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# Soil-structure interaction effects on seismic response of elevated, ground-based, and buried tanks

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## ABSTRACT

Effects of soil-structure interaction on the seismic response of elevated, ground-based, and buried, liquid storage tanks are assessed. Two-dimensional models of x-braced elevated tanks supported on isolated footings and subjected to horizontal ground motions were analyzed under static, dynamic elastic, and dynamic inelastic conditions. Further, the interaction between ground-supported, flexible-base, cylindrical tanks and the underlying soil under vertical ground excitations was examined. Flexibility of the shell and the base plate as well as stiffness and damping characteristics of the foundation soil were included. Lastly, stresses developed in the walls of underground rectangular tanks subjected to three components of ground motion were computed. Wall inertia, liquid hydrostatic and hydrodynamic pressures, in addition to static and dynamic earth pressures were considered.

## ELEVATED TANKS

A common configuration of storage tanks in municipal water supply systems is the elevated type to provide the required head for water distribution. These structures consist of two main parts: a tower and a vessel. The former can be a steel braced frame, a multi-column assembly, or an axisymmetric pedestal shell, whereas the vessel comes in a variety of geometric shapes. Many elevated tanks are regarded as essential facilities, yet they are vulnerable to earthquakes mainly because of the relatively small resistance that the supporting system offers. This has been demonstrated by incidents of seismic damage which have been mostly confined to the supporting system rather than the vessel.

An extensive study of the earthquake response of elevated tank systems was conducted by Ellaithy [3]. It evaluated liquid-induced forces on top of the supporting structures, and estimated the behavior of x-braced towers in both 2- and 3-dimension spaces as well as the response of axisymmetric pedestal towers. The present analysis further examines the effects of soil-foundation-tower interaction on the seismic response of x-braced elevated tanks. Lumped-parameters method is used to model the soil-foundation system, and coupled with a two-dimensional model of a x-braced tower, the static, dynamic elastic, and dynamic inelastic responses of the overall system were evaluated.

