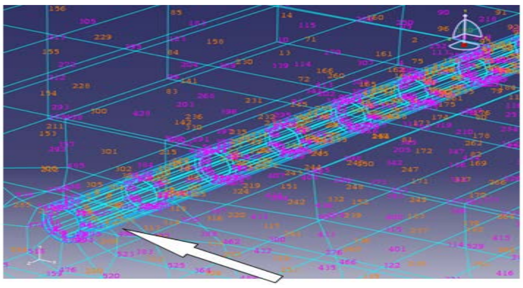

c

Fig. 3: (a) Finite element model (a) Soil model and (c) Pipe model

4.3 Hourglassing

The reduced-integration scheme has a disadvantage such that it can lead to mesh instability during analysis. This instability is known as hourglassing. This consequence does not cause any strain, consequently it does not contribute to energy integral. It only behaves in a manner that is similar to that of a rigid body mode. The common causes of this consequence if excessive are the concentrated of forces at a single node and in the study of the response of underground structures due to blast loads, the forces could be distributed among several nodes by applying a distributed load; hence, hourglasing would be avoided and secondly, boundary condition at a single node which could be rectified in the study by distributing the boundary constraint among several nodes [1]; [10].

4.4 Contact Definition

In the study of the dynamic response of underground structures due to accidental explosions, there are soil-structure interactions from the various parameters that are involved in the analysis. As a result of these, there is need for the definition of these interactions between the constituents of blast. The explicit integration method efficiently solves extremely discontinuous events. Contact is an extremely discontinuous form of nonlinearity. It is possible to solve complicated, very general, three-dimensional contact problems with deformable bodies in ABAQUS/Explicit numerical tool. It provides two algorithms for modeling contact: (a) General contact, which allows the definition of contact between many or all regions of constituents of blast in a model with a single contact; (b) Contact pair, which describes contact between two surfaces and it requires more careful definition of contact. In this case, every possible contact pair interaction must be defined and it has restrictions on the types of surfaces involved. The pair algorithms could be used for two-dimensional models. Contacts between the constituents of blast could be defined for various coefficients of friction and parametric studies using this algorithm [1]; [2]; [11].

4.5 Factors to be considered in the selection of Numerical Tools

In other to select a numerical tool to the study of the response of underground structures due to various accidental explosions, the various constituents and their interactions must be taken into consideration. This interactions involves the contact between the constituents. ABAQUS/Explicit numerical tool provides the capability to analyze high-speed dynamics like drop test and crash analyses of structural members as well as large, nonlinear, quasi-static analyses like deep drawing, blow molding, and assembly simulations. It can also analyze high discontinuous post buckling and collapsing simulations as well as extreme deformations like bulk metal forming, impact and crushing, coupled temperature-displacement (dynamic) and structural acoustics. Other challenging problems which ABAQUS/Explicit can handle efficiently and effectively are: rubber door seal, wire crimping, gas tank impact, column impact, metal forming, wiper blade, etc.

The advantages of ABAQUS/Explicit over other modules in the numerical code are; it has been designed to solve highly discontinuous, high-speed dynamic problem efficiently and it has a very robust contact algorithm that does not add additional degrees of freedom to the model. In addition to these, it does not require as much disc space as ABAQUS/Standard for large problems and it often provides a more efficient solution for very large problems. It also contains many capabilities that make it easy to simulate quasi-static problems, among others. Finally the impact analysis (including all deformable components) uses elastic materials and the constitutive models available for all materials commonly found in impact analysis are: Elastic/plastic models for metals, soil, etc; Pressure-dependent plasticity models for thermoplastics; Hyper-elastic models for solid rubbers; Hyper foam models for foam rubbers; Failure models for vulnerability analysis and solder joint; etc. Most materials can be made strain-rate and direction dependent. The limiting factor is generally the availability of material data [1], [17], [18], [19].

5. CONCLUSION

The various numerical methods were highlighted and constituents of blast were equally discussed. The numerical method that could be used for the study of the dynamic response of underground structures due to various blast scenarios was discussed. The numerical tool that could be used was also mentioned with focuses on finite difference incorporating finite element in the analysis, bulk viscosity, hourglassing, contact definition, impact analysis, deciding factors, etc. Finally, various applications of ABAQUS numerical tool with emphasis on ABAQUS/Explicit were extensively discussed.

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