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Control of Vertical Nonlinear Vibrations of Foundations

Paper No. 12.17

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SYNOPSIS Sandy soil behaves nonlinearly which affects on the vibration of machine foundations. In order to control the foundation response, damping can be introduced using tuned mass dampers. It is shown the foundation nonlinear vertical response using two different dynamic soil models, and the control of the response by linking linear or nonlinear tuned mass dampers to the foundation.

INTRODUCTION

Sandy soil behaves nonlinearly due to the effects of creep, void ratio, and large strain magnitude, Arya et al (1979), Richart et al (1970). The nonlinearity affects the dynamic response at primary and secondary resonances due to machine harmonic operation, Nayfeh and Mook (1979). An analytical investigation on the influence of soil nonlinearity on the dynamic response of footings was carried out by Nayfeh and Sarhan (1989).

This paper shows the vertical vibration response of a machine foundation built on sandy soil and the control of the response by linking the foundation with linear or nonlinear tuned mass dampers.

BEHAVIOUR OF FOUNDATION ON SANDY SOIL

A plate loading test was carried out on the local sandy soil using a circular plate of 30 cm diameter. The obtained results are shown in Fig. 1 which can be modeled by the following relationship:

$$P = K_1 y + K_2 y^2 + K_3 y^3 + K_4 y^4 + K_5 y^5 + K_6 y^6 \quad (1)$$

in which P is load in Kg; y is the settlement in cm; $K_1 = 21855.1 \text{ Kg/cm}$; $K_2 = -71790.6 \text{ Kg/cm}^2$; $K_3 = 119988 \text{ Kg/cm}^3$; $K_4 = -76415.2 \text{ Kg/cm}^4$; $K_5 = -9154.45 \text{ Kg/cm}^5$; $K_6 = 19784 \text{ Kg/cm}^6$.

The equation of vertical motion of the block foundation shown in Fig. 2, neglecting the friction between the foundation and the soil, is given by

$$M\ddot{y} + c\dot{y} + K_1 y + K_2 y^2 + K_3 y^3 + K_4 y^4 + K_5 y^5 + K_6 y^6 = Q(t) \quad (2)$$

in which M is the mass of the block foundation; c is the material and geometric damping of soil; Q(t) is the dynamic load applied on the foundation, assumed here harmonic = $Q \cos \Omega t$.

The steady-state response of the foundation can be obtained either by any of the analytical perturbation techniques, Nayfeh and Mook (1979); or by numerical integration. A second order perturbation usually provides close results between the analytical and numerical solutions. In this paper the numerical solution was used.

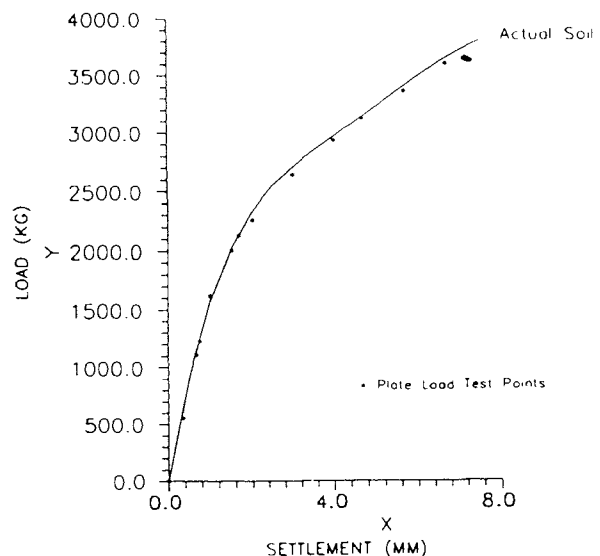


Figure 1 Modelling of Actual Soil

Considering the numerical data $M = 71.755 \text{ Kg.s}^2/\text{cm}$; $Q = 287 \text{ Kg}$, damping ratio 5%, one finds that the natural frequency $\omega = \sqrt{K_1/M} = 17.45 \text{ rps}$. Figure 3 shows the steady state vertical response of the foundation in the forced frequency range between $\Omega = 12 \text{ rps}$ and 24 rps , as compared with considering linear soil (K_2, K_3, K_4, K_5, K_6 are zeros). At a higher value of the loading $Q = 717.5 \text{ Kg}$, the response is as shown in Fig. 4, which is more tilted towards the left. It is obvious that nonlinearity of the soil would provide at certain forced frequencies a response higher than the linear response.