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## METHOD OF ANALYSIS

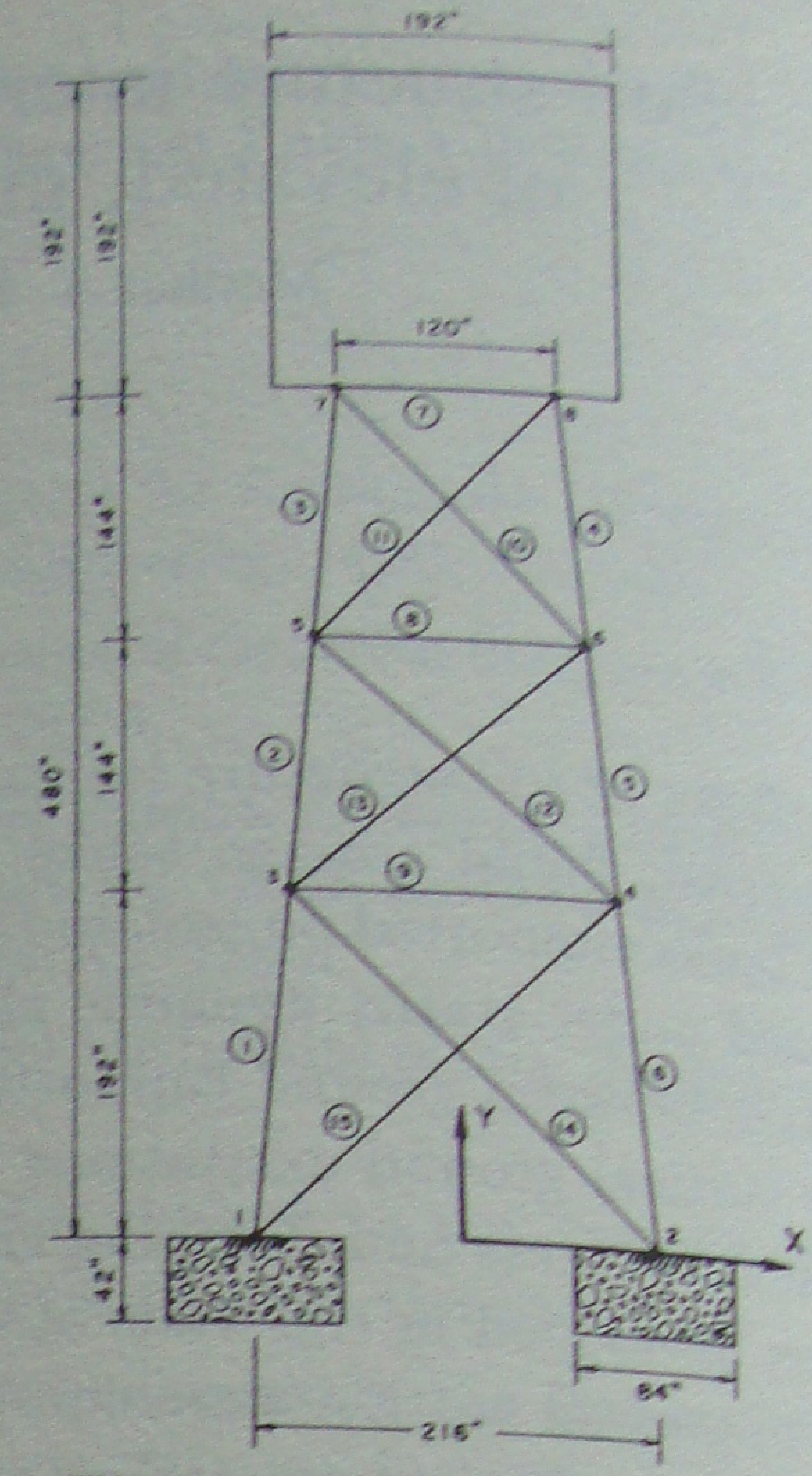

Figure 1: X-braced tower.

A typical tower is essentially a three dimensional structure; however, Ellaithy [3] showed that the difference in response between three- and two-dimensional models ranges from 5% to 10%. Therefore, it was decided to employ a two-dimensional idealization of the tower as shown in Fig. (1). All members numbered 1 to 9 are designed as frame members while the rest are bracing members; their properties and dimensions can be found in [8]. Footings are designed to resist developed seismic uplift forces by both their own weight and the friction forces mobilized along their sides.

In current design standards, soil effects are explicitly represented by coefficients which reflect soil type and amplification of ground motion, but the degree of fixation of the tower as well as the foundation characteristics are not considered. In this study, the foundation system is represented by a discrete three degree of freedom model undergoing vertical, horizontal, and rocking motions, and effects of footings embedment are accounted for by modifying the spring constants.

### UBC-Based Loads

The Uniform Building Code (UBC) [9] and the American Water Works Association Standard D100 (AWWA) [2] are widely used for evaluating equivalent static lateral forces on towers of elevated tanks. The AWWA standard adopts a formula for calculating the total lateral force which is similar in form to that used in the earlier UBC versions prior to 1988. It is noted that the value of the structural system factor for a cross-braced tower supporting an elevated tank was among the highest for all types of structures, reflecting a perceived absence of hidden reserve strength. The UBC no longer requires that supporting towers be designed to resist torsional effects, not to compensate for a loading condition which occurs during failure. The 1988 UBC revised its formula for calculating the lateral shear force and uses a newly-defined structural system factor $R_w$.

### Mechanical Model-Based Loads

In calculating lateral static loads according to current codes, the tank is assumed totally filled with water whose entire weight is augmented with the weight of container and tower to yield the total weight of the structure. As proposed by Haroun, only the weight of liquid accelerating with the vessel shall be considered as an "effective weight" contributing to lateral load computations. These loads are magnified by the ratio of the spectral acceleration, obtained from a response spectrum, divided by peak ground acceleration. Moreover, the additional overturning moment of the vessel must also be considered by equating it to two opposite vertical forces acting at the tower top.

### Soil-Dependent Lateral Forces

Soil-tower interaction affects not only the kinematics of the supporting system but also the values of the equivalent lateral static loads. Changes in the horizontal displacement of the tower in addition to its rocking motion imply a corresponding change in the inertia forces applied at the top of tower. This could be accounted for by evaluating the horizontal and angular accelerations at the tower top through a simplified dynamic analysis of the system, from which the equivalent lateral static forces can be computed.

### Dynamic Elastic Analysis

The response to earthquake excitations was determined by direct time-integration of the matrix equation of motion of the overall system. A Rayleigh damping model was used for the tower whereas the damping matrix of the soil-foundation system was defined by lumped parameters. The water tower was investigated under the action of a horizontal component of ground acceleration of the 1940 El Centro earthquake.

### Dynamic Inelastic Analysis

It is known that bracing members of x-braced towers undergo inelastic deformations. Therefore, the model developed by Ellaithy [3] which incorporates expected theoretical and observed experimental inelastic behavior of such members was used to reproduce the inelastic deformations. The overall stiffness matrix of the supporting cross-braced steel frame and the soil-foundation system was reformulated, but the overall mass and damping matrices remained similar to those used in the elastic analysis.

## ILLUSTRATIVE NUMERICAL EXAMPLES

For the foundation-tower system shown in Fig. (1), the total lateral 1988 UBC-based shear force was found to be 104.2 kips, whereas Haroun's model when used with the ground motion of the 1940 El Centro earthquake (2% damping) yields a total lateral force of 99.2 kips, in addition to two vertical forces, each 40.5 kips, resulting from the rocking motion of the vessel. Figure (2) shows the variation of the horizontal displacement at the top of tower with the shear wave velocity of the soil. It is seen that the UBC and Haroun's model follow the same general trend but have different response values. This is because the UBC formula does not account for the additional overturning moment exerted on the tower by the vessel nor the influence of the height-to-radius ratio of the container on the effective mass of liquid.

