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Effect of Soil Treatment on the Dynamic Response of Machine Foundations

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SYNOPSIS: Improvement of foundation soils using existing treatment techniques such as chemical, compaction and jet grouting can significantly enhance the general load bearing capacity of foundations. This paper describes the effect of soil treatment on the dynamic response of a rigid foundation subjected to steady-state, low-amplitude high-frequency vibrations, such as those encountered in machine foundation problems. Dynamic finite element analysis were performed to evaluate the effect of soil treatment as a function of treatment type and geometry. The treatment of foundation soil significantly reduced the amplitude of vibration of the foundation with the reduction being highly dependent on the type and geometry (i.e., width and depth) of the treated zone.

INTRODUCTION

In-situ soil stabilization or ground treatment is an effective method for improving soil's engineering properties, i.e., strength and permeability. Currently there are several in-situ controlled processing techniques used for ground treatment. These include chemical grouting (Baker, W. H., 1982), compaction grouting (Mitchell, J. K., 1981), jet grouting, Vibro-Compaction and Vibro-replacement (Welsh, J. P., 1986). These techniques which are highly practiced in Europe and Japan are being increasingly used in the United Sates for a wide range of geotechnical applications. Chemical and compaction grouting, for example, have been particularly successful in improving load bearing capacity of foundations (underpinning) and settlement control of foundations adjacent to underground construction.

Although soil improvement techniques significantly increase the bearing capacity of foundations under static loads, their effect on the foundation response to dynamic loads is yet to be investigated. In this paper results of an analytical study on the effect of foundation soil treatment on the dynamic response of a simple foundation block (strip footing) is presented. The response of the foundation is determined for both cases of treated and untreated foundation soil, and the effect of treatment is evaluated as a function of treatment geometry (width and depth of treatment) and type.

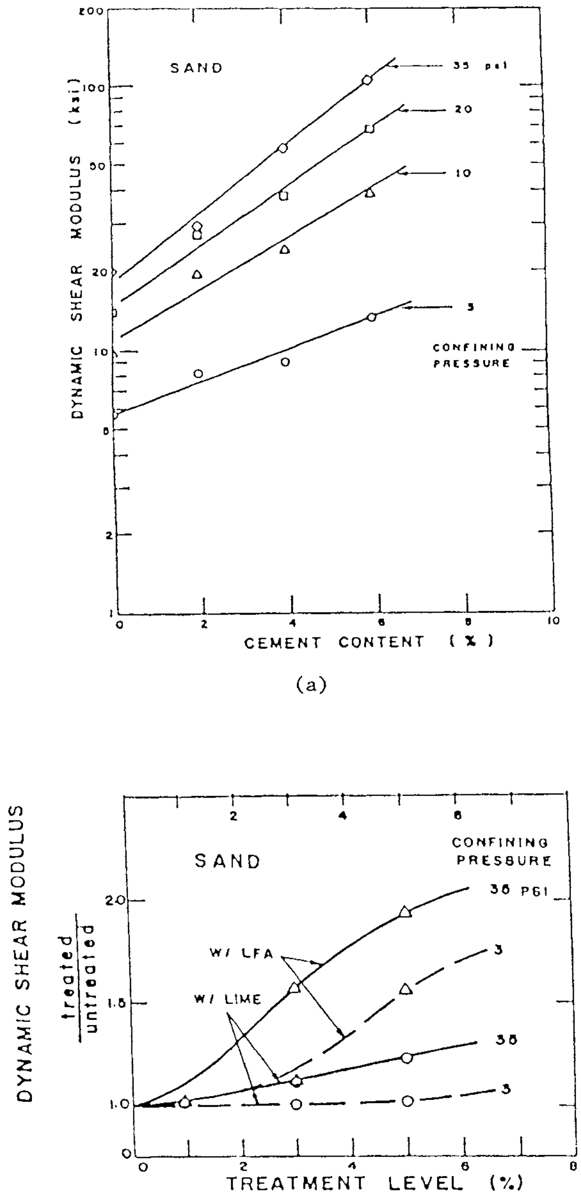
BEHAVIOR OF TREATED SOILS UNDER LOW-AMPLITUDE, HIGH-FREQUENCY DYNAMIC LOADS

Dynamic properties of treated soils, i.e., shear modulus and damping, under the conditions of low-amplitude, high frequency vibration were first studied by Chae, Y. S. and Chang Y. C. (1978). In this study the dynamic shear modulus and damping characteristics of a uniform sand and a silty clay treated with cement, lime and lime-fly ash was investigated using the resonant column technique. Results of this study showed that both the dynamic shear modulus and damping of low strength soils can be significantly improved by treatment with cementitious additives (Fig. 1).

