Nonlinear Rocking Analysis of Nuclear Reactor Building Simultaneously Subjected to Horizontal and Vertical Earthquake Motions

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SUMMARY

PURPOSE

In the dynamic analysis of a nuclear reactor building, the response acceleration of the building is largely amplified during an earthquake and it's base mat may be lifted by a response overturning moment caused by a strong earthquake. And it makes geometrical nonlinear interaction between the base mat and rock foundation beneath it, which produces very complex phenomena by horizontal and vertical earthquake motions.

In this paper, the dynamic behavior of a BWR type reactor building is studied considering the uplift of the base mat subjected to simultaneous horizontal and vertical earthquake motions.

ANALYTICAL METHOD

It is assumed that the base mat is a rigid body and that the vertical rigidity of the rock foundation is idealized by uniformly distributed vertical springs which bear only compressive stress. Under these assumptions, the equation of motion is derived considering the geometrical nonlinearity due to the uplift.

For the mathematical vibration model, the "Lattice Model" is used, which is the discretized lumped mass model including the building and it's surrounding soil. And the actual recorded earthquakes (El Centro 1940 and Taft 1952) are used for the input motion to "Lattice Model".

In parallel to the nonlinear (uplift) analysis subjected to simultaneous horizontal and vertical inputs, similar nonlinear analysis and linear analysis are also conducted subject to only horizontal input. Their results are compared in respect to the nonlinearity of the uplift and of the effect of the vertical input.

RESULTS

(1) The horizontal maximum response values of the building (acceleration, shear force and bending moment) have little effect by the existence of the vertical input.

(2) The vertical acceleration of the building is generated by the uplift of the base mat caused by horizontal input.

(3) The horizontal acceleration response spectrum of the building takes some effect by the uplift within it's high frequency range.

1. Introduction

In general, the response acceleration of a rigid structure such as a nuclear reactor building is largely amplified during an earthquake and its base mat may be lifted up by response overturning moment caused by a strong earthquake. And a geometrical nonlinear interaction occurs between base mat and rock foundation. This nonlinearity produces very complex phenomena under horizontal and vertical input motions.

A typical BWR type reactor building is selected for the analysis regarding geometrical nonlinearity by uplift of base mat subjected to simultaneous horizontal and vertical components of El Centro 1940 and Taft 1952 earthquakes. In parallel, a similar nonlinear analysis and a linear analysis are also conducted subject to only horizontal component. And their results are compared in respect to nonlinearity of the base mat and effect of a vertical input.

2. Analytical Theory

2.1 Assumption

(1) The base mat of the building is assumed to be rigid.

(2) The vertical rigidity of the soil beneath the base mat is idealized by uniformly distributed vertical springs which bear only compressive stress (no tensile stress).

(3) For vertical response, the whole building is considered to be one mass model supported by the above mentioned vertical springs.

2.2 Evaluation of Uplift

(1) Compressive Spring of Foundation

The compressive spring coefficient kv of the foundation is evaluated by eq. (1) after Ref. [2].

$$kv = \frac{E}{m\sqrt{DL}(1 - \nu^2)} \tag{1}$$

where E, ν: Young's modulus and Poisson's ratio of foundation

D, L: Width and length of base mat

m: Coefficient which depends on shape of base mat (=0.95 for square mat constantly used in this study)

(2) Vertical Force and Moment of Base Mat

i) Case of Full Contact

Vertical force N and overturning moment M of base mat (reaction of the foundation) of full contact are given as follows,

$$N = kvDL(do + Z),\ M = k_\theta \Theta f \tag{2}$$

where do: Vertical displacement of static state

Z: Vertical deflection of center of gravity

Θf: Rotational angle of base mat

k_θ: Rotational spring coefficient of rock foundation ($= \frac{DL^3}{12} kv$)

ii) Case of Uplift

Increasing the overturning moment $|M|$, uplift phenomena occurs. The uplift of the base mat is judged by eq. (3).

$$|M| > \frac{NL}{6} \text{ ----- uplift} \tag{3}$$

The geometrical relation between base mat and foundation is simplified as Fig. 1. It yields eq. (4).

$$\ell = \frac{1}{|\Theta f|}(do + Z) + \frac{L}{2} \tag{4}$$

where, ℓ: Contact length between base mat and foundation

Consequently, vertical force and overturning moment in case of uplift is expressed as eq. (5).

