NONLINEAR SEISMIC RESPONSE OF A SERIES OF INTERACTING FUEL COLUMNS CONSISTING OF STACKED ELEMENTS

T.H. LEE and D.A. WESLEY

General Atomic Company, San Diego, California 92138, U.S.A.

SUMMARY

A theoretical investigation of the dynamic response of an HTGR core during a seismic disturbance has been conducted by developing a nonlinear dynamic model to characterize the motion of the fuel elements in a vertical plane of the core. The analytical model considers a series of fuel columns placed in a plane with boundary structures at the two ends simulating the reflector columns which are elastically supported by the prestressed concrete reactor vessel (PCRV). Each column is formed by a series of stacked fuel elements constrained by dowels which restrict the relative horizontal movement but allow vertical and rocking motions between elements. The fuel columns are separated from one another by gaps. The motions of the doweled elements are interacting with those of the adjacent columns or boundary structures through the phenomena of impact.

The solution to the problem was made computationally feasible by using only the rigid-body displacements of each individual fuel element as coordinate variables and thereby minimizing the total number of degrees of freedom required. The elements are treated as rigid bodies with only surface flexibility characterized by discrete spring elements. For the two-dimensional problem considered here, each element has two translational displacement coordinates and one rotation coordinate. The nonlinear governing equations were derived, using the Lagrangian formulation, with consideration of large rotation effects.

Numerical results are presented for the motions of the fuel elements. Both the free-vibration responses and the forced motions due to boundary excitations resulting from earthquake motion are discussed. Computations were made for problems involving a single column as well as multiple columns. In the multi-column problems, both the staggered and non-staggered configurations were studied.

Some experimental results of the fuel element motions are also discussed. For the simpler problems in which the response quantities could be accurately measured, good correlation between the theoretical results and experimental values has been achieved. The results of this investigation have indicated that the idealization adopted in the fundamental modeling of stacked elements is reasonably accurate in predicting the dynamic behavior of the fuel columns during earthquakes.

1. Introduction

The large high-temperature gas-cooled reactor (HTGR) core consists of many thousand hexagonal graphite elements [1]. These individual elements are stacked to form several hundred fuel columns. In each column, the stacked elements are constrained by dowels placed at the element-to-element interfaces as shown schematically in Fig. 1. The restraining effects of these dowels are to prevent the relative horizontal movement but allow vertical and rocking motions between elements. The fuel columns are separated from one another by gaps. During an earthquake of sufficient magnitude to cause rocking, the motions of the doweled elements interact with those of the adjacent columns or boundary structures through the phenomena of impact. This paper presents an analysis technique employed in a theoretical investigation of the dynamic response of such core structures during a seismic disturbance.

The dynamic response of an HTGR core has been studied by using an analytical model to characterize the motions of the fuel elements in a vertical plane of the core. Similar analytical techniques have also been developed which treat a horizontal section of the core but are not discussed in this paper. The dynamic model, which is intrinsically nonlinear, consists of a series of interacting fuel columns placed in a plane with boundary structures at the two ends simulating the reflector columns (Fig. 1). The reflector columns may be modeled as dissimilar columns or as boundary walls having prescribed input motion.

2. Description of Theoretical Model

The theoretical solution of this problem involves a very large number of degrees of freedom which must be handled in a direct integration process. The required numerical computations were made tractable by using only the rigid-body displacements of each fuel element center of gravity as coordinate variables and thereby minimizing the total number of coupled equations to be integrated. This was done by treating the elements as rigid blocks with only localized surface flexibility represented by discrete spring elements (Fig. 2). The locations of these surface springs are determined from the mode of contact during impact. In general, discrete springs at the block corners are required, and springs may be placed at appropriate intermediate locations in order to improve the stiffness properties for flat-to-flat impacts. All springs have associated viscous dampers which are assumed to be joined in parallel. Unlike the conventional spring-mass systems, the motion of an element due to its own weight, such as rocking on top of one another, is considered in this model. The problem studied here is two-dimensional and, therefore, each element has three degrees of freedom; two translational displacements at the block c.g. denoted by u and w, and one rotation θ. Figure 3 shows the global and local coordinate systems used in the analysis together with the degrees of freedom of a rigid block.