Chang, T. S. (1986) and Chang, T. S. and Woods, R. D. (1987) carried out an extensive study on the effect of confining pressure on the dynamic shear modulus of treated sands with the objective of establishing a complete relationship between dynamic shear modulus, confining pressure, initial void ratio, and the degree of treatment (or cementation) of treated sands based on which engineers could specify optimum depths for a given treatment (or grouting) operations. The results of this work showed that the shear modulus ratio, M_g, defined as the ratio of sand's shear modulus after and before cementation, decreases with increasing confining pressure. The reason being that the dynamic shear modulus of sand at high confining pressure is high already and the increase in the dynamic shear modulus of sand after treatment is not as significant as that of the increase at low confining pressures.

Furthermore, a depth of limiting effect of treatment was introduced by Chang and Woods, below which the modulus ratio, M_g, never exceeds a given value. This is basically the optimum depth for a given treatment project. A typical relationship between the optimum modulus ratio, M_g, and the depth of limiting effect for a given additive (Lime/Cement/H2O) mixed with various soil types is shown in Fig. 2.

Dynamic behavior of grouted sands was also the focus of another study carried out at the Univ. of Michigan by Li, N. and Woods, R. D. (1987). In this study dynamic shear modulus of Ottawa Sand 20-30 mixed with various types of chemical grouts (AC-500, Sodium Silicate 40, and MC-500) was evaluated using resonant column technique. The results of this investigation showed that: a) Addition of grout to sand significantly increase sand's dynamic shear modulus - with the increase being more pronounced for looser sands. b) Increase of dynamic shear modulus in sand was proportional to increase in grouting degree- for some grouts there was a threshold degree, about 80%, beyond which the modulus increased sharply, showing the importance of proper grout penetrability. c) Increase in dynamic shear modulus was proportional to the curing time of the grout up to a limiting value and inversely proportional to increase in confining pressure. In other words, modulus increase ratio (modulus of grouted/modulus of sand) decreased with increase in confining pressure. This finding was consistent with the work of Chang, and Chang and Woods. d) Dynamic shear modulus of grouted sand was relatively unaffected with previous stress history (for confining pressure < 30 psi) and dynamic strain amplitude ($< 8 \times 10^{-3}$ %). The data obtained from these studies can be used to assess



(a)

(b)

Fig. 1 Effect of Treatment on the Dynamic Shear Modulus of Sand: a) Shear Modulus vs. Cement Content for Sand with Cement Additive, and b) Normalized Shear Modulus vs. Additive Content for Sand with Lime and Lime/Fly Ash (Chae, Y. S. and Chiang, A. M., 1978).

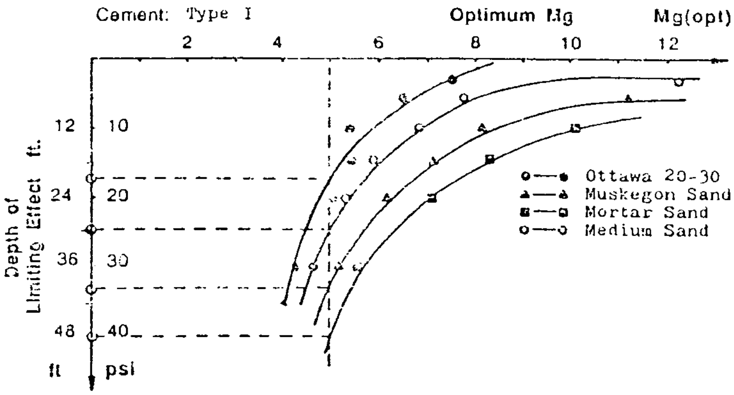


Fig. 2 Modulus Ratio, Mg, vs. Limiting Depth Effect for Soil Treated with Fly Ash and Cement (Chang, T.S., and Woods, R. D., 1987).