$$N = \frac{1}{2} kv\Theta \ell^2 |\Theta f|, \quad M = \mathrm{sgn}\Theta f \left(\frac{L}{2} - \frac{\ell}{3}\right) N \tag{5}$$

2.3 Equation of Motion

Total equation of motion is expressed as follows,

$$\left[\begin{array}{c|c} \tilde{M} & \\ \hline & W \end{array}\right] \left\{\begin{array}{c} \ddot{X} \\ \ddot{\Theta} \\ \ddot{\Theta}f \\ \hline \ddot{Z} \end{array}\right\} + \left[\begin{array}{c|c} \tilde{C} & \\ \hline & Cv \end{array}\right] \left\{\begin{array}{c} \dot{X} \\ \dot{\Theta} \\ \dot{\Theta}f \\ \hline \dot{Z} \end{array}\right\} + \left[\begin{array}{c|c} \tilde{K} & \\ \hline & Kv \end{array}\right] \left\{\begin{array}{c} X \\ \Theta \\ \Theta f \\ \hline Z \end{array}\right\}$$

$$= - \left[\begin{array}{c|c} \tilde{M} & \\ \hline & W \end{array}\right] \left(\left\{\begin{array}{c} 1 \\ 0 \\ 0 \\ \hline 0 \end{array}\right\} \ddot{\alpha}o + \left\{\begin{array}{c} 0 \\ 0 \\ 0 \\ \hline 1 \end{array}\right\} \ddot{Z}o \right) + \left\{\begin{array}{c} 0 \\ 0 \\ Rm \\ \hline Rv \end{array}\right\} \tag{6}$$

where $\tilde{M}$, $\tilde{K}$, $\tilde{C}$: Mass, stiffness and damping matrix respectively

- W, Kv, Cv: Mass, stiffness and damping coefficient of vertical direction respectively
- αo, Zo: Horizontal and vertical input acceleration
- Rv, Rm: Pseudo external force expressing nonlinearity of vertical force and overturning moment

Rv and Rm are given as follows,

1) In case of full contact

$$Rv = 0, \quad Rm = 0 \tag{7}$$

2) In case of uplift

$$Rv = KvZ - (N - Wg), \quad Rm = K_\theta \Theta f - \mathrm{sgn}\Theta f\left(\frac{L}{2} - \frac{\ell}{3}\right)N \tag{8}$$

3. Analysis of Reactor Building

3.1 Analytical Model

Fig. 2 shows a typical BWR (MARK-I) type reactor building embedded in the soil. The building is settled on rock. And its surrounding soil consists of sand (shear wave velocity: Vs = 200 m/s) of 20m depth and a rock (Vs = 1000 m/s) underneath.

(1) Building Model

The earthquake resistant element of the building is composed of the outer and inner box walls, and shield wall. These walls are idealized by three stick model with consideration of their shearing and bending deformations as shown in Fig. 3, evaluating their effective areas. (Ref. [3])

(2) Soil Model

Soil beneath and surrounding the building is idealized by lumped masses and springs regarding horizontal movement as a plain-strain problem. (Fig. 4) Masses, representing discretized soil, are connected by the shearing and axial springs to each other. The authors call this model the "Lattice Model". (Ref. [3][4][5])

3.2 Damping

Following damping factors are used for analysis: h = 5% for the building and the soil, h = 7.5% for the rocking spring of base mat.

3.3 Input Motion

El Centro 1940 (NS, UD) and Taft 1952 (EW, UD) earthquakes (Ref. [6]) are used for the input motion and are normalized to be of maximum acceleration 500 Gal and 300 Gal for horizontal and vertical components respectively. Their acceleration time histories are shown in Fig. 5.

The horizontal motion is defined at the surface of the rock (GL-20m), and the input motion for the "Lattice Model" is obtained by a deconvolution technique as shown in Fig. 3.

The vertical motion is also defined at the surface of the rock (GL-20m), but it is assumed to be directly input to the building through the vertical spring.

3.4 Analytical Case of Variation

Following three cases are analized.

Case-1: Nonlinear (uplift) analysis of simultaneous horizontal and vertical inputs ---------- NONLINEAR (H+V)

Case-2: Nonlinear (uplift) analysis of only horizontal input ---------- NONLINEAR (H)

Case-3: Linear analysis of only horizontal input ---------- LINEAR (H)

3.5 Result

(1) Earthquake Response of Building

Maximum response values (horizontal acceleration, shear force, bending moment) of the building by El Centro and Taft are shown in Figs. 6 & 7. Some small difference is shown in the accelerations at the upper part of building among three cases, but the shear forces and the bending moments are almost the same among them.

