06 Apr 1995, 10:30 am - 12:30 pm

Control of Vertical Nonlinear Vibrations of Foundations

M. Abdel-Rohman
Kuwait University, Kuwait

H. Al-Sanad
Kuwait University, Kuwait

Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 2–7, 1995, Volume II, St. Louis, Missouri

Control of Vertical Nonlinear Vibrations of Foundations

Paper No. 12.17

M. Abdel-Rohman and H. Al-Sanad
Professor and Associate Professor, Civil Engineering Department, Kuwait University, Kuwait

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 Kg/cm; K_2 = -71790.6 Kg/cm^2; K_3 = 119988 Kg/cm^3; K_4 = -76415.2 Kg/cm^4; K_5 = -9154.45 Kg/cm^5; K_6 = 19784 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 Ω 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.

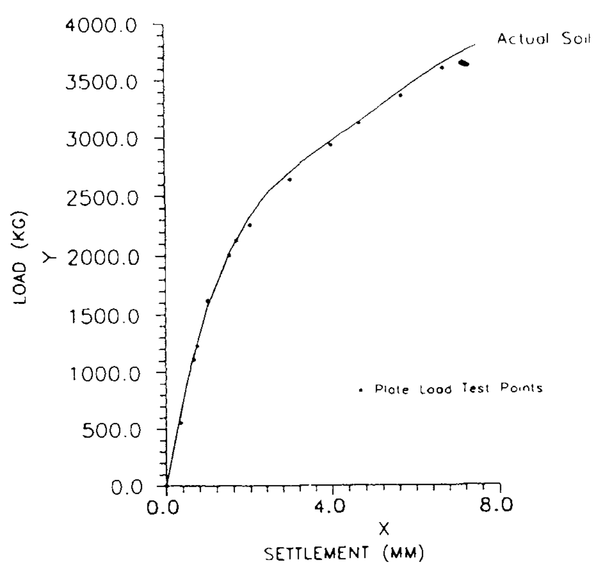

Figure 1 Modelling of Actual Soil

Considering the numerical data M = 71.755 $Kg.s^2/cm$; Q = 287 Kg, damping ratio 5%, one finds that the natural frequency $\omega = \sqrt{K_1/M} = 17.45$ rps. Figure 3 shows the steady state vertical response of the foundation in the forced frequency range between Ω = 12 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 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.