3. Surface Displacement

One of the main advantages of this approach is that no additional degrees of freedom are required for displacements of points on the surface of a fuel block since these displacements are now defined in terms of the c.g. displacements through rigid-body transformation. For example, the two components of the displacement of an arbitrary point p on the block surface (Fig. 3) are

$$u^p = u + \bar{z} \sin\theta - \bar{x}(1 - \cos\theta) \tag{1}$$

$$w^p = w - \bar{x} \sin\theta - \bar{z}(1 - \cos\theta) \tag{2}$$

where $\bar{x}$ and $\bar{z}$ are the Cartesian coordinates of point p in the local reference frame. In writing the equations of transformation (1) and (2), the effects of large rotation are retained. These equations were used in deriving the potential energy terms associated with the surface flexibility which is simulated in the present analysis by the spring deformation. The deformation of a spring, which gives rise to the impact force, is expressed in terms of the relative displacement of two surface points involved in a block-to-block contact during collision.

4. Lagrange Equations for System

The governing dynamic equations for the entire system involving multiple columns may be derived by considering first the equations for a single column. The equations of motion for a single column having N number of fuel blocks may be written as three sets of equations for the degrees of freedom u_i, w_i and θ_i where $i = 1,2,\cdots N$. However, they may be condensed into only one set of Lagrange's equations as follows:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_n}\right) + \frac{\partial R}{\partial \dot{q}_n} + \frac{\partial V}{\partial q_n} + \frac{\partial U}{\partial q_n} = 0, \quad (n=1,\cdots,3N) \tag{3}$$

where q_n are the generalized coordinates defined as the elements in the column matrix

$$\{q\} = \left\{ \begin{array}{c} u_i \\ \vdots \\ \hline w_i \\ \vdots \\ \hline \theta_i \\ \vdots \end{array} \right\} \quad (i=1,\cdots,N) \tag{4}$$

T is the kinetic energy of the column, and V and U are the potential energy expressions associated respectively with the gravity force and the spring deformation. R is the Rayleigh's dissipation function.

Introducing superscripts for identifying fuel columns and adding the energy expressions accounting for the interaction between columns, the Lagrange equations for the multi-column system may be written compactly as

$$\frac{d}{dt}\left(\frac{\partial T^{(r)}}{\partial \dot{q}_n^{(r)}}\right)+\frac{\partial R^{(r)}}{\partial \dot{q}_n^{(r)}}+\frac{\partial V^{(r)}}{\partial q_n^{(r)}}+\frac{\partial U^{(r)}}{\partial q_n^{(r)}}+\left\{\frac{\partial R^{(r-1,r)}}{\partial \dot{q}_n^{(r)}}+\frac{\partial R^{(r,r+1)}}{\partial \dot{q}_n^{(r)}}+\frac{\partial U^{(r-1,r)}}{\partial q_n^{(r)}}+\frac{\partial U^{(r,r+1)}}{\partial q_n^{(r)}}\right\}=0, \quad (5)$$

$$(r = 1,\cdots,K)$$

where K is the number of the column in the system and the terms enclosed in the brackets { } correspond to the interaction forces resulting from the impact against adjacent columns (or boundary structures). The superscript (r,r+1) indicates that the energy expression is associated with those spring-dashpot units for the impact between the rth and r+1th columns.

5. Dowel Model

The dowels are represented as deformable structures with the mating hole clearance taken into consideration. Figure 4 shows two types of dowel representations depending on whether a single (possibly large) dowel or multiple dowels are used. Also shown in Fig. 4 is the representation of the Coulomb friction at the contact surfaces. Since the dowels are not rigid and since clearance between the dowel and the mating hole typically exists, relative sliding motion can occur at the block-to-block interface and a considerable amount of shear force is transmitted in friction. The friction forces vary depending on whether the contact between the blocks is flat to flat or whether rocking is occurring as well as what the vertical acceleration and dead weight forces are between the blocks. The dowel springs also have associated dampers and the dowel clearances need not be uniform.