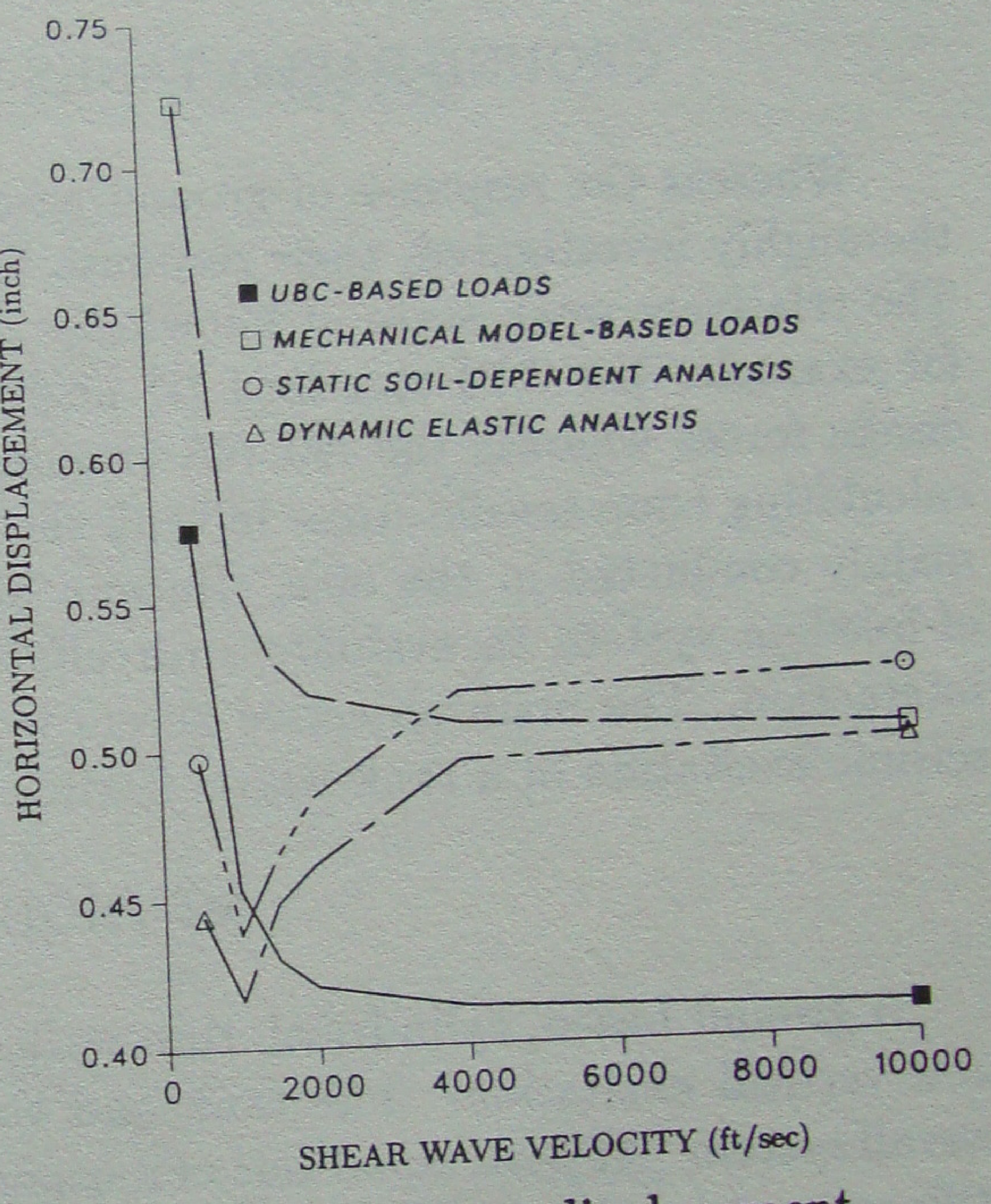

Figure 2: Tower displacement.

Whereas the absolute lateral translations of towers supported on flexible soils are higher than those supported on infinitely-stiff soil, most member end actions are hardly affected as their values depend on the relative displacements between joints. Only bending moments developed at the connection between tower leg and footing were magnified for soft soils.

It was generally noted that employing the mechanical model to evaluate the tower's static response, the resulting displacements and member end actions were usually on the conservative side, especially for soft soils. For stiff soils, the mechanical model reliably predicted the dynamic response of the tower. It was also observed that the inelastic behavior redistributed the internal forces in the tower. Most notably, there was an increase in the member end actions of those members located at or near the top of tower where braces experienced significantly higher axial forces than those obtained from an elastic analysis, and this in turn produced higher end moments in the elastic members. Figure (3) shows that inelastic deformations in braces increase the maximum axial force in bracing member no. 10 whereas they reduce it in member no. 1 for all values of soil shear wave velocity.

