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Simple Model for Active Isolation of Machine Foundations by Open Trenches

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Simple Model for Active Isolation of Machine Foundations by Open Trenches

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SYNOPSIS: Ground disturbance due to waves generated by a machine foundation can be detrimental to adjacent structures or operation of sensitive equipment nearby. For machine foundations vibrating at moderate to high frequencies, the amplitude of ground motion can be reduced significantly by installing a wave barrier around the source. A three-dimensional boundary element algorithm incorporating quadratic elements has been used to perform an extensive parametric study on the effectiveness of open trenches as wave barriers. Based on the results of the study, a simple model in the form of an algebraic expression is developed for estimating the vibration screening effectiveness of open trench wave barriers. Furthermore, through comparisons with published field test data and rigorous boundary element solutions, the validity of the simple model is established.

INTRODUCTION

Isolation of ground transmitted vibrations generated by machine foundations can be an important engineering problem, in densely populated urban areas, where prevention of disturbance to adjacent structures and sensitive equipment is necessary. Sometimes ground borne vibrations can be mitigated through the use of localized isolators such as rubber or composite pads, springs or spring-damper systems, and pneumatic absorbers. However, there are situations where such mechanical isolation is inadequate. Furthermore, vibration amplitudes of a machine-foundation system that are within acceptable limits at the time of its commissioning may increase with time due to deterioration of the machine and/or supporting soil. For such cases, a suitable wave barrier (such as an open trench or a solid barrier) around the foundation may provide the remedial solution. This measure of providing a barrier in the immediate vicinity of the source is defined (Woods, 1968) as active isolation.

A good account of literature on the experimental and analytical evaluation of vibration screening can be found in Beskos et al. (1986) and Ahmad & Al-Hussaini (1991, 1994). Most studies have dealt with the passive isolation problem (modelled as a 2-D plane strain problem), and very limited work has been reported on the active isolation problem (requires 3-D modelling). The most noteworthy work on active isolation work is Woods (1968) experimental investigation. He conducted a series of field model tests on active isolation by open trenches, and investigated the influence of the location and depth of an open trench on its effectiveness as a wave barrier. He concluded that a minimum trench depth of 0.6 times the Rayleigh wave length is needed to achieve a 75% reduction in ground displacement amplitude. Dasgupta et al (1986) and Banerjee et al (1988) have used Boundary Element method to present a few examples of active isolation by open trench barriers.

Analytical and numerical work done to date on the active isolation problem seems to lack a systematic in-depth investigation into the various parameters that adequately describes the vibration screening process of an annular open trench wave barrier. The objective of this work was to conduct such a systematic in-depth investigation, and based on the results of the study develop a simple design formula for the estimation of vibration screening effectiveness of open trenches in active isolation.

In this work, three-dimensional analyses of vibration isolation of machine foundations by open trenches have been performed by utilizing a three-dimensional BEM algorithm. The soil was modeled as a homogeneous, isotropic viscoelastic half-space, and a rigid surface foundation undergoing harmonic vertical vibration was considered as the vibratory source.

Extensive parametric results are displayed in the form of dimensionless graphs for a wide range of depth and width of trench, location of trench, and size of foundation. These results are intended to improve understanding of the mechanism of active isolation by an open trench. Furthermore, the design formula presented here can be readily used in practical applications to estimate the vibration screening effectiveness of an annular open trench. This formula incorporates the influences of depth and location of the trench, size of the foundation, and poissions ratio of the soil. Thus, it is an improvement over the existing design guidelines provided by Woods (1968).