The detailed procedures for deriving the nonlinear force terms from the energy expressions in Eq. (5) may be found in the paper by Lee [2]. Performing the required differentiation of Eq. 5 leads to a set of equations of the form:

$$I_{ij}\ddot{\theta}_j + M_i^{YV} + M_i^{YB} + M_i^{YS} = 0 \quad , \quad (6)$$

$$m_{ij}\ddot{u}_j + F_i^{XB} + F_i^{XS} = 0 \quad , \quad (7)$$

$$m_{ij}\ddot{w}_j + F_i^{Z} + W_i = 0 \ , \qquad (i,j = 1,2,\cdots,KXN) \quad , \quad (8)$$

where the M_i^Y and F_i^X must be further decomposed into friction and dowel forces for all possible combinations of friction factors, contact conditions, dowel spring constant, dowel spring damping coefficient, and dowel hole gap. The present investigation resulted in the development of a computer code MCOCO (Multiple COre COlumns). The code also has a built-in graphical display capability which can generate displacement plots for visual observation of the fuel block response.

6. Correlation with Experiment

In order to provide a verification of the analytical method described above, the theoretical results of the fuel element dynamic response have been correlated with experimental data for several cases, and will be further validated by means of an extensive test program still underway. Figure 5 shows a comparison between the computer results and the test data for the rocking motion of a single block whose bottom surface is constrained by dowels. As part of the HTGR core seismic test program conducted by General Atomic, the test data were obtained for a 1/5 scale element model in a fuel block rocking study. The block was released from an initially displaced position and its nonlinear free-vibration motion was characterized by an amplitude-dependent period of oscillation. The test values were registered by two gap sensors. For the first two peaks, reliable data were obtained only from one of the sensors owing to an instrument electrical saturation problem.

The analytical models in general can predict the response with reasonable accuracy. To demonstrate the validity of the theoretical model, the theoretical displacement amplitudes of fuel blocks in a 14-block graphite column subjected to harmonic input were compared with the corresponding experimental data after proper adjustment of the parameters in the computer model. The comparison is displayed in Fig. 6. The test was performed for a 1/4 scaled column with a vertical preload of 30 pounds. The displacement amplitudes shown in Fig. 6 are the c.g. lateral displacement of block No. 6 (6th from the top) and the experimental values were taken from the column vibration test reported by Skoff [3]. The computer results exhibited the same nonlinear characteristics as the test data. In general, a close correlation between the motion of a tuned model and that of a test specimen can be achieved for problems in which the response quantities can be accurately measured.

7. Analysis of Multi-Column Systems

In the analysis of systems considering interaction between adjacent columns, both the "staggered" (Fig. 7a) and "non-staggered" (Fig. 7b) configurations were used. In the problem using a non-staggered configuration, harmonic input at 1.0 Hz was used and the columns tend to move in-phase with one another. For the staggered pattern, two components of boundary motion due to artificial earthquake excitation were applied. At the instant the motion was examined (Fig. 7b), the middle column struck its adjacent columns on both sides.

An arbitrary number of columns may be considered in the analysis. Figure 8 shows the response configuration of a staggered 5-column model enclosed in a box type of boundary. At t = 1.3 seconds, the displacement pattern is typified by the phenomenon often referred to as the "element lumping." The figures presented here for the response of multi-column models were traced from the computer-generated plots. It is important to point out that the displaced block positions plotted by the machine have indicated that the element displacements obtained in a theoretical solution are compatible with the constraints imposed on each of the fuel blocks in the system.

Further improvement of the computer model is in progress to incorporate additional effects contributed from the core support blocks (Fig. 9).