(2) Earthquake Response of Base Mat

Response time histories of rotational and vertical accelerations of base mat, and footprints of uplift (contact width) are shown in Fig. 8. Uplift phenomena affect the rotational and vertical accelerations, especially in Case-2 (NONLINEAR (H)) vertical acceleration can be shown to be generated by uplift.

(3) Acceleration Response Spectrum

Horizontal acceleration response spectra at 4th floor and B2nd floor of building are shown in Fig. 9. Some differences are shown at the low period range (high frequency range).

4. Conclusion

(1) The vertical input and the nonlinearity of the uplift have little effect on the horizontal response of the building (maximum acceleration, shear force and bending moment).

(2) The vertical acceleration of building is generated by the uplift of base mat due to overturning moment by horizontal earthquake motion, not only due to vertical motion.

(3) The nonlinearity of the uplift causes some effect on the horizontal acceleration spectrum of the building within the high frequency range.

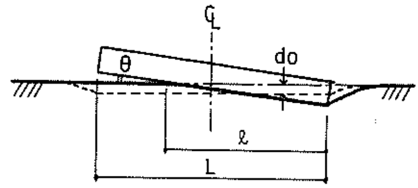

Fig. 1 GEOMETRICAL NONLINEAR

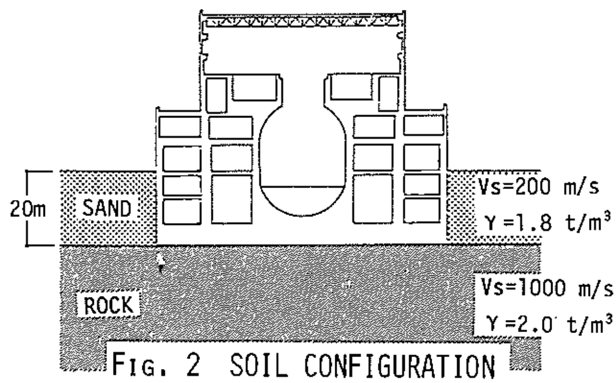

Fig. 2 SOIL CONFIGURATION

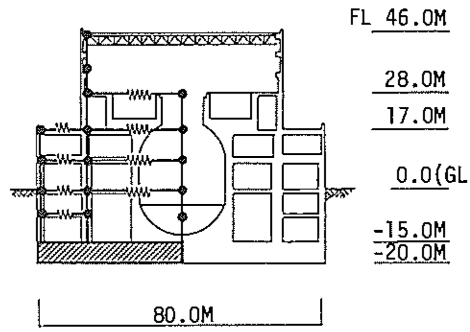

Fig. 3 BUILDING MODEL

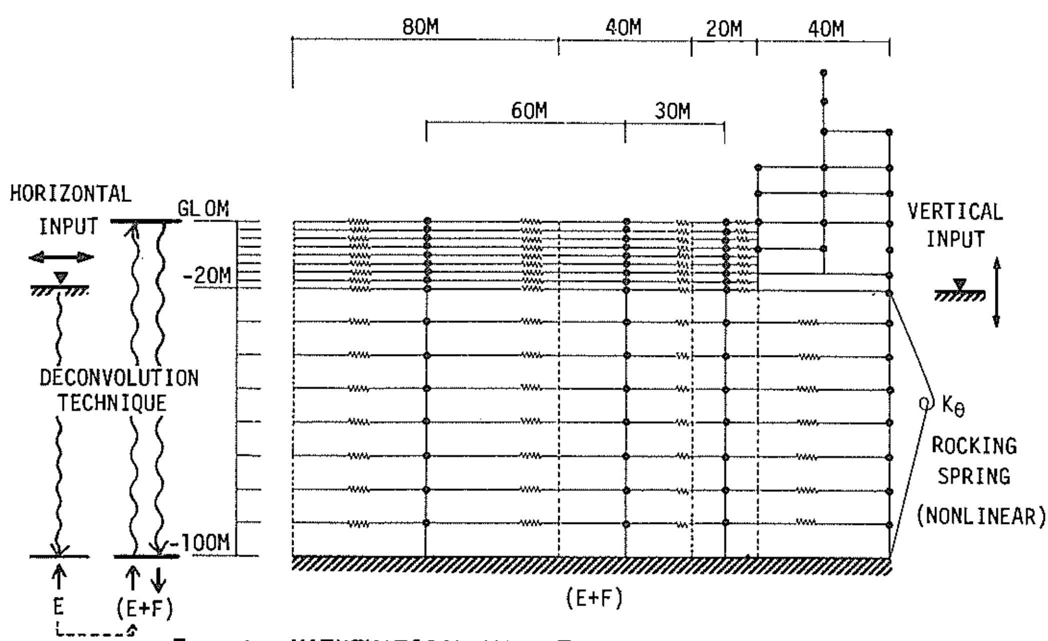

Fig. 4 MATHEMATICAL VIBRATION MODEL (LATTICE MODEL) AND INPUT MOTION

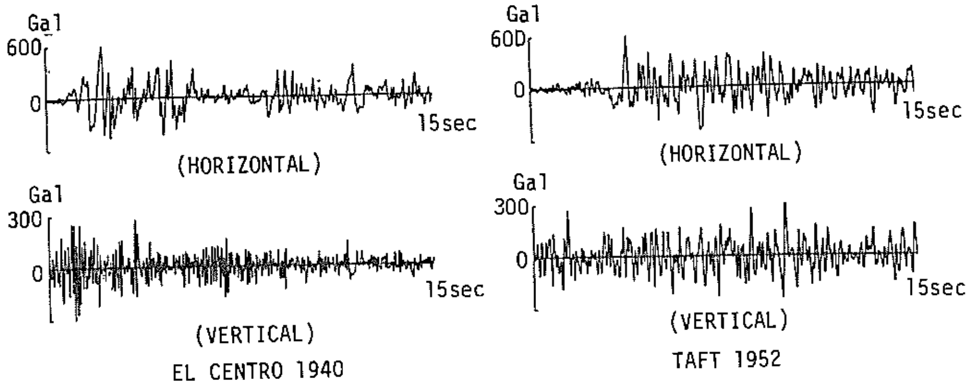

FIG. 5 INPUT WAVE (ACCELERATION TIME HISTORY)

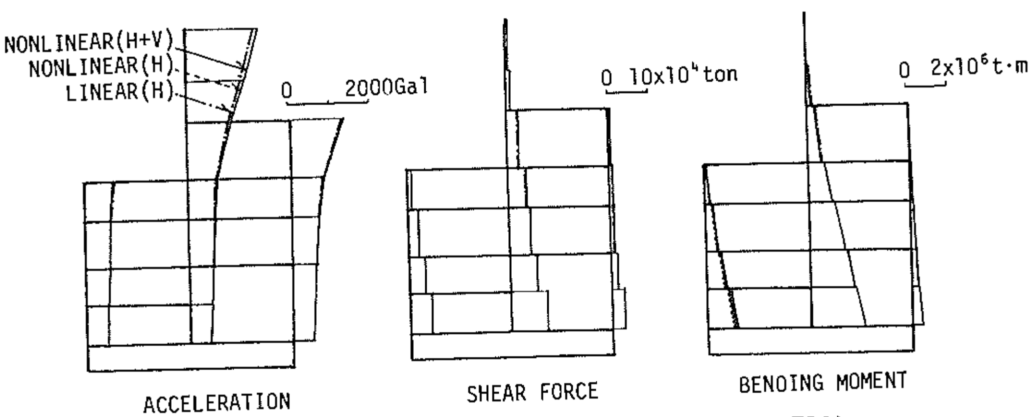

FIG. 6 MAXIMUM RESPONSE VALUES (EL CENTRO)

