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Dynamic Soil-Structure Interaction Analysis of Reinforced Concrete Buildings

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Abstract**—**The objective of this paper is to evaluate the effects of soil-structure interaction (SSI) on the modal characteristics and on the dynamic response of current structures. The objective is on the overall behaviour of a real structure of five storeys reinforced concrete (R/C) building typically encountered in Algeria. Sensitivity studies are undertaken in order to study the effects of frequency content of the input motion, frequency of the soil-structure system, rigidity and depth of the soil layer on the dynamic response of such structures. This investigation indicated that the rigidity of the soil layer is the predominant factor in soil-structure interaction and its increases would definitely reduce the deformation in the R/C structure. On the other hand, increasing the period of the underlying soil will cause an increase in the lateral displacements at story levels and create irregularity in the distribution of story shears. Possible resonance between the frequency content of the input motion and soil could also play an important role in increasing the structural response.

Keywords**—**Direct method, finite element method, foundation, R/C frame, soil-structure interaction.

I. Introduction

FOLLOWING the Algerian earthquake of magnitude Mw6.8 which struck Boumerdes-Algiers on May 21st, 2003, which is considered among the largest earthquakes to have occurred in the region since the El-Asnam earthquake, Ms7.3 in 1980 [1]. The earthquake caused important damage in the Boumerdes region, where many recent buildings totally collapsed and many of them have been seriously damaged.

A large investigation have been undertaken in order to look for what have caused such defects in modern design buildings. Amongst other causes, soil conditions at the Boumerdes region are suspected to have played a role in the amplification of earthquake input motions. In this respect, taking advantage of the new and emerging concept of seismic structural design, the so-called performance-based design (PBE), careful consideration of all aspects involved in structural analysis are considered. One of the most important aspects of structural analysis is soil-structure interaction (SSI). Such interaction may alter the dynamic characteristics of structures and consequently may be beneficial or detrimental to the performance of structures. Not taking into account these structural response amplifications may lead to an under-designed structure resulting in a premature collapse during an earthquake.

Analytical methods of SSI concentrate mainly on single degree of freedom systems and analysis/design of long and important structures such as large bridges and nuclear power plants, and rarely on regular type buildings. Thus, the main idea behind this investigation is motivated by the fact that there is still great uncertainty as to the significance of seismic soil-structure interaction (SSI) for ordinary structures typically encountered in Algeria. There may be both beneficial and adverse effects of SSI. However, in many cases, SSI is simply ignored in design without establishing whether it will increase or decrease the response of the structure. A second objective is that the probability of an earthquake of magnitude 7 or larger may occur in regions that have experienced strong earthquakes such as El-Asnam or Boumerdes. Therefore, studies which include SSI effects will help to better predict the performance of structures during future earthquakes.

The first studies of SSI showed that there are mainly two types of SSI effects that are inertial and kinematic interactions. Inertial interaction effects are generally accompanied by an increase of the fundamental period of the system, while kinematic interaction effects do affect the foundation input motions [2], [3].

Past practical procedures available for design purposes generally neglect kinematic interaction, while inertial interactions are taken into account. Structural models on which SSI effects has been studied has not changed over the last thirty years. Where an elastic equivalent simple damped, oscillator having a rigid foundation resting on, or partially embedded into a homogeneous or stratified half-space has been adopted. Therefore, solutions are available for rigid circular, rectangular and strip foundations on various soil profiles [4].

Currently, efforts are made by some researchers to allow full SSI analyses (kinematic and inertial interactions) to be performed on structures of general shape [5].

It is appropriate to note that the main assumption behind all the methods that have been briefly reviewed thus far is elastic behaviour of superstructure, a major limitation for structures that are expected to behave inelastically under severe earthquake motions. Under such conditions, soil non-linearity is also expected to contribute or influence the overall deformation of the soil structure system. At present, this can only be dealt approximately.

SSI studies that take into account the yielding of structures and soil non-linearity are scarce, if at all. This study investigates the effects of the non-linearity of the soil-structure system on the overall behaviour in terms of displacements and

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stresses.