STATEMENT OF THE PROBLEM

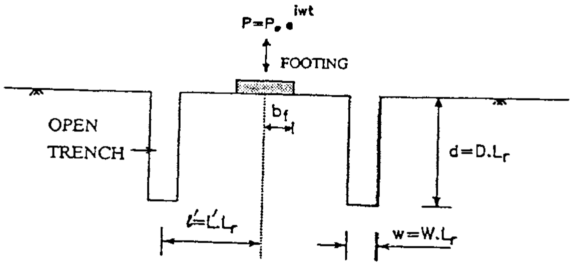
Fig. 1 presents a schematic of the problem studied. A rigid circular footing (source) of radius b_f resting on the surface of a viscoelastic half-space is subjected to a harmonic vertical force $P_o e^{i\omega t}$. An annular open trench of depth, d, and width, w, is located at a center-to-center distance of ℓ' from the source. Since vibration isolation by a trench is primarily achieved by screening of surface (Rayleigh) waves, the actual dimensions d, w, ℓ', b_f are normalized with respect to the Rayleigh wave length, L_r to give D, W, L', B_f, respectively. Because of the axisymmetric nature of the problem (Fig. 1b), the amplitude reduction along all radial lines should be identical. Hence, the amplitude reduction ratio for circular footings isolated by a circular trench is computed along a radial line and is represented by A_{rr}:

$$A_{rr} = \frac{\textit{Vertical displacement amplitude of ground surface}}{\textit{Vertical displacement amplitude of ground surface w}}$$

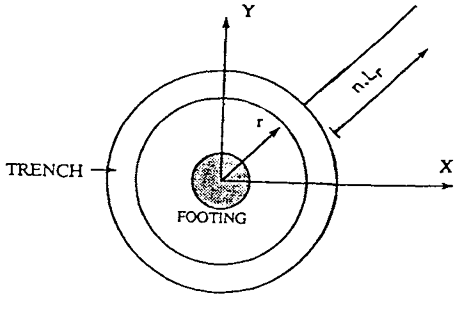
The average value of A_{rr} is computed along a radial line and is given by

$$\overline{A_{rr}} = \frac{1}{n}L_r \int_{r_b=0}^{nL_r} A_{rr}\,dr_b \qquad \textbf{(1)}$$

where, r_b $(=r-\ell')$ is the radial distance beyond the barrier and nL_r represents the extent of the region considered for computing the average value.



(a) Elevation



(b) Plan

Fig. 1: Schematic Diagram of Active Isolation by Open Trenches

COMPARISON WITH PUBLISHED EXPERIMENTAL DATA

Woods (1968) performed a series of active isolation field model tests with an annular open trench surrounding a model circular surface footing of 4 inches diameter undergoing periodic vertical vibration. The depth of the open trenches were 0.5, 1.0 and 2.0 feet, and the trenches were located at distances of 0.5 and 1 feet from the vibrating footing. Width of all trenches was 0.25 feet. The range of nondimensional parameters for Woods' active isolation tests were: $L' = 0.222$ to 0.92, $B_f = 0.074$ to 0.152, $D = 0.222$ to 1.82, and $W = 0.11$ to 0.228. These field tests (conducted on a two-layered soil deposit) have been numerically simulated utilizing the BEM code, and a comparison between the results of one of Woods' test and the BEM solution is presented here. For additional comparisons, the reader may refer to Al-Hussaini (1992). The first step in simulating a real problem by a numerical method is to obtain realistic soil parameters that correspond to the field condition. The soil profile at Wood's test site consisted of a 4 feet thick layer overlaying a relatively deep homogeneous soil deposit. This two-layered site soil profile is modeled by the BEM code with ease, because the BEM code used is capable of analyzsing multi-region medium. The measured in-situ Rayleigh wave lengths were L_r(ft) = 2.25, 1.68, 1.38 and 1.10, for Rayleigh wave velocities of V_r (ft/sec) = 450, 420, 415 and 385 respectively.

The soil parameters needed for the BEM analysis of this problem were the dynamic shear modulus (at small strains) G_s, mass density ρ_s, Poisson's ratio ν_s, and material damping coefficient β_s. Utilizing the published soil data, these parameters are estimated as follows:

Top layer:

$\rho_s=3.456$ *slugs*, $\nu_s=0.35$, $G_s=\rho_s(V_r/0.936)^2 lb/ft^2$;

Bottom layer:

$\rho_s=3.476$ slugs, $\nu_s=0.45$, $G_s=1015780 lb/ft^2$,

where V_r is the Rayleigh wave velocity corresponding to one of the measured Rayleigh wave lengths on the ground surface. The material damping for both soils is assumed to be 5%.