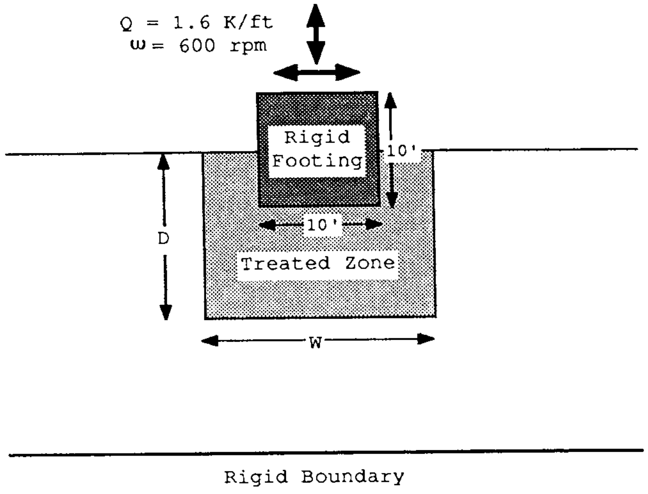


Fig. 3 Schematic Diagram of the Treated Zone.

TABLE.1 Treatment Types and Their Composition (Chang, T. S., 1986)

Type	Mixture Description	Mixture Proportion
I	Fly ash / Cement/ H2O	45:5:50
II	Lime / Cement / H2O	45:5:50
III	Sodium Silicate / H2O / Ethylacetate & Foramide	50:42:8

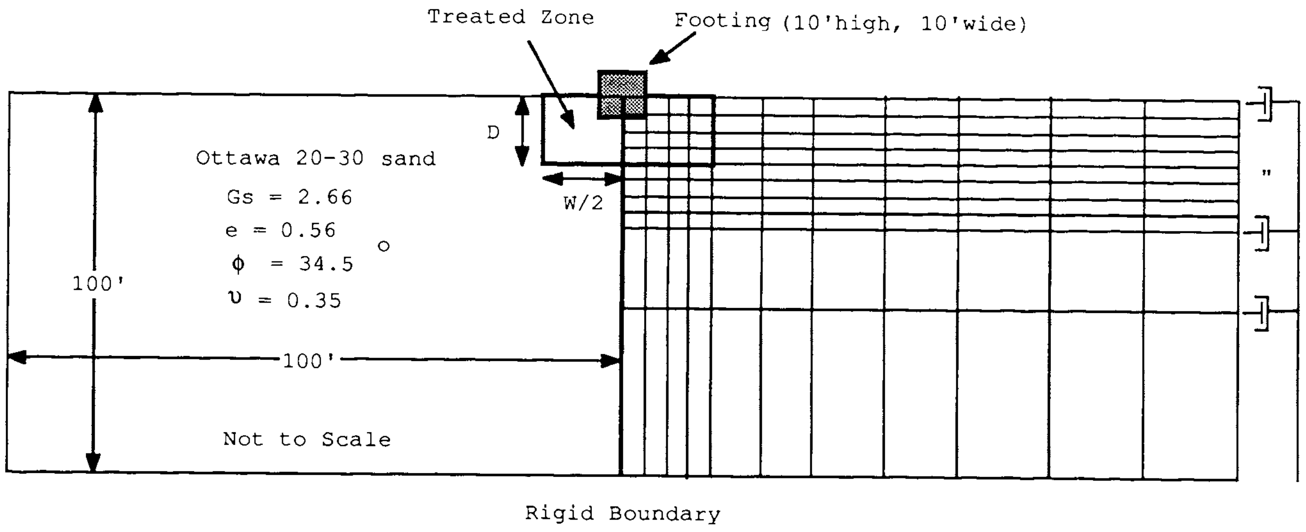


Fig. 4 Schematic Diagram of the Finite Element Mesh

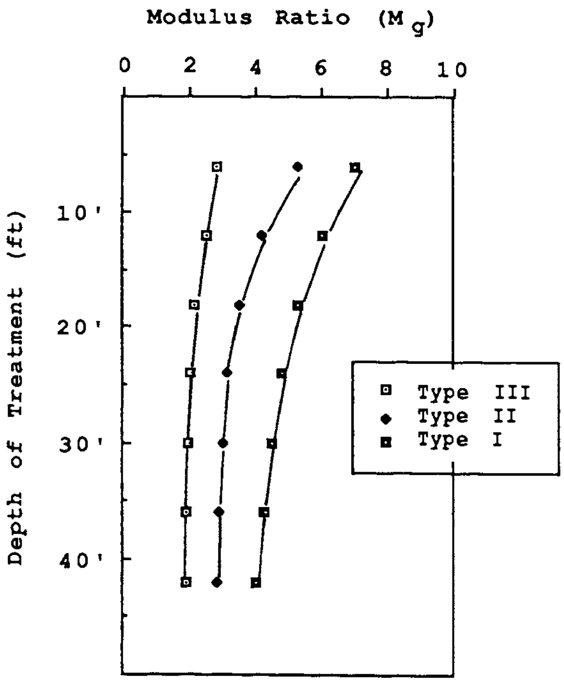


Fig. 5 Modulus Ratio, Mg, vs. Limiting Depth of Treatment for Ottawa 20-30 Sand Treated with Various Types of Treatment (Data deduced from Chang, T. S., 1986).