8. Conclusions

A theoretical model for studying the seismic response of an HTGR core has been developed by considering a series of interacting fuel columns placed in a vertical plane. The solution is made tractable by using the rigid body displacements for each block together with discrete spring and damper forces to represent surface deformations. Included in the model is the capability to treat problems varying in complexity from single block free rocking response through multicolumn response to two dimensional arbitrary inputs. Flexibility of the locating dowels as well as varying dowel clearances is treated as is the Coulomb friction resulting from relative motion between adjacent blocks. Finally, spring rates resulting from flat to flat or line to line contacts are included in the model.

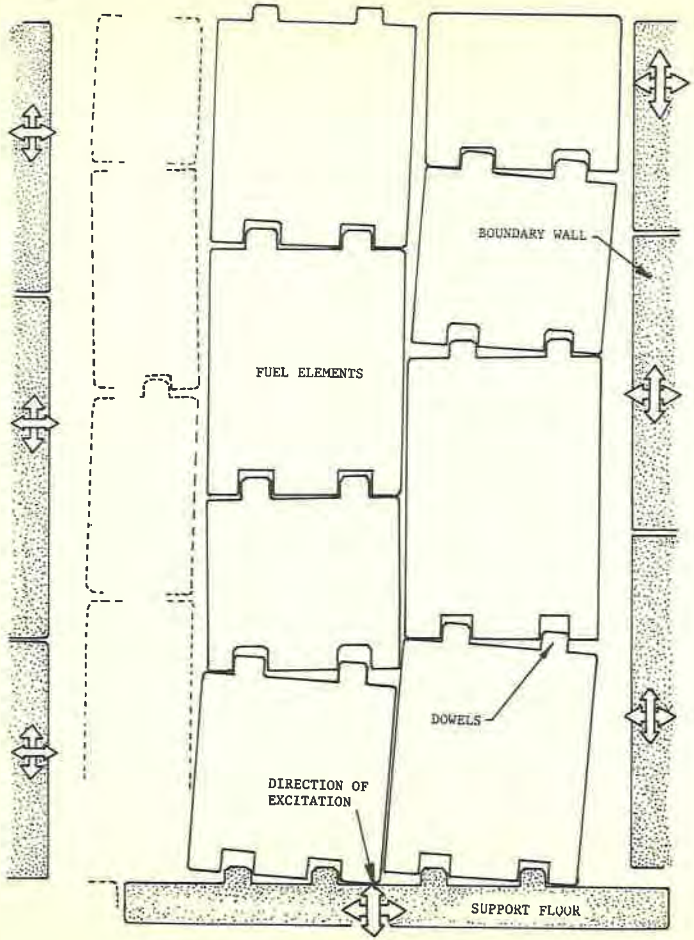
Correlation of the analytical model with several experimental cases is presented. In general, this correlation has been shown to be quite acceptable. It is felt that the dynamic response of an HTGR core including block-to-block and block-to-boundary impact forces, dowel forces, and core restraint system forces can be analytically predicted.

References

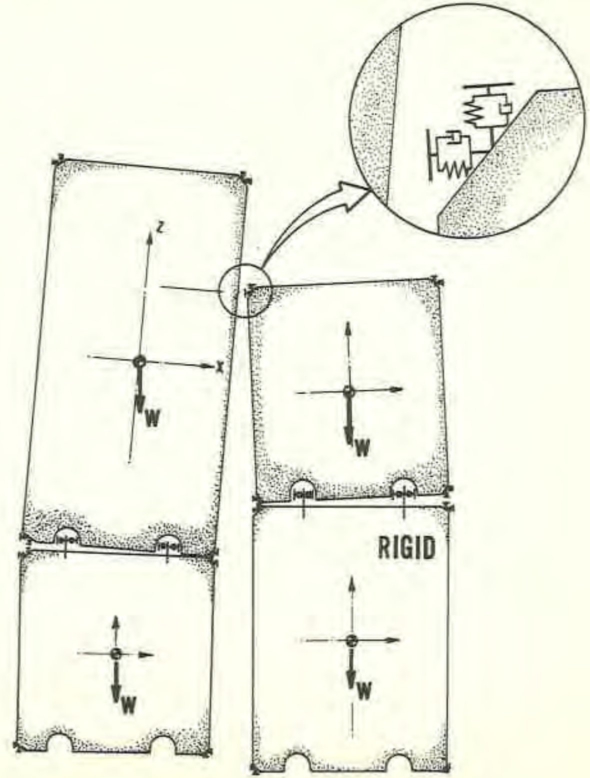
[1] NEYLAN, A. J., GORHOLT, W., "Design Development of the HTGR Core and its Support Structure - Seismic Considerations," Nuclear Engineering and Design, 29 (1974) 231-242.