Fig. 2 presents a comparison of BEM results with Woods' test data for test number AF 6-300 ($L' = 0.726$, $W = 0.182$, $D = 1.452$, $f = 300Hz$)

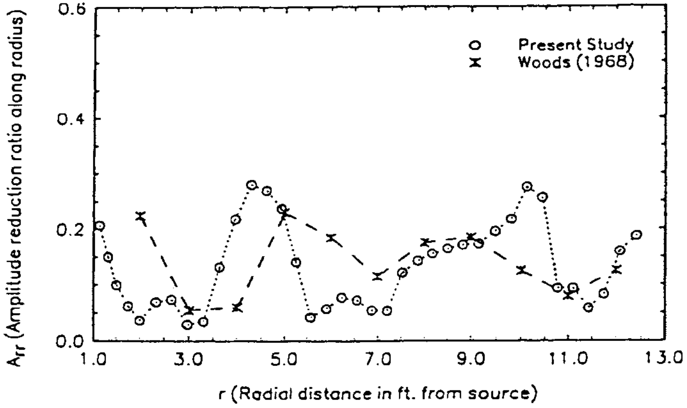


Fig. 2: Comparative Study for Active Isolation by Open Trench (L'=0.726, D=1.452, W=0.182, f=300 Hz.)

The amplitude reduction ratio presented by Woods' (1968) is the average of the amplitude reduction ratio along eight radial directions. This was done to average out the nonhomogeneity at the site in different directions. Fig. 2 reflects that the BEM solution in an average sense agrees reasonably well with Woods' test results. However, the variation of amplitude reduction ratios along the radial distance from the source are not identical for the two. This may be accounted to the local inhomogeneity at the test site and possible error in estimation of shear moduli of the two layers.

PARAMETRIC STUDY

The influence of various key parameters on active isolation by open trenches in a relatively deep homogeneous soil deposit (elastic half-space, constant G_s) has been studied. Material properties of the soil (i.e., shear modulus G_s and unit weight γ_s) and the excitation frequency, f, have been chosen in such a way that the Rayleigh wave length L_r was always equal to unity. The material damping of soil β_s is taken as 5%. Unless otherwise stated, Poisson's ratio of soil ν_s=0.4, and a normalized trench width W=0.1 have been used. The average amplitude reduction ratio $\overline{A_{rr}}$ evaluated over a distance extending to $5L_r$ beyond the (edge of) trench was found to be a good representation of the screening effectiveness of the barrier (Ahmad & Al-Hussaini, 1994). The vibration source was modelled by a rigid circular surface footing undergoing periodic vertical vibration.

Effect of Footing Size

The normalized radius B_f $(=b_f/L_r)$ of the vibrating foundation which is dependent on the frequency of vibration is found to be an important parameter. Its influence on active isolation by an open trench may be studied by comparing Figs. 3, 4 and 5; where the values of average amplitude reduction ratio, $\overline{A_{rr}}$, are plotted against normalized clear distance, $L = L' - B_f - W/2$. These figures present the amplitude reduction ratios for B_f values of 0.5, 1.0 and 2.5, respectively. It can be seen from the figures that contrary to Woods' (1968) design recommendations a trench depth $d \geq 0.6\ L_r$ does not in itself always guarantee an average amplitude reduction of 75% ($\overline{A_{rr}}$ = 0.25). Rather, the screening effectiveness of an open trench depends on depth of the trench as well as its location and the size of the footing. The importance of B_f may also be seen in Fig. 6, where the amplitude reduction ratio $\overline{A_{rr}}$ for a trench depth D=1.0 is plotted as a function of B_f and L.

Effect of Trench Depth

The influence of the normalized trench depth D on average amplitude reduction ratio $\overline{A_{rr}}$ can also be observed in Figs. 3 to 5. Its effect is coupled in a complicated way with the effect of the normalized source width, B_f, and the distance of the trench from the source, L. For larger B_f values (Fig. 6 for B_f = 2.5), it appears that greater depths are required for achieving maximum efficiency.