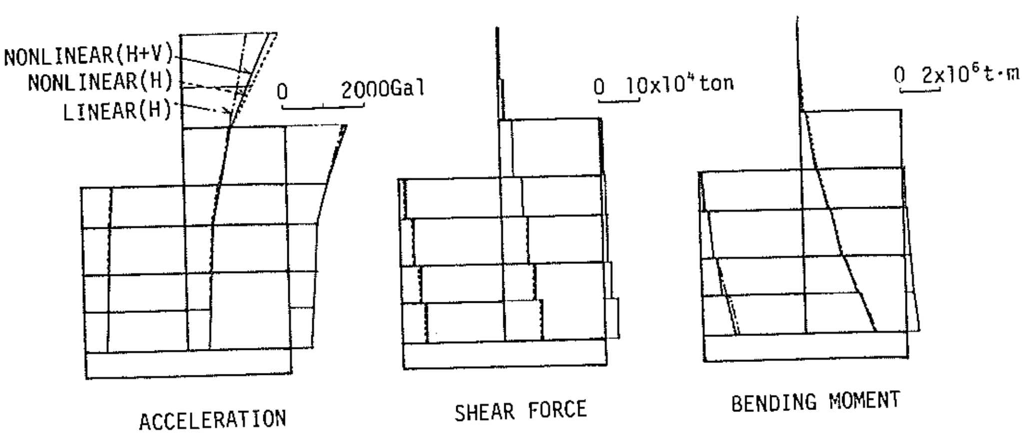

FIG. 7 MAXIMUM RESPONSE VALUES (TAFT)