[2] LEE, T. H., "Nonlinear Dynamic Analysis of a Stacked Fuel Column Subjected to Boundary Motion," General Atomic Report GA-A12933, August 29, 1974. to appear in Nuclear Engineering and Design.

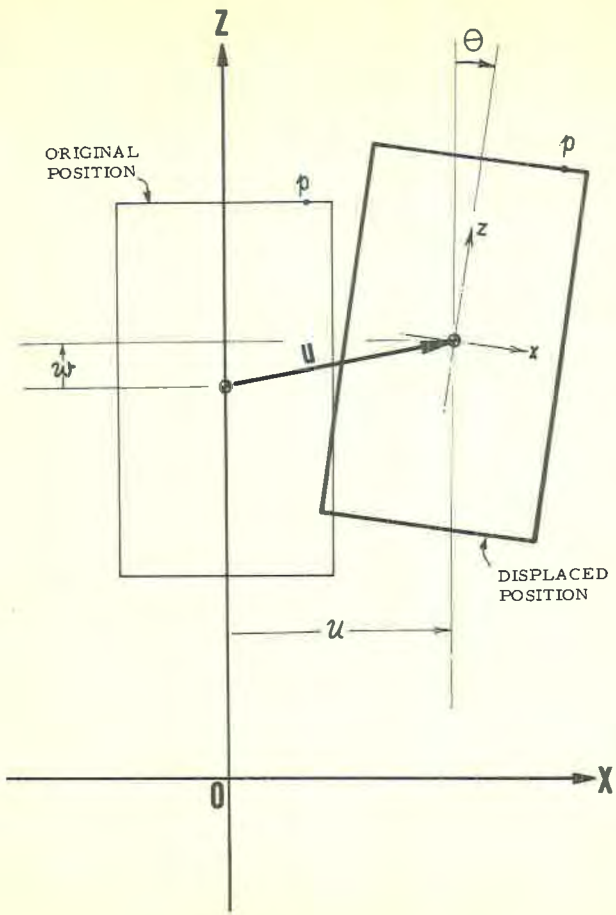
[3] SKOFF, R., "Scaled Column Vibration Test, L-2284", Gulf General Atomic Report GA-P-913-7, July 28, 1970.



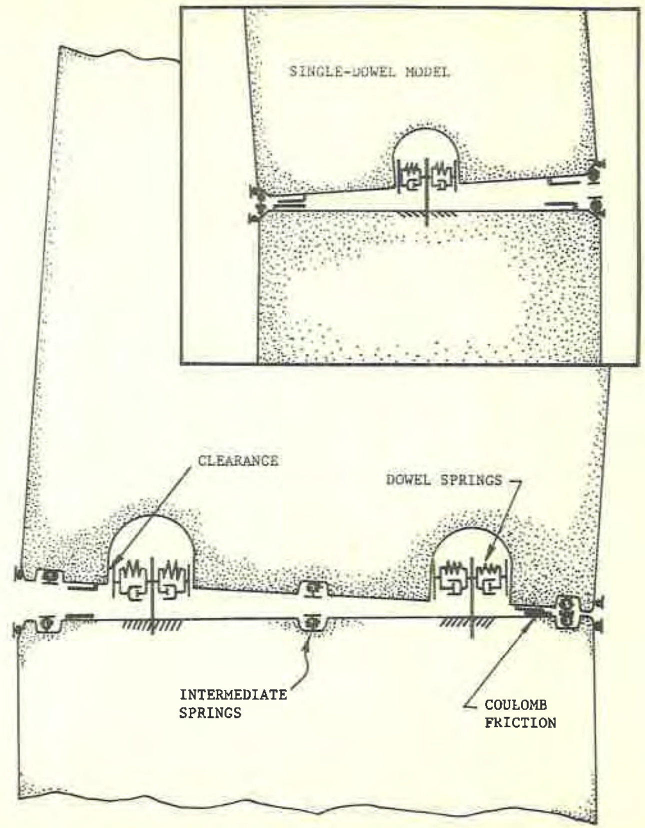
1. The HTGR Core in a Vertical Plane.