Effect of Trench Location

The screening efficiency of an open trench barrier in active isolation is also found to be a function of the normalized clear distance L $(=L'-B_f-W/2)$ between the source and trench as can be seen in Figs. 3 to 6. The optimum value of L is a function of B_f, and it increases with an increase in foundation size. For B_f values of 0.1 to 1.0, the influence of the trench location is found to be insignificant for $B_f/L \leq 1.0$, provided $L \geq 0.25$. For large values of B_f, such as B_f =2.5, the influence of L becomes complex, probably due to a higher level of wave interference effects. At distances close to the source, the screening efficiencies of different trench depths D varies considerably. Also interference between waves emitted by the source and waves reflected from the trench becomes more prominent as the distance between the source and the trench becomes smaller.

Effect of Trench Width

The normalized width W was varied from 0.1 to 0.5 to study its effect on active isolation for a wide range of values of B_f, D and L. It was observed that for practical purposes the influence of trench width is insignificant.

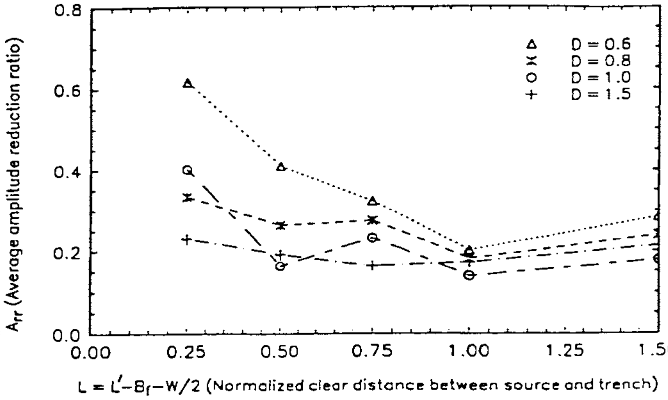


Fig. 3: Effect of Normalized Distance between Source and Trench for B_f=0.5

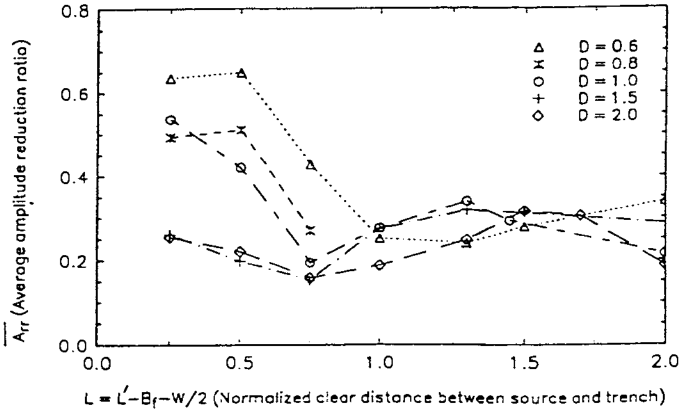


Fig. 4: Effect of Normalized Distance between Source and Trench for B_f=1.0

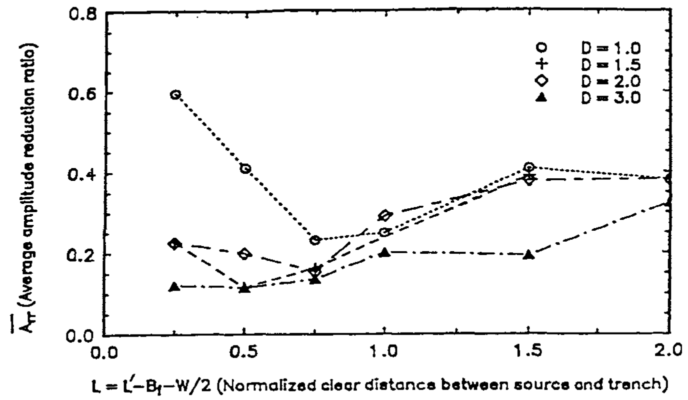


Fig. 5: Effect of Normalized Distance between Source and Trench for B_f=2.5

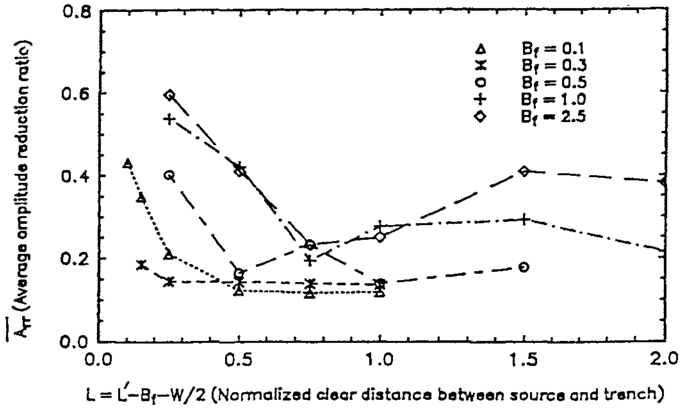


Fig. 6: Influence of Normalized Footing Radius for Different Barrier Locations for D=1.0

Effect of Poisson's Ratio of Soil