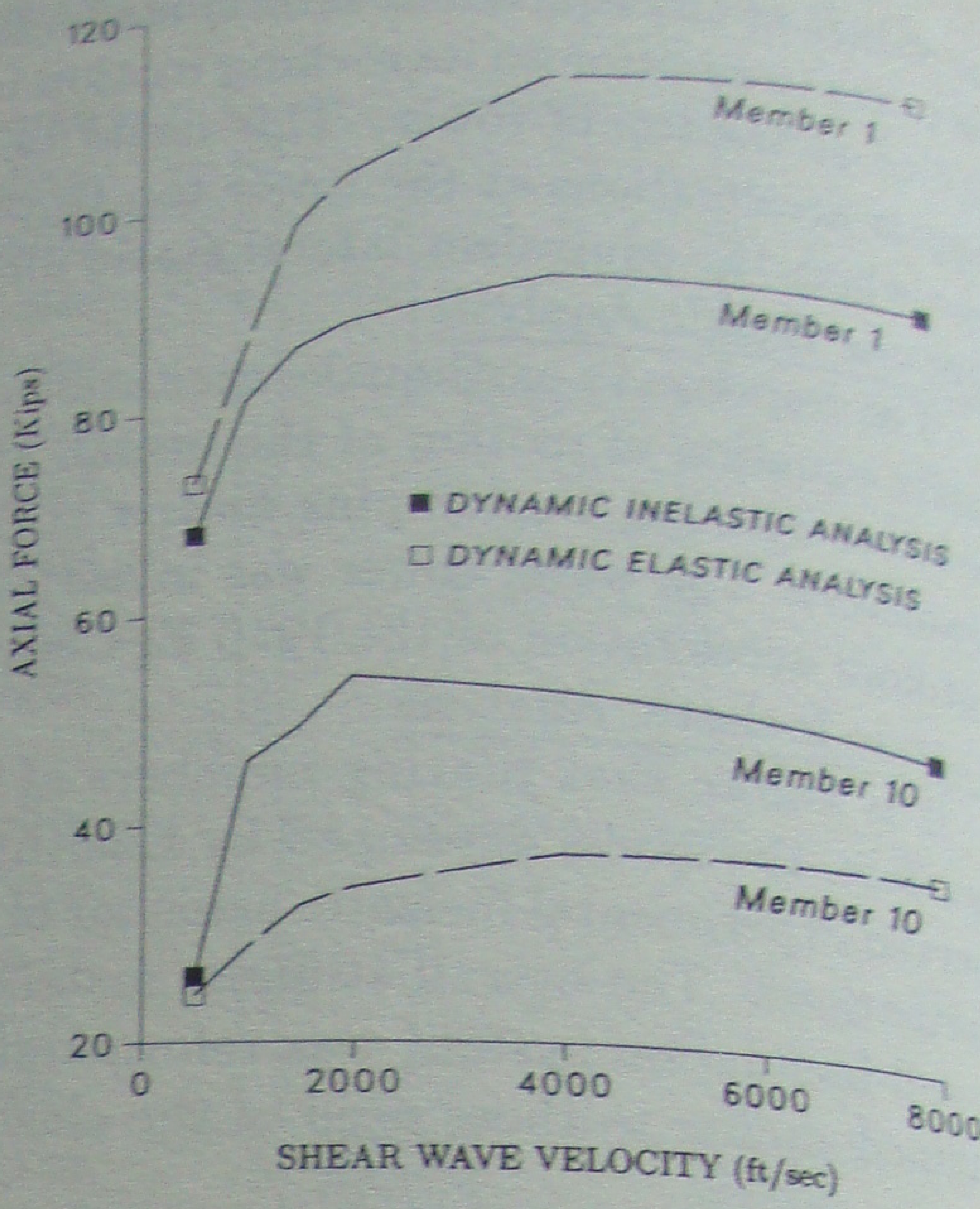

Figure 3: Axial forces.

## GROUND-BASED TANKS UNDER VERTICAL EXCITATIONS

Whereas the response of ground-based tanks to horizontal earthquake excitations was thoroughly investigated, their response to vertical excitations has received little attention. The relatively weak state of knowledge of this behavior is reflected in current standards; for example, the API standard [1] neglects entirely the effects of vertical excitations on design forces whereas the AWWA standard [2] crudely considers such effects, and only in calculating hoop tensile stress in tank shell. Research into effects of vertical excitations was mainly conducted in the 80's. Haroun and Abdel-Hafiz [5] used a simplified two-degree-of-freedom system to evaluate such effects on rigid-base tanks considering soil-structure interaction. The main objective herein is to accurately evaluate the response to a vertical seismic excitation of a tank whose flexible base plate rests directly on a compacted soil.

## METHOD OF ANALYSIS

A ground-based, cylindrical, thin-walled container supported on flexible soil is subjected to a vertical excitation. The tank and the soil were treated as substructures [10] of the overall system. At first, equations of motion of the soil were formulated to obtain its dynamic stiffness matrix; the elements of which represent the dynamic stiffness corresponding to those degrees of freedom located at the interface between soil and tank. Equations of motion of the liquid-filled tank were separately formulated and the dynamic stiffness matrix of soil was then added to the structural stiffness matrix for the degrees of freedom at the interface only. Finally, only the equations of motion of the tank (including soil effects) were solved in the frequency domain to yield its response. Since the free-field earthquake motion is specified at structure-soil interface, this procedure eliminates deconvolution calculations.