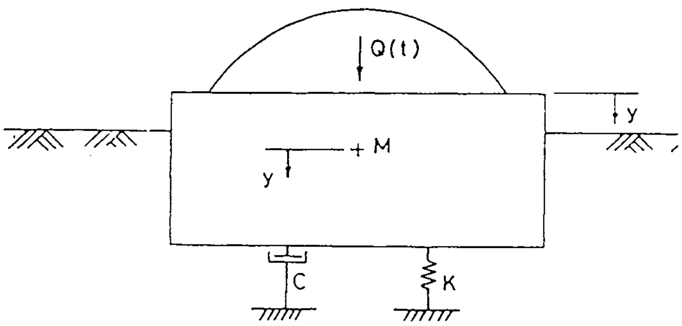

Figure 2 Schematic Representation of Machine Foundation

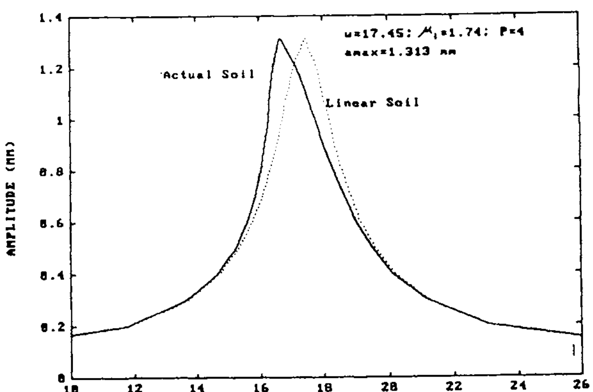

Figure 3 Uncontrolled Steady Response of Footing on Actual & Linear Soil

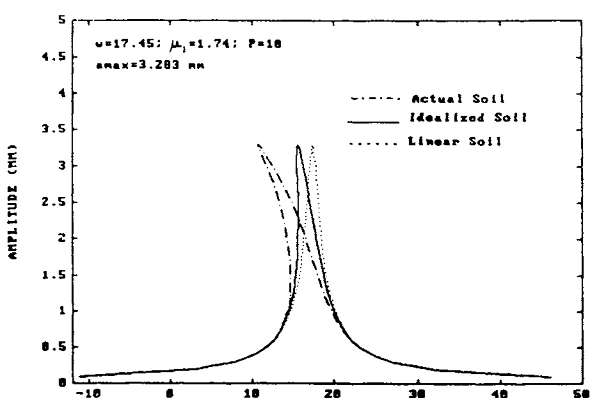

Figure 4 Uncontrolled Steady Response of Footing on Actual, Linear & Idealized Soil Model using Analytical Solution

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.

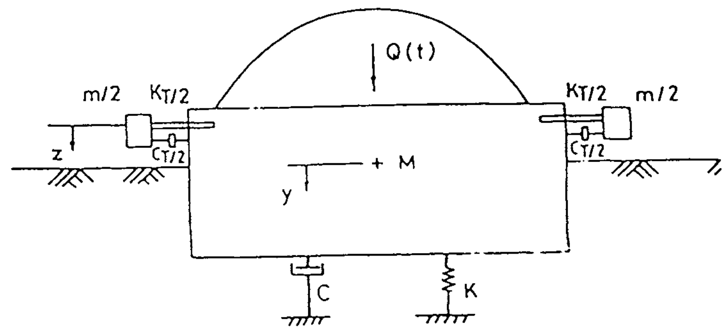

Figure 5 Schematic Representation of Machine Foundation Attached with LTMD

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), $\omega_T = \sqrt{\alpha_T} = 0.98\ \omega$, ρ = 25, and damping ratio in the damper is 15%. Thus α_T = 11.7/sec^2 and μ_3 = 0.205/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 Ω = 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 α_n = 200. The nonlinearity could provide further reduction in the response within the frequency range Ω = 18 to 20 rps. However, an increase in the steady state response is observed in the frequency range Ω = 14.5 rps to 18 rps. Figures 10 and 11 show respectively the steady state response using nonlinear tuned mass dampers with α_n = -100 and -200. The softening nonlinearity in the damper could reduce the response in the frequency range Ω = 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.

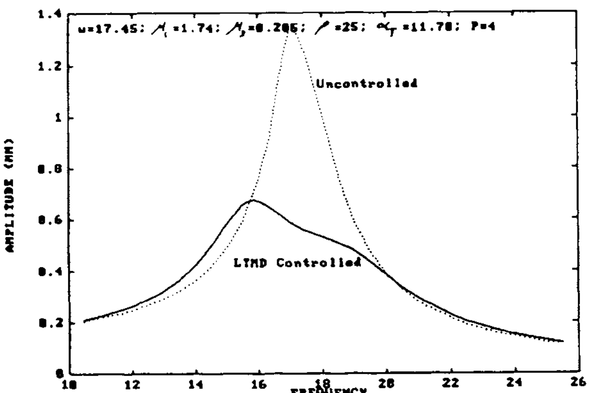

Figure 6 Uncontrolled & LTMD Controlled Response of Footing using Numerical Integration of Equations of Motion

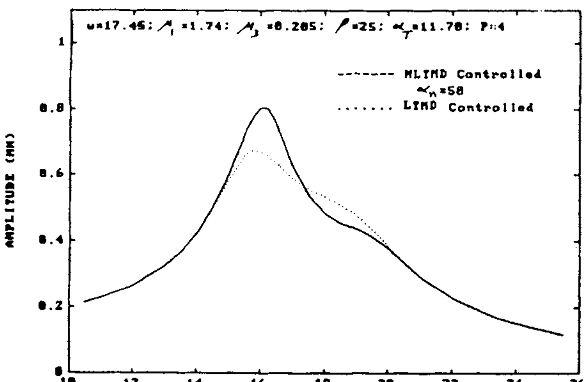

Figure 7 Controlled Response of Footing using LTMD & MLTMD using Numerical Integration of Equations of Motion