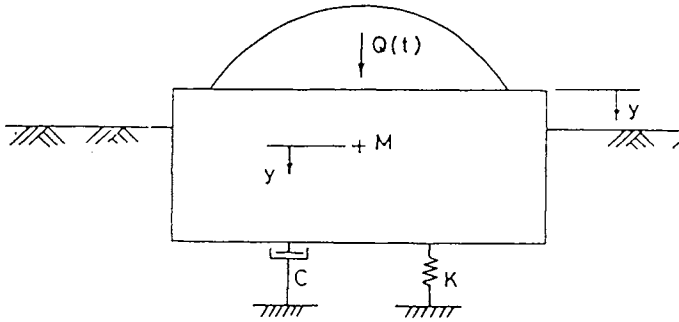


Figure 2 Schematic Representation of Machine Foundation

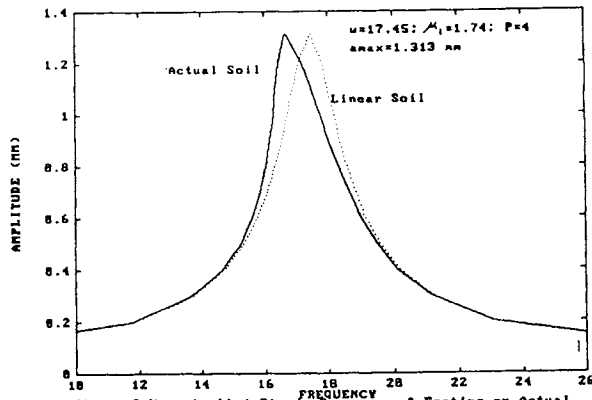


Figure 3 Uncontrolled Steady Response of Footing on Actual & Linear Soil

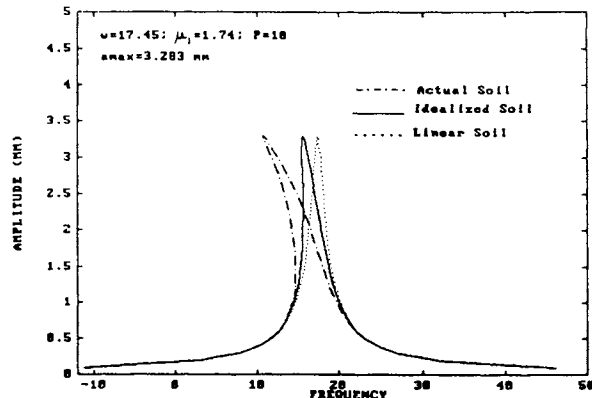


Figure 4 Uncontrolled Steady Response of Footing on Actual, Linear & Idealized Soil Model using Analytical Solution

CONTROL OF VIBRATIONS USING TUNED MASS DAMPERS

Tuned mass dampers can be connected to the foundation as shown in Fig. 5. The damper consists of a small mass linked with the foundation through springs and viscous dampers. The springs could be linear or nonlinear. The equations of motion of the foundation coupled with the tuned mass damper are given by

$$M\ddot{y} + c\dot{y} + K_1 y + K_2 y^2 + K_3 y^3 + K_4 y^4 + K_5 y^5 + K_6 y^6 - C_T(\dot{z}-\dot{y}) - K_T(z-y) - K_n(z-y)^3 = Q(t) \cos \Omega t \quad (3)$$

$$m\ddot{z} + C_T(\dot{z}-\dot{y}) + K_T(z-y) + K_n(z-y)^3 = 0 \quad (4)$$

in which m is the total mass of the tuned mass dampers; C_T is the total damping; K_T the linear spring constant of the damper; and K_n is the nonlinear spring constant.

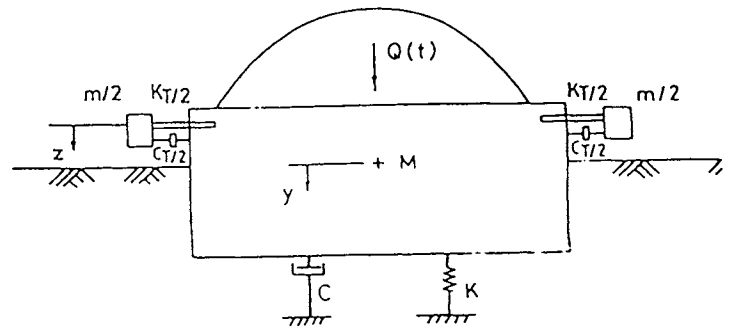


Figure 5 Schematic Representation of Machine Foundation Attached with LTMD

Equations 3 and 4 can be written as

$$\ddot{y} + \mu_1 \dot{y} + \alpha_1 y + \alpha_2 y^2 + \alpha_3 y^3 + \alpha_4 y^4 + \alpha_5 y^5 + \alpha_6 y^6 - \mu_3(\dot{z}-\dot{y}) - \alpha_T(z-y) - \alpha_n(z-y)^3 = P \cos \Omega t \quad (5)$$