The influence of the Poisson's ratio of soil on the screening effectiveness of open trenches for various combinations of B_f, L and D is presented in Fig. 7. It can be seen that for Poisson's ratios in the range of 0.25 to 0.4, the average amplitude reduction ratio $\overline{A_{rr}}$ at ν_s=0.4 may be used safely to represent the amplitude reduction for the entire range. However, for Poisson's ratio for larger than 0.4, there is a trend of increase in the $\overline{A_{rr}}$ values for some cases.

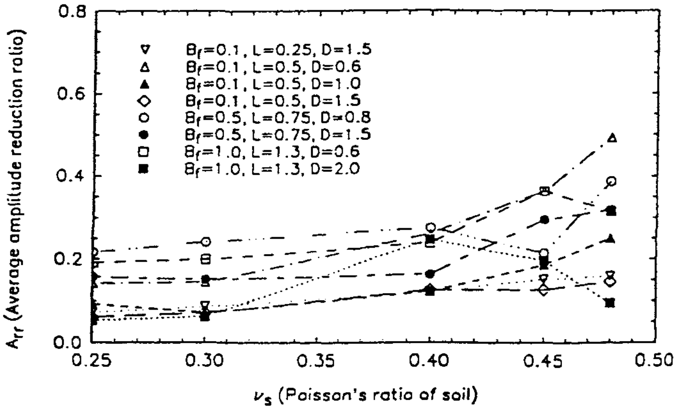


Fig. 7: Influence of Poisson's Ratio of Soil

DEVELOPMENT OF A SIMPLE MODEL

Based on the results of the extensive parametric investigation, the dimensionless parameters that govern active isolation by open trench barriers are found to be B_f, L, D and ν_s. The influence of B_f, L and D are coupled and can not be treated individually. A simple model incorporating the effects of the key parameters is developed. It expresses the average amplitude reduction ratio $\overline{A_r}$ as:

$$\overline{A_r} = I_{BLD} I_{\nu} \tag{2}$$

where I_{BLD} = influence factor due to B_f, L and D; I_{ν} = Poisson's ratio factor.

The influence factor I_{BLD} is obtained by regression analysis, and has the form:

$$I_{BLD} = C_0 + C_1 L + C_2 L^2 + C_3 L^3 \tag{3}$$

where,

$$C_0 = -0.55 + 0.96 B_f - 0.28 B_f^2 - 0.11 D^2 \tag{4}$$

$$C_1 = -3.28 D + 1.68 D^2 - 0.7 B_f D^2 + 0.19 B_f^2 D^2 \tag{5}$$

$$C_2 = -1.34 + 6.22 D - 2.67 B_f D + 0.8 B_f^2 D - 2.84 D^2 + 2.06 B_f D^2 - 0.59 B_f^2 D^2 \tag{6}$$

$$C_3 = 1.24 - 0.94 B_f + 0.27 B_f^2 - 3.5 D + 3.0 B_f D - 0.89 B_f^2 D + 1.52 D^2 - 1.56 B_f D^2 + 0.45 B_f^2 D^2 \tag{7}$$