In the solution of SSI problems, it is required to carefully model the unbounded nature of the underlying media. Many numerical methods have been developed to solve this problem, such as using transmitting or absorbing boundaries at the truncated region of the soil.

There are two main approaches for analyzing soil-structure interaction, namely the direct method and the substructure method [6].

Both methods are still being developed to overcome the shortcomings related to each of them, especially the non-linearity and unboundedness nature of the problem. Recent developments in the finite element method made by [7], have shown that using the direct method with a limited zone of the soil may capture the essential aspects of the non-linear nature of the problem related to soft soil conditions.

In general, SSI will influence the soil-structure system in three ways:

(1) It will alter the dynamic characteristics of the soil-structure system, such as modal frequencies and vibrating mode shapes. In particular, the fundamental period will elongate and the rigid body motion of the structure will be changed.
(2) It will increase the modal damping as part of the soil will contribute to the overall damping of the soil-structure system (the so called radiation damping).
(3) It will modify the free-field ground motion [8].

In a seismic soil-structure interaction analysis, it is necessary to consider the infinite extent and layered nature of soil strata, and the nonlinear behaviours of soft soils. The objective of this study is to perform a rigorous seismic non-linear soil-structure interaction analysis in the time domain to satisfy the above requirements while the results are compared with those of fixed base conditions.

Analytical models were developed by Finite Element Method (FEM) for numerical analysis. Different analyses were performed on a real 5 storey reinforced concrete building in terms of comparative results. The dynamic behaviour of structural systems is observed and the comparative results are presented in this paper in order to clarify the importance of nonlinear calculation of soil-structure systems.

II. FINITE ELEMENT ANALYSIS

In the present study we assume plane strain conditions, that is, all frames parallel to the plane of calculation in Fig. 1 deform identically. This represents regularly spaced frames in the transverse direction, which are assumed to lie at each meter distance.

A. Soil Elements

A 15-node triangular element is chosen for a 2D analysis Fig. 2. This element is powerful and provides an accurate calculation of stresses and strains. The stresses are evaluated at the 12 stress points contained in the element as indicated in Fig. 2.

Mohr-Coulomb model is used as a first approximation of soil behaviour in general. The model involves five parameters, namely Young's modulus, E, Poisson's ratio, ν, the cohesion, c, the friction angle, ϕ, and the dilatancy angle, ψ.

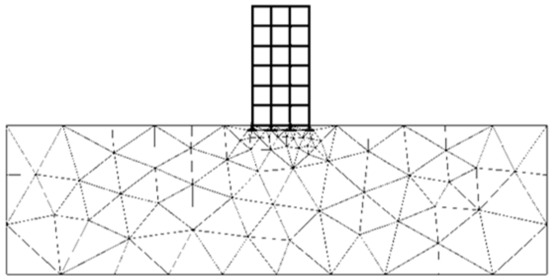

Fig. 1 Finite element discretization of the soil-structure system

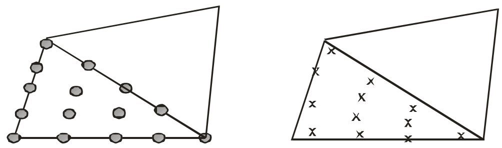

Fig. 2 Position of nodes and stress points in soil elements [9]

B. Interfaces

Interfaces are used to model the interaction between structures and the soil. A typical application of interfaces would be to model the interaction between a foundation and the soil. The interaction is modelled by choosing a suitable value for the strength reduction factor in the interface. This factor relates the interface strength (foundation friction and adhesion) to the soil strength (friction angle and cohesion).

C. Interface Elements

Interfaces are composed of interface elements. Fig. 3 shows how interface elements are connected to soil elements. When using 15-node soil elements, the corresponding interface elements are defined by five pairs of nodes. In the same figure, the interface elements are shown to have a finite thickness, but in the finite element formulation the coordinates of each node pair are identical, which means that the interface element has a zero thickness.