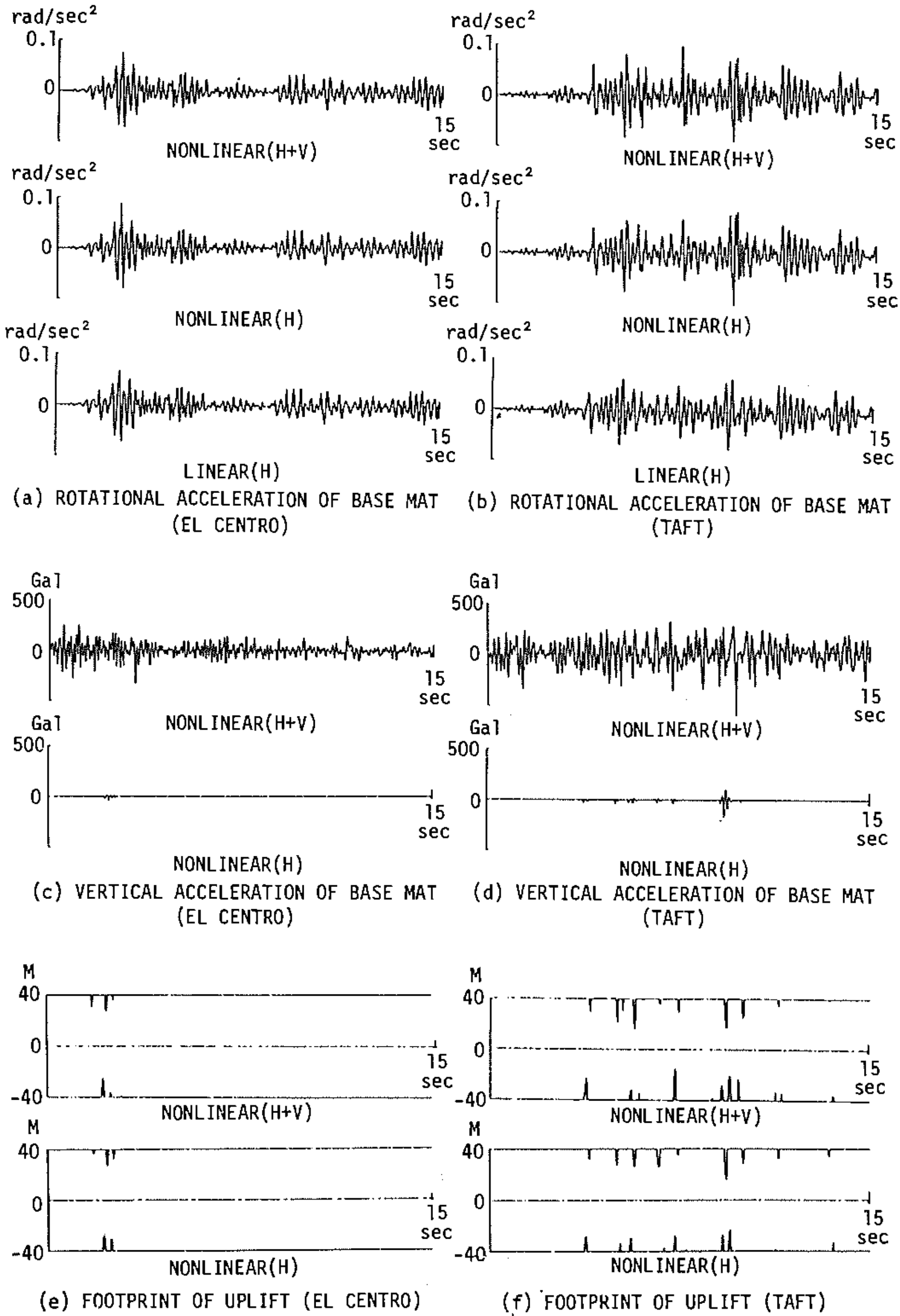

FIG. 8 TIME HISTORIES OF RESPONSE VALUES

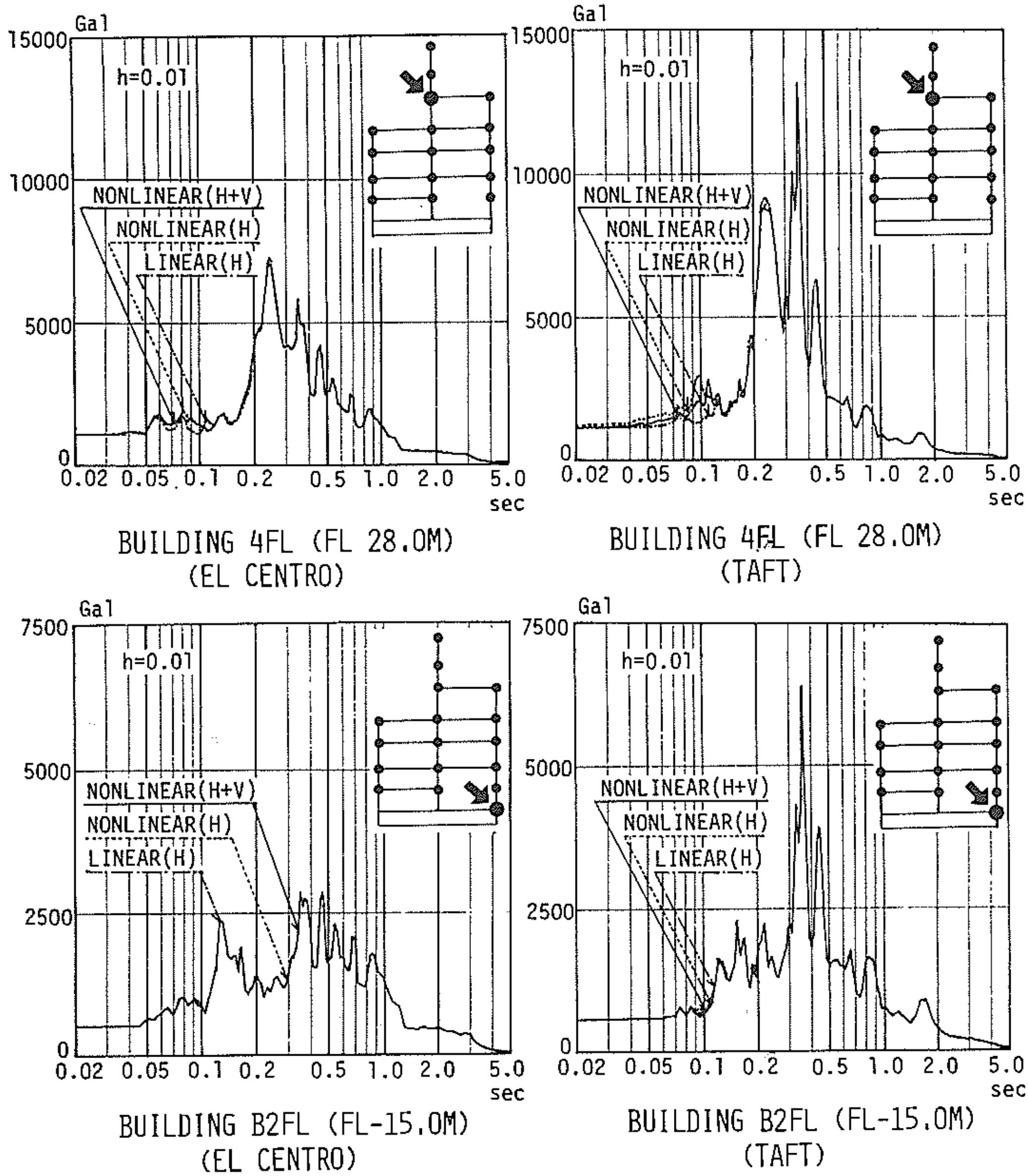

FIG. 9 ACCELERATION RESPONSE SPECTRA

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