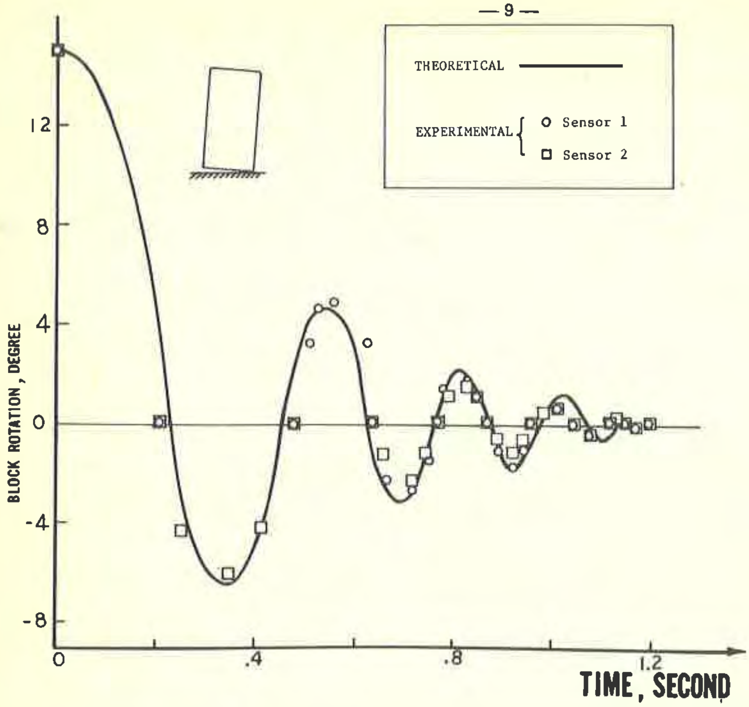
2. Idealized Model with Rigid Blocks and Surface Springs.



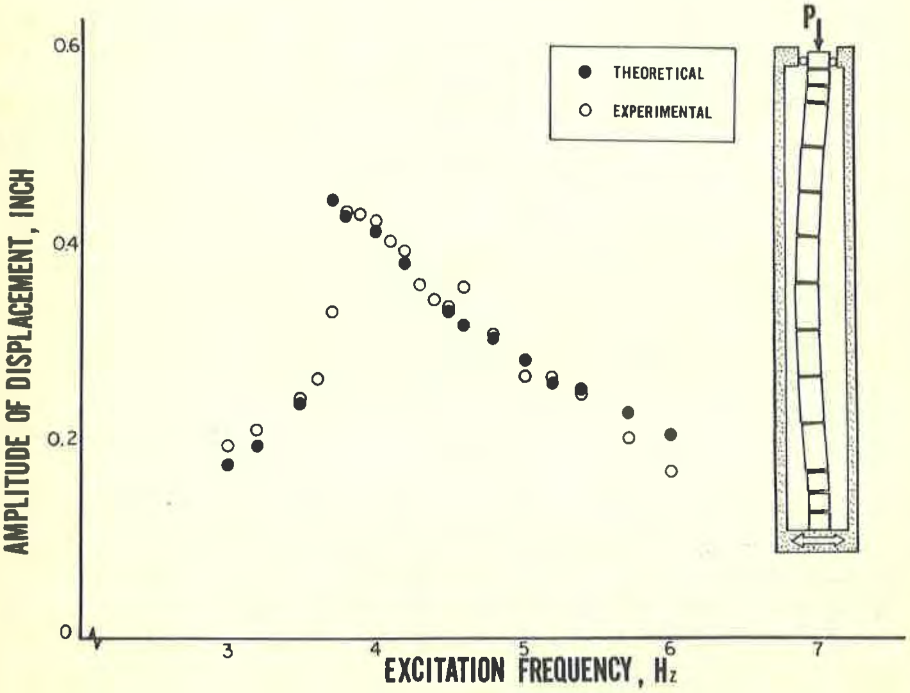
3. Coordinate Systems and Rigid-Body Displacement of Fuel Blocks.