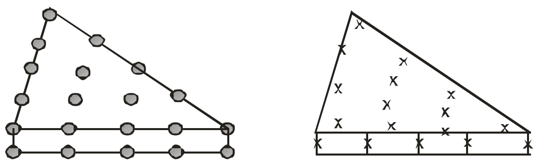

Fig. 3 Distribution of nodes and stress points in interface elements and connection with soil elements [9]

D. Interface Strength

The Coulomb criterion is used to model the elastic-plastic behaviour of interfaces, where small and large displacements are taken into account. Thus allowing proper modelling of soil-structure interact problems.

For small displacements (elastic) the interface shear stress τ is given by:

$$|\tau| < \sigma_n \tan \phi_i + c_i \quad (1)$$

For plastic behaviour τ is given by:

$$|\tau| = \sigma_n \tan \phi_i + c_i \quad (2)$$

where ϕ_i and c_i are the friction angle and cohesion of the interface and σ_n and τ are the normal stress and shear stress at the interface element. The strength properties of interfaces are linked to the strength properties of the soil layer. The interface associated strength reduction factor (R_{inter}) is calculated from the soil properties by applying:

$$c_i = R_{\text{inter}} c_i \quad (3)$$

$$\tan \phi_i = R_{\text{inter}} \tan \phi_{soil} \leq \tan \phi_{soil} \quad (4)$$

$$\psi_i = 0° \text{ for } R_{\text{inter}} < 1, \text{ otherwise } \psi_i = \psi_{soil} \quad (5)$$

E. Boundary Conditions

The unbounded nature of the soil medium requires special Boundary Conditions (BC) that do not reflect seismic waves into the soil-structure system.

Various models of BC exist that enable the energy transmission [10]; the most commonly used in the FEM are of the viscous type.

The position of the local viscous boundaries should be far away from the structure in order to obtain realistic results. From recent studies it is recommended that the location of the transmitting boundary to be selected far away 8-10 times of the foundation base width [11].

The BC used in this study is based on the method described by [11].

The normal and shear stresses absorbed by a viscous damper are:

$$\sigma_n = -c_1 \rho V_p \dot{u}_x \quad (6)$$

$$\tau = -c_2 \rho V_s \dot{u}_y \quad (7)$$

where, ρ is the density of the materials, V_p and V_s are the P wave velocity and the S wave velocity, respectively; c_1 and c_2 are special relaxation coefficients that are introduced to improve the absorption effect of the viscous damper. For practical applications, reasonable values are: c_1=1 and c_2=0.2. However, these values do not assure fully absorbed S waves, and additional research is needed on this point.

III. Characteristics of Soil-Structure Model

In order to investigate the soil-structure-interaction of regular type reinforced concrete buildings with isolated footings response due to earthquake ground motion, 48 models of the 5 storey building have been examined. Table I shows the dynamic properties and the geometry of the 5-storey R/C building model.

Since the dynamic response of this soil-structure system depends on the frequency content of the input motion and its variation through the soil layers, the interaction between foundation and it's underneath soil layers has been studied. Three different types of soil layers with different depths 30, 50 and 100m have been considered. In each analytical model different shear wave velocities ranging from 50 to 1200m/s simulating soft to hard soil conditions have been used.

The dynamic characteristics of three types of soil layers will be considered, simulating soft, medium and hard soil conditions Table I. To study the dynamic response of soil-structure interaction, the 5-storey building model is submitted to El Centro earthquake ground motion.

IV. Discussions of Results and Conclusions

For the real 5-storey R/C structure mentioned above a comparison of the results is undertaken in order to evaluate the effects of SSI, initially, in terms of fundamental periods Table I. One limits our presentation and analyzes of results for three types of ground only (Vs=50, 400, 1200m/s) representing soft, medium and hard soil conditions respectively.

As expected, soft soil condition amplify structural response and elongates natural periods, as opposed to hard soil, where for increasing values of shear wave velocities, we approach the fixed base condition (fixed base condition represents a theoretical case of a surface soil having an infinite rigidity). The severity of damages will be amplified when the frequency content of the earthquake input motion will be near the fundamental mode of vibration of the soil – structure system.