In modeling the soil, two types of damping were considered: radiation and material. The former is produced by energy radiation due to propagation of waves away from the structure, whereas the latter is a frictional loss of energy which produces a damping force proportional to displacement but in phase with velocity. As for the other major substructure, the shell was analyzed by axisymmetric ring-shaped finite elements and the base plate was represented by annular elements. Liquid effects were in the form of hydrodynamic added mass on tank shell and base plate, and in this analysis, a novel approach for its computation was adopted [8].

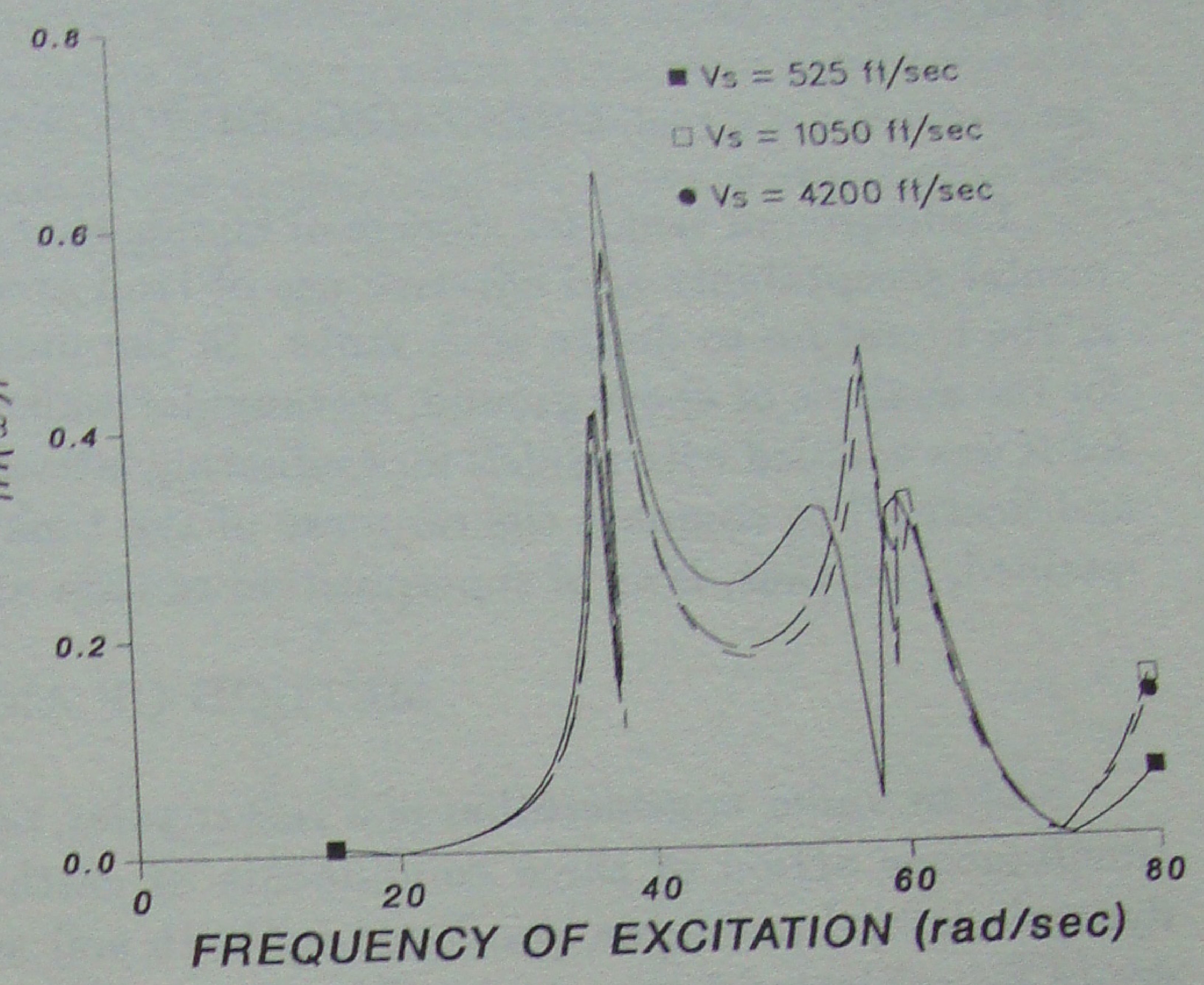

Figure 4: Frequency response functions.

## ILLUSTRATIVE NUMERICAL EXAMPLES

Two tanks representing the class of broad and tall tanks, and three shear wave velocities representing soft, medium, and stiff soils were analyzed, subject to the vertical component of the 1940 El Centro earthquake as free field motion. Figure (4) plots the frequency of excitation versus maximum amplitude of the broad tank's radial displacement. In the case of a tall tank, the effect of changing the stiffness of soil was less pronounced. By employing these transfer functions and applying Fourier Transform, the time history of shell radial displacement can be determined. It was observed that soil-tank interaction, for same material damping ratio, reduces the maximum shell radial displacement on the softer soil to about 60% of that on the stiffer soil. It was also noted that the general shape of time history produced by other vertical components remains similar to that obtained using El Centro record.