The Poisson's ratio factor I_{ν} is a simple function of ν_s so as to give reasonably good and conservative estimates of $\overline{A_r}$ for the entire range of Poisson's ratio.

$$I_{\nu} = 1.0 \qquad \text{for } \nu_s \le 0.4 \tag{8}$$

$$I_{\nu} = 1.0 + 1.82(\nu_s - 0.4)/I_{BLD} \quad \text{for } \nu_s > 0.4 \tag{9}$$

For B_f values smaller than 0.1, the vibration source acts almost like a point source and hence, the screening behavior should be similar to the B_f=0.1 case. Thus; for footings with B_f less than 0.1, the amplitude reduction may be obtained by considering B_f =0.1 in equation (2).

Illustrative Examples on the Use of the Design Formula

The developed model is used here to estimate the average amplitude reduction ratio for several example problems and its validity is established through comparisons with numerical (BEM) results as well as published experimental data.

(a) Circular footings on half-space

Example of a circular surface footing of normalized radius B_f undergoing harmonic vertical oscillation and isolated by a circular trench of normalized depth D, located at a normalized clear distance L away from the footing, is considered. Comparison of the design formula with the BEM results, for a few test cases, are given in table 1. All comparisons indicate that the algebraic expression gives reasonable estimates of $\overline{A_r}$

TABLE 1. Comparison of Design Formula with BEM Results

V_s	ν_s	f (Hz)	B_f	L	D	$\overline{A_r}$ (BEM)	$\overline{A_r}$ (Model)
269.4	0.3	50	0.5	0.75	0.8	0.24	0.25
269.4	0.3	50	0.5	0.75	1.5	0.15	0.16
171.6	0.35	30	0.18	0.5	0.73	0.22	0.21
159.0	0.4	10	1.0	1.3	0.6	0.24	0.24
71.9	0.45	20	0.3	0.6	1.0	0.28	0.26

(Note: V_s = Shear wave velocity in soil, ν_s = Poisson's ratio of soil)

(b) Circular footing on layered soil

The simple model (which is based on idealization of soil as a homogeneous elastic half-space) is compared in Table 2 against the Woods' (1968) field test data (conducted on a two-layered soil profile). The average amplitude reduction ratio for the field test data is evaluated from Woods' curves for amplitude reduction ratio versus radial distance. Only six such curves are available in Woods' (1968), and thus the comparison here is limited to those six field tests.

Predictions by the design formula agree reasonably well with the field data. Although the actual site soil profile homogeneous soil layer on half-space, the assumption of a homogeneous half-space in the design formula provide good results.

TABLE 2. Comparison of Design Formula Model with Woods' (1968) Field Test Data

Test Number	B_f	L	D	W	$\overline{A_{rr}}$ (Woods)	$\overline{A_r}$ (Model)
AF7-300	0.121	0.514	0.363	0.182	0.33	0.29
AF5-300	0.121	0.514	0.726	0.182	0.15	0.17
AF6-300	0.121	0.514	1.452	0.182	0.14	0.10
AF5-200	0.074	0.315	0.444	0.110	0.21	0.32
AF5-250	0.100	0.422	0.596	0.149	0.25	0.23
AF5-350	0.152	0.644	0.91	0.228	0.16	0.13

[Note: V_{s1} = Shear wave velocity of the top soil layer (Fig. 4), V_{s2} = Shear wave velocity of the bottom soil layer (Fig. 4) and V_{r1} = Rayleigh wave velocity, and h = thickness of the top soil layer]

c) Rectangular footings on half-space

In engineering practice, most often machine foundations are rectangular in shape. Hence, in this example, vibration isolation of rectangular machine foundations by an annular open trench is studied. Fig. 8 shows a schematic of the problem. First, the actual geometry of the problem is modelled with the BEM to obtain a rigorous solution. Then, the simple model is used to estimate the amplitude reduction ratio of an equivalent circular foundation isolated by a circular trench. The equivalent radius of a rectangular footing is obtained by equating the static vertical stiffness of the rectangular footing with that of a circular footing. Thus, the equivalent radius may be expressed as:

$$b_{eq.} = b[0.3623 + 0.7643\,(a/b)^{0.75}] \qquad \textbf{(10)}$$

The clear distance between the source and the trench is obtained as an average value of the clear distance between the edges of the rectangular footing and the trench, i.e.