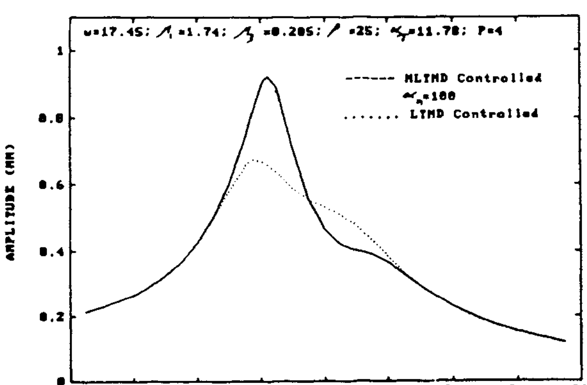

Figure 8 Controlled Response of Footing using LTMD & NLTMD using Numerical Integration of Equations of Motion

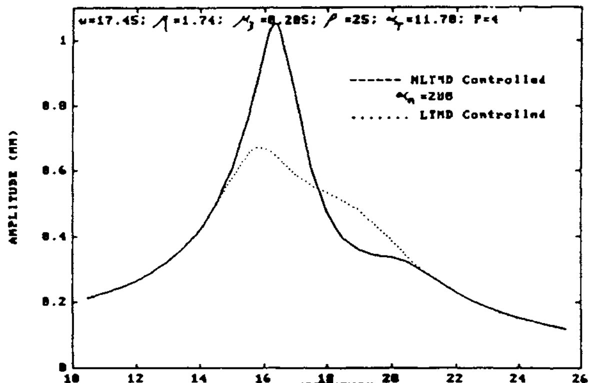

Figure 9 Controlled Response of Footing using LTMD & NLTMD using Numerical Integration of Equations of Motion

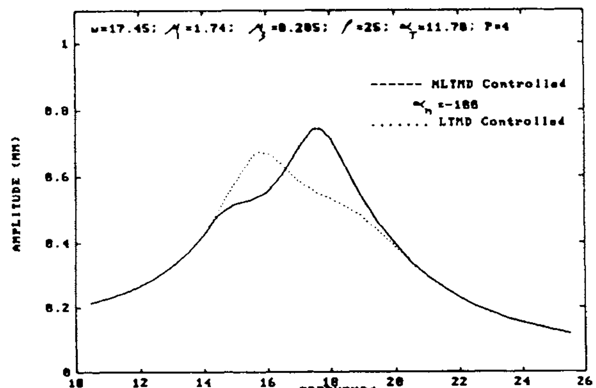

Figure 10 Controlled Response of Footing using LTMD & NLTMD using Numerical Integration of Equations of Motion

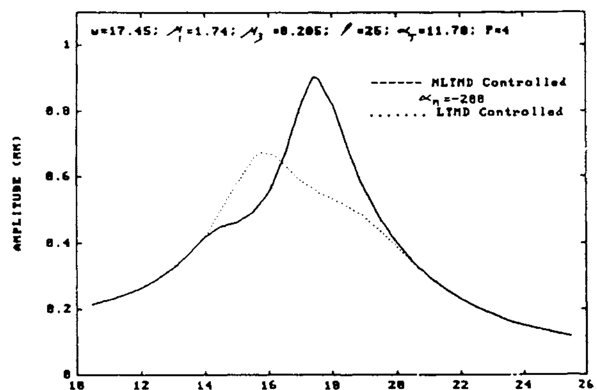

Figure 11 Controlled Response of Footing using LTMD & NLTMD using Numerical Integration of Equations of Motion

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:

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

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 Ω = 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 Ω = 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 Ω = 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.

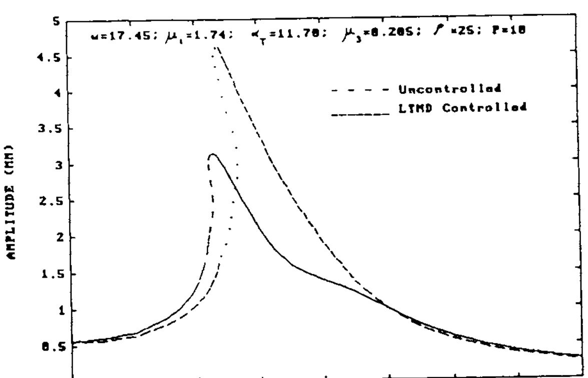

Figure 12 Comparison of Uncontrolled & Controlled Steady Footing Resp. for Actual Soil without considering absolute values by Numerical Intgn.