When the depth of the soil layer increases and its stiffness decreases, the period of the soil-structure system will increase and in these cases the adjacent soil stiffness plays very important role in decreasing or increasing the base shear for the type of structure considered.

One of the aims of this study is the necessity to explicitly consider the occurrence of one or more nonlinearities (geometric and material); i.e., allowing for the structure to slide and uplift at the foundation interface.

It is interesting to compare the behaviour of the building that is not allowed to uplift nor slide with the behaviour of the same building that is allowed to uplift and slide Table II. By allowing the uplifting and the sliding of the foundations the lateral displacement at the top of the structure has not changed significantly (displacement and acceleration time histories are given in Figs. 4 and 5 respectively). However, allowing foundation uplifting reduces significantly the base shear (-74,0%) and overturning moments Table III.

In addition of the insight gained from SSI analysis it improves our understanding of the behaviour of real structures. As a result of this understanding, design and construction practices can be modified so that future earthquake damage is minimized. As reported in the literature SSI analysis is seldom performed for ordinary structures. Even, when SSI effects are negligible in terms of loads, they do affect structural stability in terms of large deflection and nonlinear response; this is rarely investigated.

It is possible to investigate such effects, by first creating a model that represents the real structure and then perform a sensitivity analysis as for different support conditions allowing for the structure to uplift and slide.

TABLE I
DYNAMIC CHARACTERISTICS AND GEOMETRY OF 5-STOREY MODEL

Structural properties	Shear Wave Velocity Vs(m/s)	Depth of Soil Layer H(m)
Superstructure: Exterior Footing=1.5 x 1.5(m); thickness=0.36 m; Interior Footing=2.1 x 2.1(m); thickness=0.51m; Area of cross-section of members = 0.3x0.3m2; storey height = 4.08m with a bay of 4.20m. Poisson's ratio = 0.20; mass of each storey = 40.21 KN/m; mass of roof = 26.38 KN/m. critical damping ratio =10% modulus of elasticity= 24821129 KN/ m2 mass density=2.40 KN/m3 Soil : Poisson's Ratio of soil = 0.20; mass density = 1.70 KN/m3; critical damping ratio =10%		30 50 100
		Fundamental Period of Vibration T_1(sec)
	50	2.54055 2.74284 2.73103
	400	0.81089 0.84031 0.88972
	1200	0.80314 0.81222 0.81214
	Fixed Base Condition (i.e., without SSI)	0.79038

TABLE II
SUMMARY OF RESULTS FOR BUILDING ALLOWED TO UPLIFT AND SLIDE SUBMITTED TO EL CENTRO EARTHQUAKE Ξ=0.05

Cases considered	Shear Wave Velocity Vs(m/s)	Max. lateral Displacement at top of Bldg. (cm)	Max. Axial Force (KN)	Max. Base Shear (KN)	Max. Base Moment (KN.m)
Model A*	Fixed at base	11.1	575.5	440.8	108.3
Model B*	50	16.9	617.6	327.0	0.0
	400	9.6	575.8	114.5	106.9
	1200	10.0	575.0	431.2	103.4

* Model A: structure fully fixed at base, i.e., without SSI
* Model B: Nonlinear SSI, taking into account possible uplift and slide of foundation.

TABLE III
SUMMARY OF RESULTS FOR BUILDING ALLOWED TO UPLIFT AND SLIDE (IN TERMS OF PERCENT DIFFERENCE) SUBMITTED TO EL CENTRO EARTHQUAKE Ξ=0.05

Cases considered	Shear Wave Velocity Vs(m/s)	Max. lateral Displacement at top of Bldg.	Max. Axial Force	Max. Base Shear	Max. Base Moment
Model A And Model B	50	+43%	+6.8%	-25.8%	-99.9%
	400	+1%	0%	-74.0%	-1.2%
	1200	0%	0%	-2.2%	-4.4%