TABLE 2. Effect of Treatment Type on Reduction of the Amplitude of Vibration (W = D = 20')

Treatment Type	% Reduction in Amplitude		
	Vertical Oscillation	Coupled Sliding and Rocking Oscillation	
		Sliding	Rocking
I	61	76	72
II	59	73	70
III	50	61	61

the effect of soil treatment on foundation's response to low amplitude - high frequency dynamic loads, such as those encountered in machine foundation problems.

EFFECT OF SOIL TREATMENT ON THE RESPONSE AMPLITUDE OF THE FOUNDATION

In this study the effect of foundation soil treatment on the response of a rigid strip footing is analyzed using a "complete" soil-structure interaction procedure. The rigid strip footing, which has an embedment depth of 5', is considered to be 10' wide and 10' high and resting on a 100' layer of soil overlaying a rigid bedrock. A schematic diagram of the footing and a corresponding treatment zone is shown in Fig. 3. A finite element model was used to measure the amplitude of the response of the foundation undergoing steady-state machine type loading. The soil-structure interaction problem was thus classified as a "source problem."

The computer program DYNAFLOW (Prevost, J. H., 1985), a general purpose dynamic finite element program, was used to perform the finite element analysis. A two dimensional plain strain element was used and linear elastic material response was assumed for the machine foundation problem. A 258 node finite element mesh models a cross section of the footing (Fig. 4).

Two hundred twenty four 4-node isoparametric elements were used to model the foundation and underlying soil. Four rigid elements model the concrete footing (Young's modulus $E = 4.32 \times 10^{12}$ psf, Poisson ratio $\nu = 0.45$, mass density $\rho = 4.6$). The remaining 220 elements model the underlying soil. Each layer of the soil element (Ottawa 20-30) was defined with varying shear modulus which reflects the stiffening of the soil with depth. A Poisson ratio of $\nu = 0.35$ and mass density of $\rho = 3.31$ was used throughout. The magnitude of the shear modulus of the untreated soil was estimated using Hardin's empirical relationships (Richart, F. E., Jr., Hall, J. R., Woods, R. D., 1970). The nodes along the base of the mesh were constrained from movement to model the rigid bedrock underlying the soil stratum. A standard viscous boundary developed by Lysmer and Kuhlemeyer (1969) was used to model the infinite domain in the horizontal direction. The viscous boundaries were placed at about one shear wave length from the source of the excitation.

The shear modulus of the treated segment of the foundation soil, which in this case is a standard Ottawa 20-30 sand, was obtained from the work of Chang (1986) and Chang and Woods (1987). The treatment types and their characteristics are presented in Table 1.

The effect of treatment on the shear modulus, in the form of M_g (shear modulus ratio) vs. depth of treatment, for the different types of treatment investigated by Chang - and results of which were used in the present study - is shown in Fig. 5. Under the same overburden stress conditions, the shear modulus of the treated segments were determined by multiplying M_g from Figure 5 with the shear modulus of the untreated soil determined from Hardin's empirical relationships.

The sinusoidal machine loading for both cases of vertical and coupled rocking-sliding vibration was applied for one second, at 10 cycles/sec. with a maximum amplitude of 1.6 k/ft. A time step of .005 seconds or 20 steps per cycle of loading, was used. Time integration of the semi-discrete finite element equations was performed using an implicit Newmark method (Newmark, N. M., 1959) with integration parameters $\alpha = 0.55$ and $\beta = 0.28$.

Effect of Treatment Type on the Response Amplitude

The effect of treatment type on dynamic response of the rigid footing for both cases of vertical and coupled rocking and sliding oscillatory load is presented in Table 2 for a treatment depth and width of 20'. Type I treatment, which is a strong bond mixture, appears to contribute more to the reduction of the amplitude of vibration than the treatment types II, and III which possess lower bond strength and stiffness. Type III had the least contribution to the reduction of amplitude.