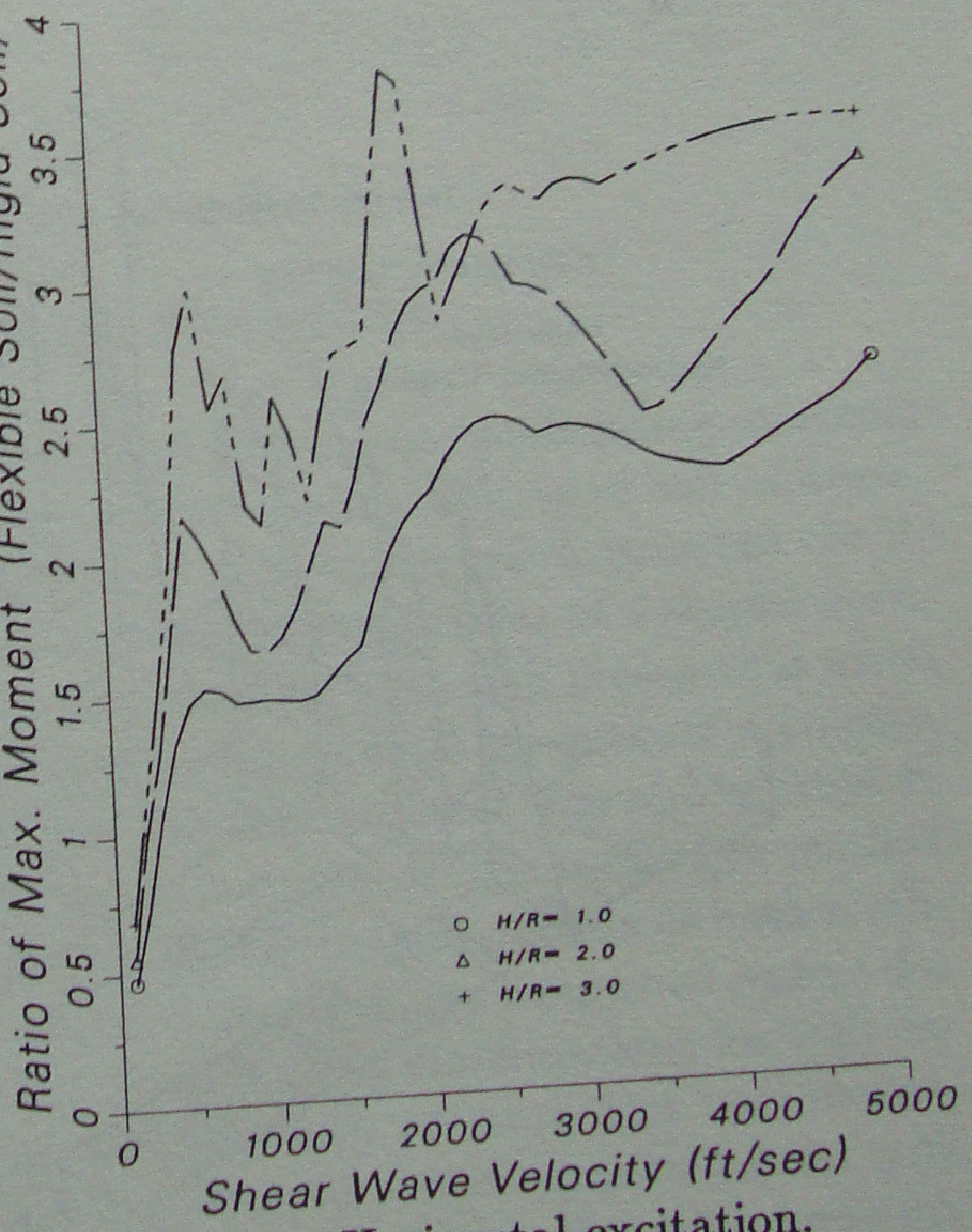

Figure 5: Horizontal excitation.

Observed reduction in tank displacements under vertical excitation is in contrast to the amplification [6] of tank response exhibited under horizontal ground motion as demonstrated in Fig. (5).

## UNDERGROUND RECTANGULAR TANKS

Underground tanks for storage of liquids have beneficial characteristics such as environmental acceptability and effective use of land area. Yet, only a few analyses are available in the literature to design such tanks. In the present study, Haroun's analytical model [4] for the analysis of above ground, rectangular walls under seismically induced hydrodynamic loads was coupled with models for evaluating lateral earth pressures due to Mononabe-Okabe and Scott [7] to compute the response of the tank-soil system. Linearity of the problem is retained, and thus, laws of superposition remain applicable.

## METHOD OF ANALYSIS

System under consideration is a rectangular tank, completely buried, and subjected to simultaneous action of three components of earthquake acceleration. Static and pseudo-dynamic lateral pressures, produced by both soil and liquid, were modeled. A typical wall would be subjected to a system of loads as shown in Fig. (6). Analytical as well as finite element solutions for the deflections and moments were evaluated at discrete points on the wall for each of the loading systems under consideration.