$$\ddot{z} + \rho \mu_3(\dot{z}-\dot{y}) + \alpha_T \rho(z-y) + \alpha_n \rho(z-y)^3 = 0 \quad (6)$$

in which $\rho = M/m$; $\alpha_T = K_T/M$; $\alpha_n = K_n/M$; $\mu_3 = C_T/M$; $P = Q/M$; $\alpha_i = K_i/M$; and $\mu_1 = C/M$.

The tuned mass damper parameters are chosen as follows, Abdel-Rohman (1984), $\omega_T = \sqrt{\alpha_T} = 0.98 \omega$, $\rho = 25$, and damping ratio in the damper is 15%. Thus $\alpha_T = 11.7/\text{sec}^2$ and $\mu_3 = 0.205/\text{sec}$ were chosen. Figure 6 shows comparison between the uncontrolled response and the controlled response using linear tuned mass damper ($\alpha_n = 0$). It is obvious the reduction in the response in the frequency range $\Omega = 16$ to 20 rps due to using the linear tuned mass damper. The effect of using nonlinear tuned mass damper is shown in Fig. 7 for $\alpha_n = 50$, Fig. 8 for α_n

= 100, Fig. 9 for $\alpha_n = 200$. The nonlinearity could provide further reduction in the response within the frequency range $\Omega = 18$ to 20 rps. However, an increase in the steady state response is observed in the frequency range $\Omega = 14.5$ rps to 18 rps. Figures 10 and 11 show respectively the steady state response using nonlinear tuned mass dampers with $\alpha_n = -100$ and -200 . The softening nonlinearity in the damper could reduce the response in the frequency range $\Omega = 14$ to 16.5 rps more than using linear tuned mass damper. Therefore, based on the forced frequency range which causes problem during machine operation the designer can select the proper parameters of the tuned mass damper to control the foundation response.

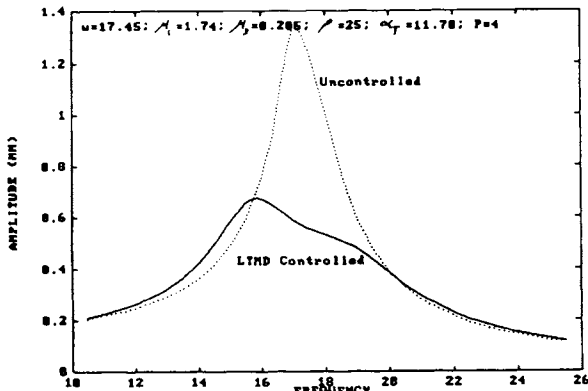


Figure 5 Uncontrolled & LTHD Controlled Response of Footing using Numerical Integration of Equations of Motion

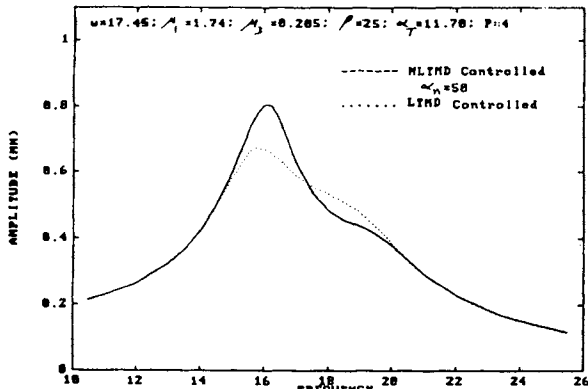


Figure 7 Controlled Response of Footing using LTHD & MLTHD using Numerical Integration of Equations of Motion

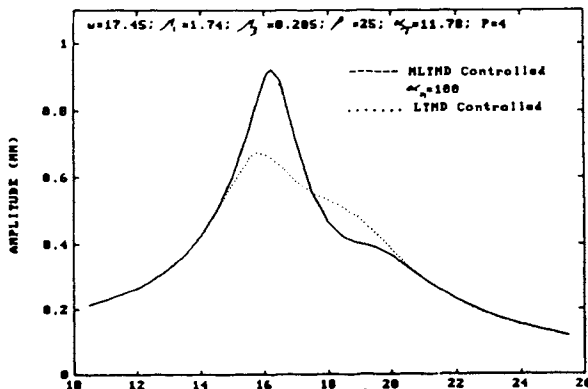


Figure 8 Controlled Response of Footing using LTHD & MLTHD using Numerical Integration of Equations of Motion