Effect of Treatment Geometry on the Response Amplitude

The effect of treatment geometry on the amplitude of response was investigated by observing the reduction in amplitude as a function of increasing (D) and width (W) of the treated zone. Three cases were considered: a) both width and depth of treated zone were increased equally, b) width was increased while depth remained constant, and c) depth was increased while width remained unchanged. Increasing width and depth of treated zone (equally) significantly reduced the amplitude of response for both cases of vertical and coupled rocking-sliding oscillations. Reduction in amplitude was in the range of 60 to 80%, respectively (Figures 6 and 7).

Increasing the width of the treated zone, with constant depth, significantly reduced the amplitude of response for both components of a rocking-sliding oscillation (Fig. 8). Widening of the treated zone was, however, not as effective for reduction of amplitude for the case of vertical oscillation. For this case, increase in depth of treatment is more effective (Fig. 9). Increasing the depth of treatment, with constant width, had a negligible effect on reduction of amplitude for the case of coupled sliding-rocking oscillation (Fig. 10).

In all of the cases studied the effect of treatment on the response amplitude reached a limiting value with increasing width and/or depth of treatment. For this particular footing the limiting value was reached near the depth and/or width of treatment of 40'.

CONCLUSIONS

Treatment of foundation soil with cementitious additives significantly influences the foundation's response to low-amplitude high-frequency cyclic loads (machine type loads). Both the type and geometry (i.e., width and depth) of treatment influence the amplitude of the response of a rigid foundation undergoing cyclic loads. Specifically:

1. The amplitude of vibration of a rigid foundation undergoing vertical and coupled sliding-rocking oscillation reduced significantly when the foundation soil is treated with cementitious additives of strong bond and stiffness such as cement and cement-fly ash.

2. An increasing in the width (as oppose to depth) of treatment was more effective in reducing the response amplitude of the foundation for the case of coupled sliding-rocking oscillation.

3. An increasing in the depth (as oppose to width) of treatment was more effective in reducting the response amplitude of the foundation for the case of vertical oscillation.

4. The effect of foundation soil treatment on reduction of the response amplitude reached a limiting value with increasing width and depth of treatment. For the footing dimensions studied in this investigation, the limiting

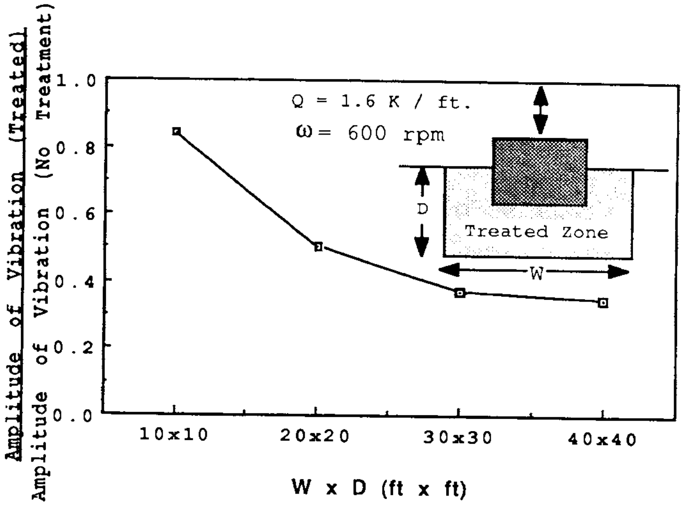


Fig. 6 Effect of Treatment on Reduction of the Response Amplitude with Equal Increase in both Width and Depth of Treatment (Foundation Embedment = 5', Vertical Oscillation and Type III Treatment).

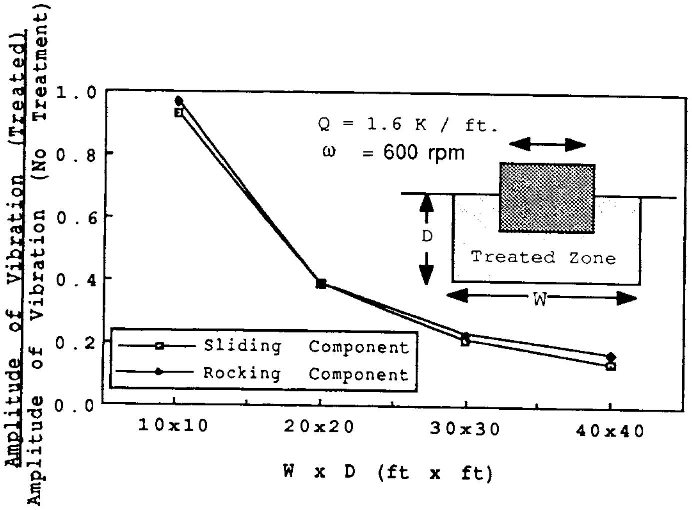


Fig. 7 Effect of Treatment on Reduction of the Response Amplitude with Equal Increase in both Width and Depth of Treatment (Foundation Embedment = 5', Coupled Rocking and Sliding Oscillation and Type III Treatment).