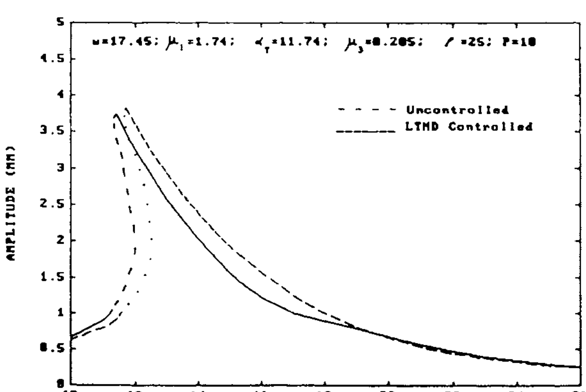

Figure 13 Comparison of Uncontrolled & Controlled Steady Footing Resp. for Actual soil considering absolute values using Numerical Integration

ACKNOWLEDGEMENT

This work was supported by the research unit of Kuwait University under grant number EV 058.

REFERENCES

Abdel-Rohman, M. (1984), "Optimal Design of Tuned Mass Damper for Building Control", International Journal of Buildings and Environment, Pergamon Press, Vol. 19, (3), pp. 191-195.

Arya, S., O'Neill, M., and Pincus, G. (1979), Design of Structures and Foundations for Vibrating Machines, Gulf Publishing Co., London.

Nayfeh, A.H. and Mook, D. (1979), Nonlinear Oscillations, John Wiley and Sons, N.Y.

Nayfeh, A.H., and Serhan, S.J. (1989), "Vertical Vibration of Machine Foundations", Journal of Geotechnical Engineering, ASCE, Vol. 115, No. 1, pp. 56-74.

Richart, F.E., Hall, J.R., and Woods, R.D. (1970), Vibrations of Soil and Foundations, Prentice-Hall, N.J.

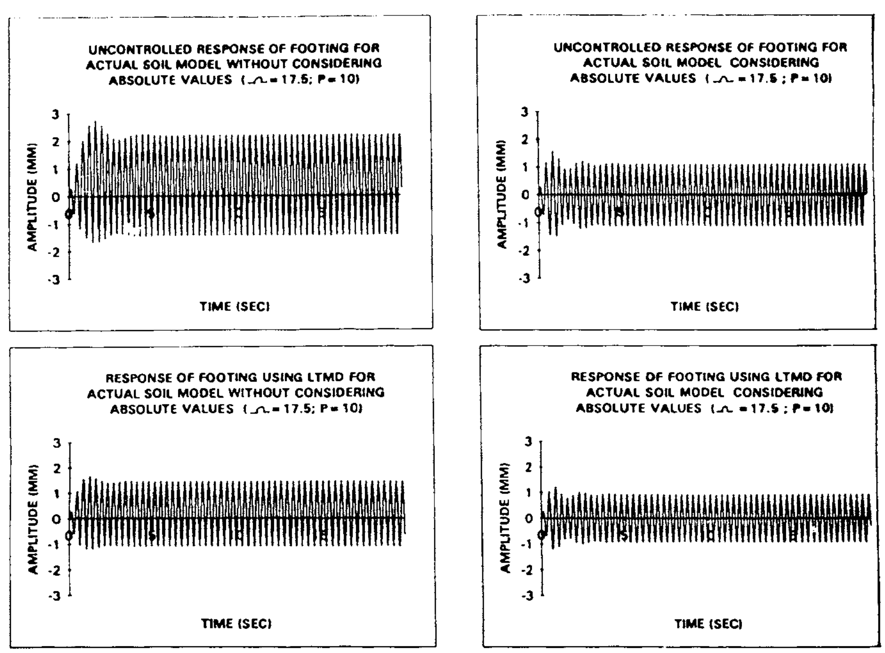

Figure 14 Response of Footing
ω = 17.45; μ_1 = 1.74; α_T = 11.70; μ_3 = 0.205; γ = 25; P = 10