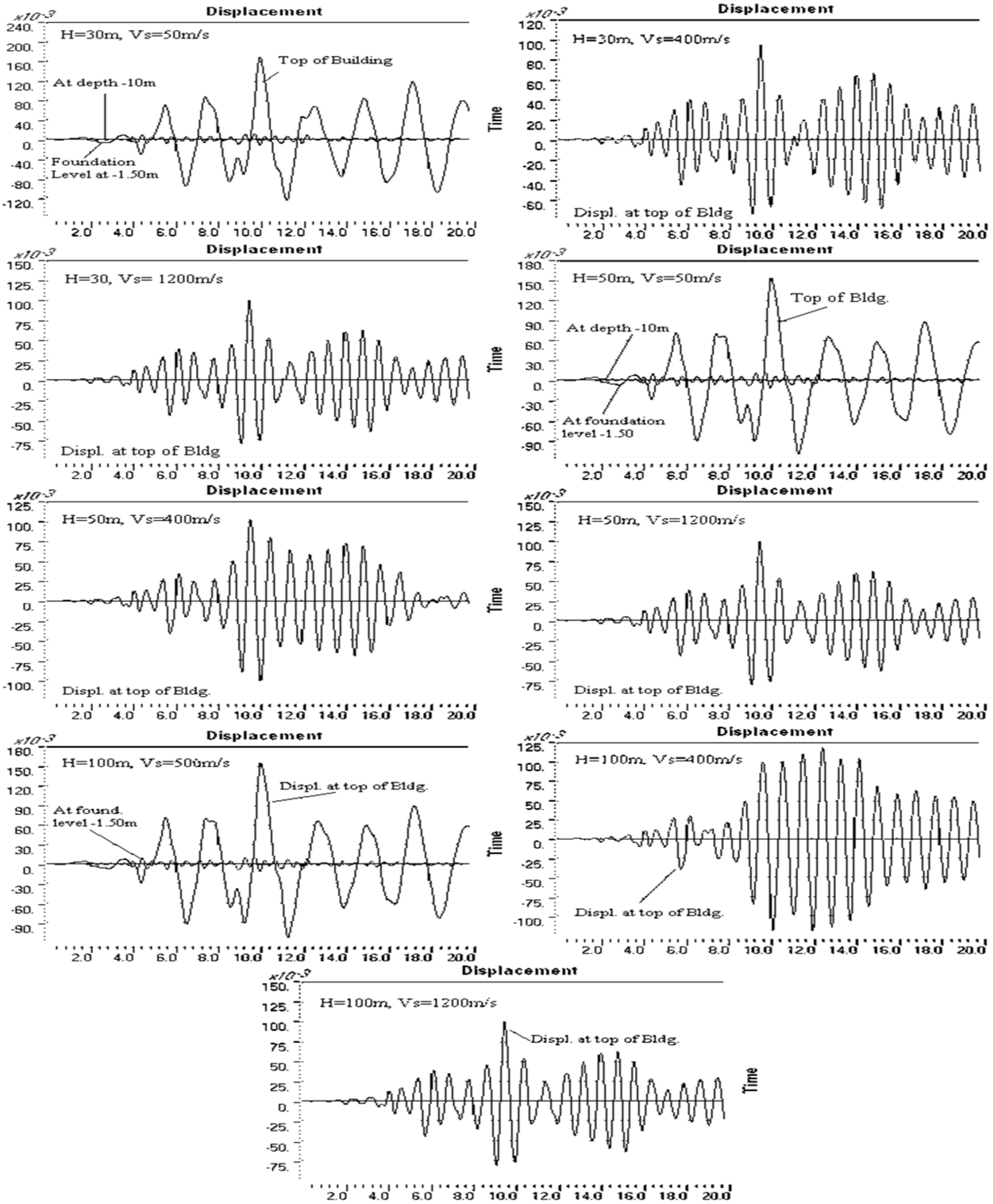

Fig. 4 Displacement time history plots for H=30, 50 and 100m; Vs= 50, 400 and 1200m/s