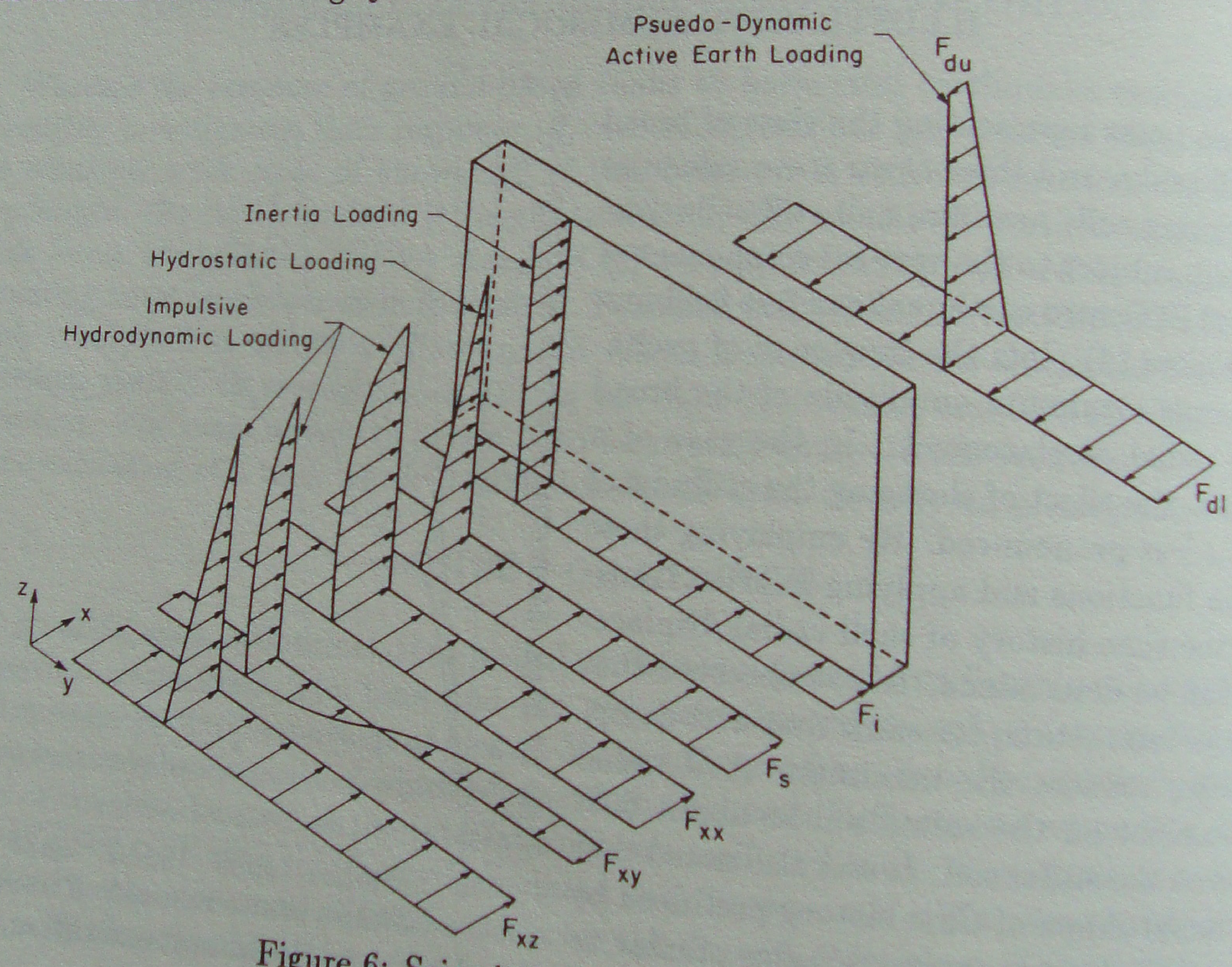

Figure 6: Seismic loads on a typical wall.

Mononobe and Okabe pressure distribution on the wall increases linearly from top to bottom and its value depends on the horizontal and vertical accelerations of an earthquake record. This pressure can also be presented in a convenient way for direct application at the design stage using seismic design coefficients [8]. In an effort to devise a more accurate method to calculate the dynamic earth pressure, Scott presented a model for a soil-retaining wall system in which the soil was considered as one-dimensional shear beam attached to the wall by springs representing soil-wall interaction.