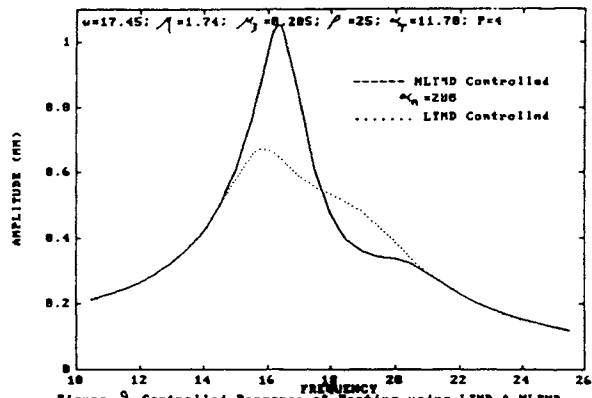


Figure 9 Controlled Response of Footing using LTHD & MLTHD using Numerical Integration of Equations of Motion

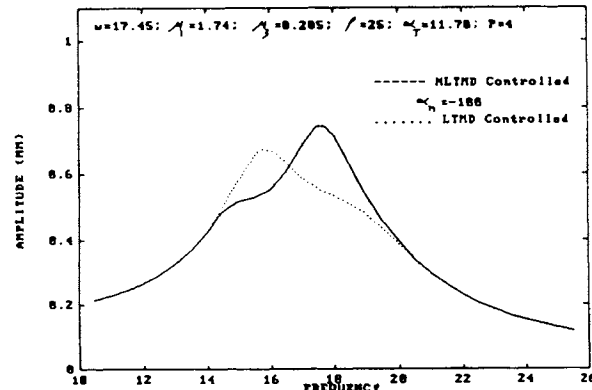


Figure 10 Controlled Response of Footing using LTHD & MLTHD using Numerical Integration of Equations of Motion

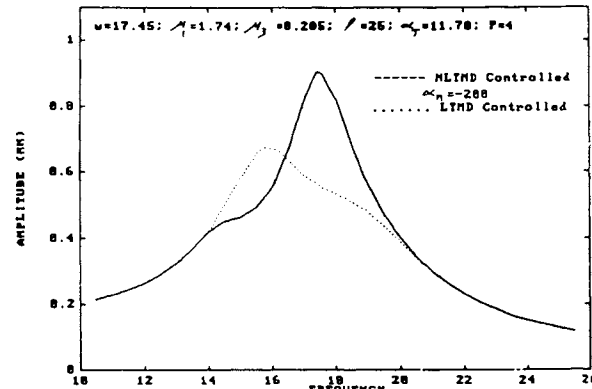


Figure 11 Controlled Response of Footing using LTHD & MLTHD using Numerical Integration of Equations of Motion

INVESTIGATION OF ANOTHER SOIL MODEL

The presence of even powered terms in the equations of motion, Eqs. 2, 3, and 5 may suggest treating these terms in another form. Equation 2, can be expressed as follows:

$$M\ddot{y} + c\dot{y} + K_1 y + K_2 y|y| + K_3 y^3 + K_4 y^3|y| + K_5 y^5 + K_6 y^5|y| = Q(t) \quad (7)$$

Consideration of this model or the previous model for dynamic analysis requires experimental investigation to conclude which model fits the soil behaviour. This issue is

still under investigation. In this section the response considering the model represented by Eq. 7 is investigated for $P = 10$.

Figure 12 shows a comparison between the uncontrolled response and the controlled response using linear tuned mass damper ($\alpha_n = 0$) for the model of Eqs. 5 and 6. It is obvious that the response is more tilted towards the left as compared with the previous figures for $P = 4$. The reduction in the response is observed within the frequency range $\Omega = 14-20$ rps. However, when the model of Eq. 7 is used, the response shown in Fig. 13 is obtained. A reduction in the response within the frequency range $\Omega = 12-19$ rps is observed which is not much as compared with the reduction in the response of Fig. 12. Figure 14 shows comparison of the response history for the uncontrolled and controlled footing when $\Omega = 17.5$ rps for both models. The model with absolute values provides a response less than the previous model for both controlled and uncontrolled footing. Similar results were obtained for various values of α_n .