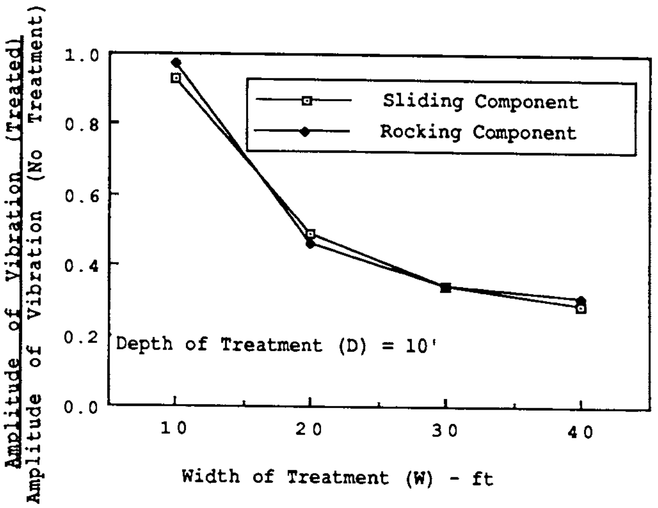


Fig. 8 Effect of Treatment on Reduction of the Response Amplitude with Increasing Width and Constant Depth of Treatment (Foundation Embedment = 5', Coupled Rocking and Sliding Oscillation and Type III Treatment).

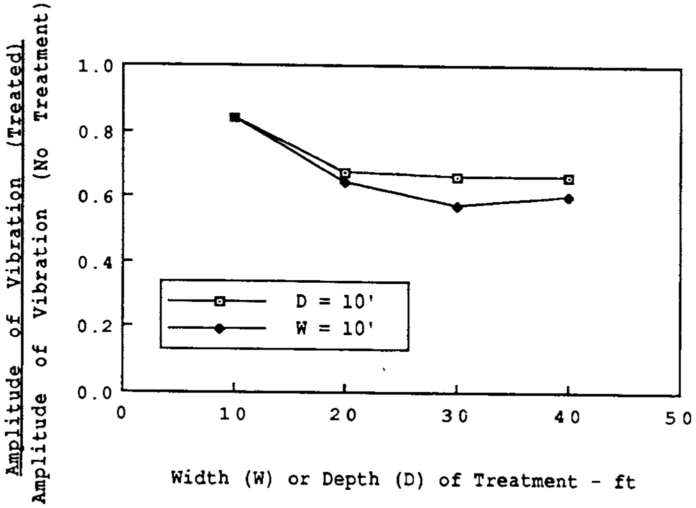


Fig. 9 Effect of Treatment on Reduction of the Response Amplitude with Increasing Width or Depth of Treatment (Foundation Embedment = 5', Vertical Oscillation and Type III Treatment).

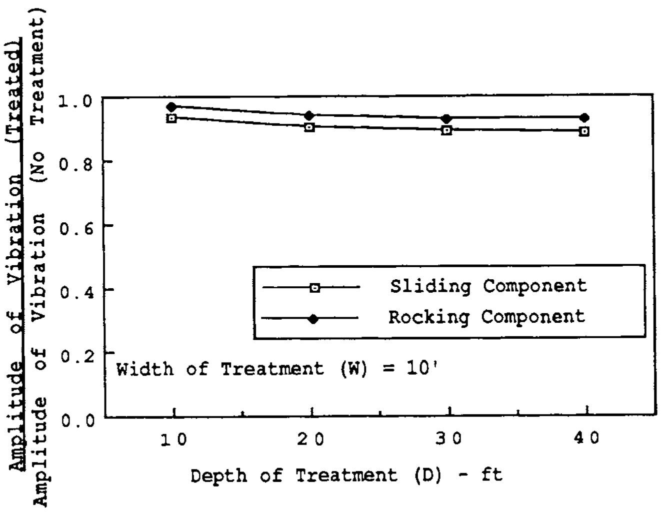


Fig. 10 Effect of Treatment on Reduction of the Response Amplitude with Increasing Depth and Constant Width of Treatment (Foundation Embedment = 5', Coupled Rocking and Sliding Oscillation and Type III Treatment).

value was reached near a treatment width and depth of 40'.

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