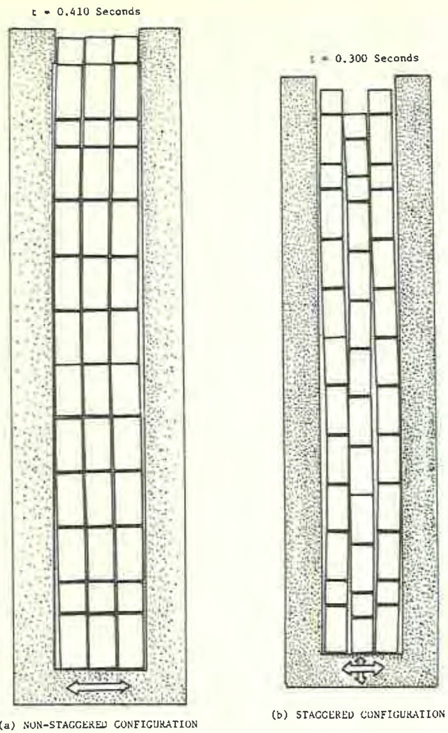
4. Single-Dowel and Multi-Dowel Representations with Coulomb Friction.



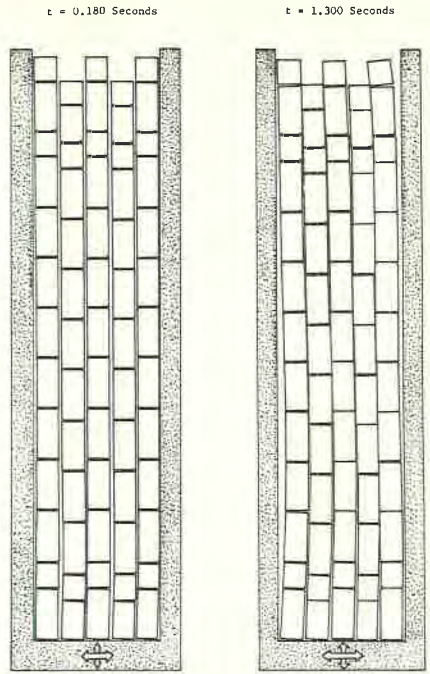
5. Comparison Between Theoretical and Experimental Results of Single-Block Rocking.



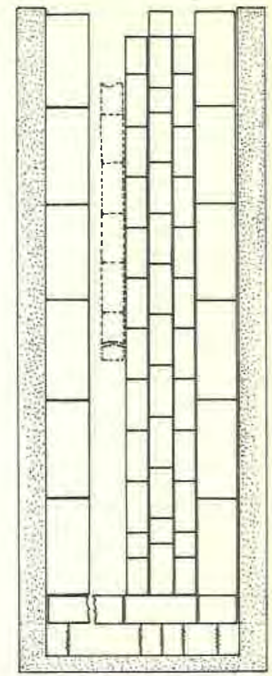
6. Amplitude of Fuel Block in a 14-Block Column as Function of Excitation Frequency.



7. Motion of a Three-Column System Using Two Different Configurations.



8. Response Configuration of a Staggered Five-Column Model Under Boundary Motion Due to Artificial Earthquake Input.



9. Staggered Multi-Column Model with Support Blocks.