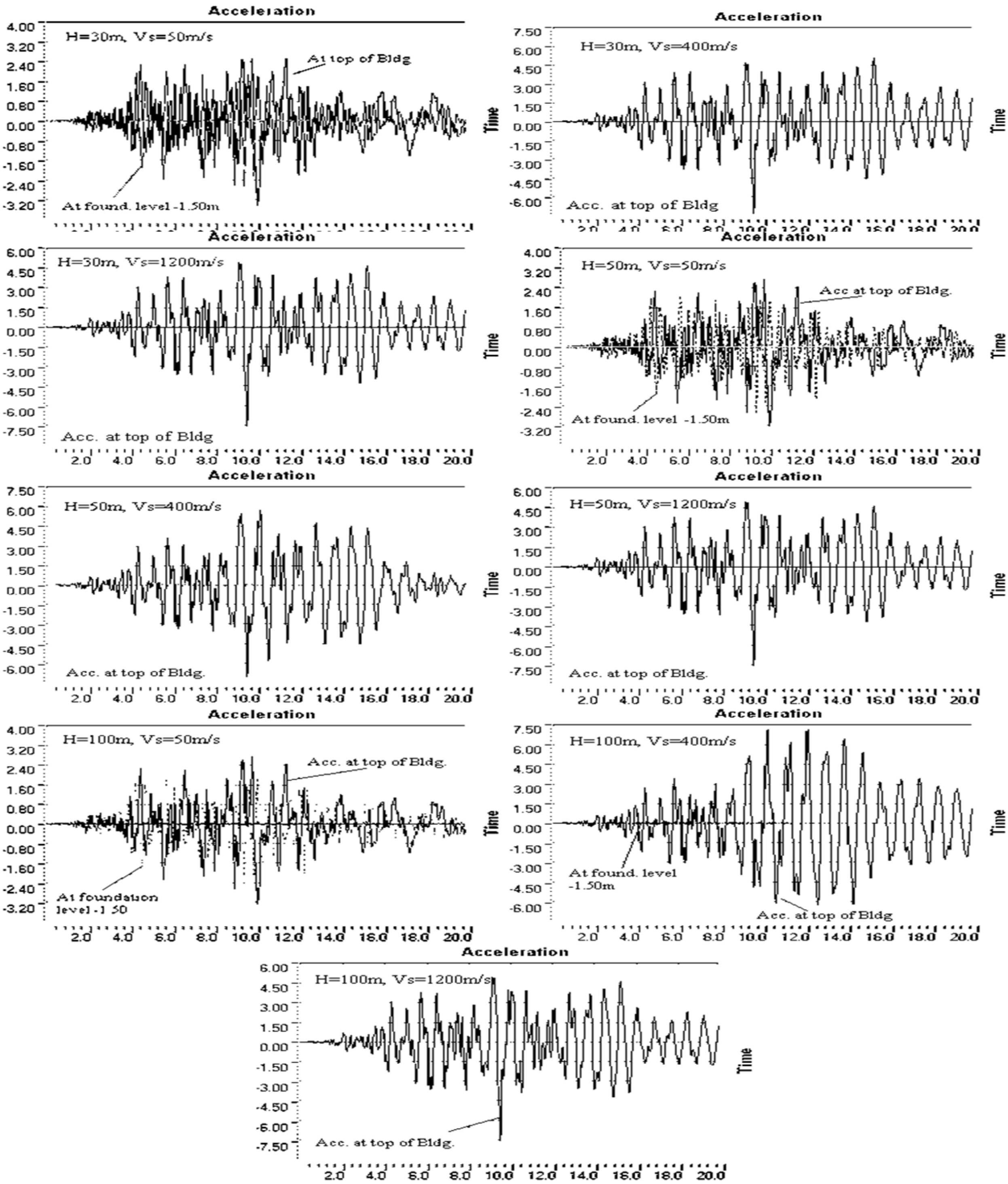

Fig. 5 Acceleration time history plots for H=30, 50 and 100m; Vs= 50, 400 and 1200m/s

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