$$\ell_{av.} = \frac{(s+b) - 4ab/\pi}{(s+b) + 0.5\,(a+b)} \qquad \textbf{(11)}$$

Comparison of the design formula (for an equivalent Circular footing) with the BEM results (for the actual rectangular footing) are given in table 3. It can be seen that the design provides a reasonable estimate of the amplitude reduction ratio for footing shapes other than circular provided $B_f < 1.0$. A more extensive comparison between the design formula and the BEM solution can be found in Al-Hussaini (1992) and Vasu (1993).

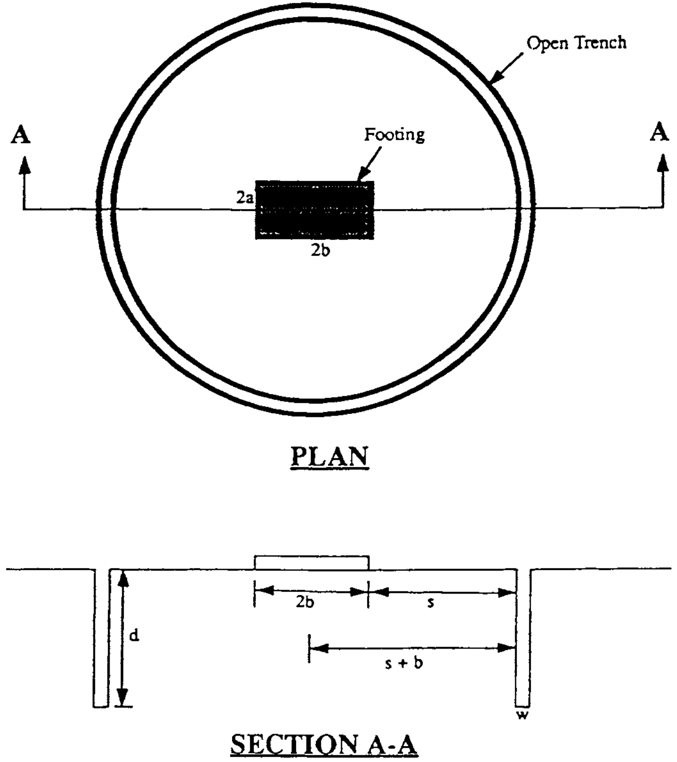


Fig. 8: Schematic Diagram of Active Isolation of Rectangular Foundation by Open Trench

TABLE 3: Comparisons of design formula with BEM results for active isolation of rectangular footings

a/L_r	b/L_r	s/L_r	B_f	L	D	$\bar{A}_r$ (BEM)	$\bar{A}_r$ (Model)
0.1	0.1	0.5	0.113	0.840	1.0	0.108	0.122
0.5	0.5	1.0	0.563	0.591	1.0	0.216	0.259
0.6	0.6	1.0	0.676	0.519	0.8	0.348	0.393
0.75	0.75	1.25	0.845	0.467	1.0	0.496	0.412
0.1	0.2	0.5	0.163	0.794	1.0	0.126	0.127
0.1	0.3	0.5	0.209	0.762	0.8	0.170	0.163
0.25	0.50	1.0	0.408	0.715	1.0	0.187	0.187
0.50	1.0	1.0	0.817	0.496	1.2	0.287	0.325

CONCLUSIONS

Based on the results of a rigorous parametric investigation, a simple model has been developed for active isolation of machine foundations by annular open trenches in a resonably deep homogeneous soil deposit. Results predicted by the simple model compares favourably well with those obtained by rigorous numerical method (BEM) and 'Woods' (1968) experimental data. Moreover, this study identifies the important parameters that controls the effectiveness of open trench wave barriers.

ACKNOWLEDGEMENT

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