CONCLUSION

Two nonlinear dynamic models for sandy soil have been investigated and the influence of using tuned mass dampers, linear and nonlinear, to control the vertical vibrations of the foundation have been shown. The tuned

mass damper is able to control the amplitude of the vertical nonlinear vibration within certain frequency range depending on whether the damper is linear, softening nonlinear, or hardening nonlinear. The designer should recognize the frequency range which affects the machine operation. He can then select the proper parameters of the tuned mass damper which control the foundation response.

ACKNOWLEDGEMENT

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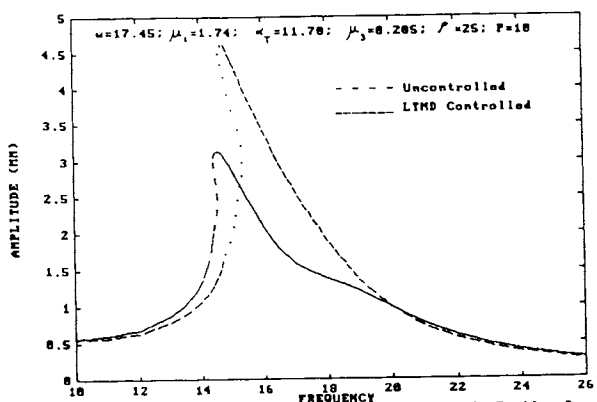


Figure 12 Comparison of Uncontrolled & Controlled Steady Footing Resp. for Actual Soil without considering absolute values by Numerical Integ.

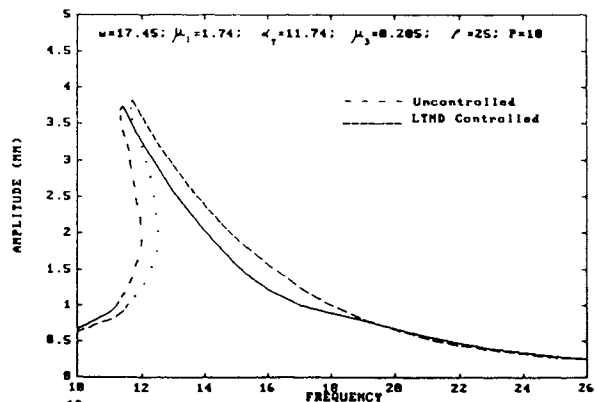


Figure 13 Comparison of Uncontrolled & Controlled Steady Footing Resp. for Actual soil considering absolute values using Numerical Integration

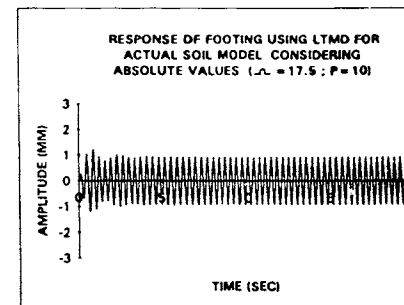
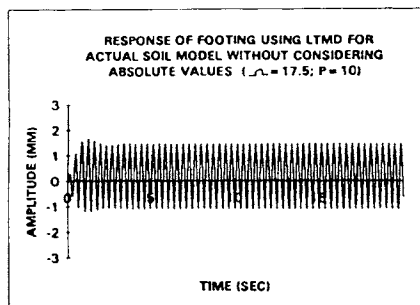
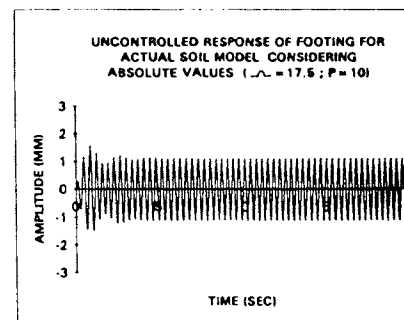
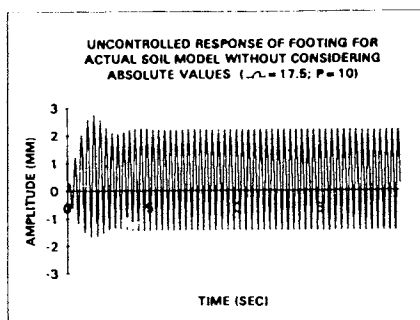


Figure 14. Response of Footing $\omega = 17.45; \mu_1 = 1.74; \alpha_T = 11.70; \mu_3 = 0.205; \zeta = 25; P = 10$