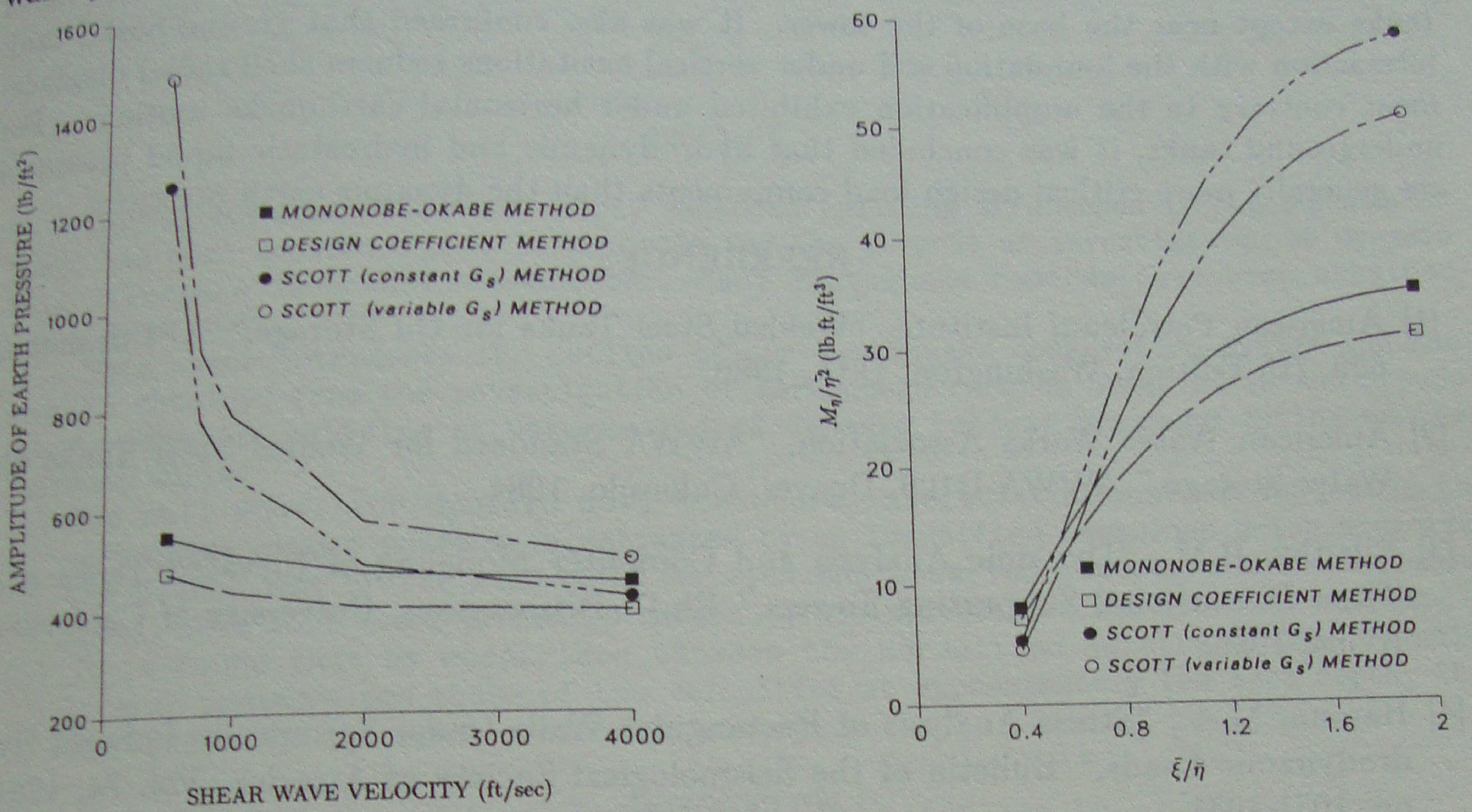

Figure 7: Soil pressure effects on tank wall.

## ILLUSTRATIVE NUMERICAL EXAMPLES

A typical wall is divided into a rectangular mesh, and deflections and bending moments in both directions of the wall are computed at each nodal point. Effects of soil stiffness, expressed by its shear wave velocity, on the amplitudes of dynamic earth pressure are illustrated in Fig. (7). It is seen that soft soils produce higher amplitudes of dynamic earth pressure than stiff soils. Furthermore, discrepancy in evaluating the earth pressures is much larger for soft soils. To depict effects of the wall width-to-height ratio on internal moments, relationships between the wall aspect ratio and the bending moment are also plotted in Fig. (7) for each dynamic earth pressure distribution. Since the design coefficient method has similar pressure distribution as that of Mononobe-Okabe method, results of both methods follow the same trend as far as effects on the wall moment are concerned except for moment amplitudes. In general, one must consider three loading combinations for wall design. In an empty tank, acting loads on the wall are the earth pressure plus wall inertia. For a full tank, an extreme situation occurs when surrounding soil is separated from tank wall. Acting forces, all in same direction, are due to inertia loads, hydrostatic pressure, and hydrodynamic pressure. The last case is for a full tank where acting forces, including opposing forces, are considered. It was observed that, in all possible cases of loading, the hydrostatic pressure was dominant, and therefore, the exclusion of the earth pressure results in the most critical loading case.

## CONCLUSIONS

Soil-tower interaction reduces, in general, the member-end actions in x-braced elevated tanks except near the base of the tower. It was also confirmed that ground-based tank interaction with the foundation soil under vertical excitations reduces shell radial displacement contrary to the amplification exhibited under horizontal earthquake motions. For underground tanks, it was concluded that hydrodynamic and hydrostatic liquid pressures are generally more critical design load components than the dynamic earth pressure.

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