International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1991 - Second International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

13 Mar 1991, 1:30 pm - 3:30 pm

Simple Design Methods for Vibration Isolation by Wave Barriers

Tahmeed M. Al-Hussaini

State University of New York at Buffalo, Buffalo, New York

Shahid Ahmad

State University of New York at Buffalo, Buffalo, New York

Recommended Citation

Al-Hussaini, Tahmeed M. and Ahmad, Shahid, "Simple Design Methods for Vibration Isolation by Wave Barriers" (1991). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 22.
https://scholarsmine.mst.edu/icrageesd/02icrageesd/session11/22

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,
March 11-15, 1991, St. Louis, Missouri, Paper No. 11.12

Simple Design Methods for Vibration Isolation by Wave Barriers

Tahmeed M. Al-Hussaini
Research Assistant, Department of Civil Engineering, State
University of New York at Buffalo, Buffalo, New York

Shahid Ahmad
Assistant Professor, Department of Civil Engineering, State
University of New York at Buffalo, Buffalo, New York

SYNOPSIS: Rectangular wave barriers (open or infilled trenches) are frequently used in engineering practice to reduce the ground vibrations caused by propagating surface (Rayleigh) waves of relatively small wave lengths. This paper presents models involving simple algegraic formulas for the design of rectangular wave barriers in homogeneous soil deposits. Both vertical and horizontal ground vibrations are considered. An extensive parametric investigation was conducted using a direct boundary element method algorithm. Simple models based on the key dimensionless parameters that controls the vibration screening effectiveness were then developed. The utility of such models is established through comparisons with rigorous numerical solutions and available experimental data. Vibration screening by open trenches in layered soils was also studied to identify the effects of layering on vibration screening.

INTRODUCTION

Surface waves generated by vibratory machinery or traffic may produce distress to nearby structures. It is possible to reduce this effect significantly by placing suitable wave barriers in the ground before the structure. The wave barrier reduces the ground vibration by interception, scattering and diffraction of the surface waves. Properly designed open or infilled trenches can be used for an effective vibration isolation (or screening) system.

Published literature reveals a good deal of research effort, both numerical and experimental for the study of isolation of the vertical ground motion. For a good literature review, readers may refer to Beskos et al (1986), Al-Hussaini and Ahmad (1991). Woods (1968) reported results on a series of field testing for vibration isolation installing open trenches near to the vibratory source (active isolation) as well as in the far-field (passive isolation). Haupt (1978) utilizing his influence matrix boundary condition concept for computational efficiency, employed the Finite Element Method (FEM) in investigating the use of solid obstacles (trenches) of different shapes and sizes for passive as well as active isolation. He also did some model experiments to verify his analytical results. Fuyuki and Matsumoto (1980) using a Finite Difference scheme with an improved treatment of corners and absorbing boundary conditions investigated Rayleigh wave scattering by rectangular open trenches.

More recently the Boundary Element method (BEM) has been used to study problems of vibration isolation. BEM is very well suited for wave propagation problems in soils involving semi-infinite domain because the radiation condition at the boundary is automatically satisfied and for linear problems, the dimensionality reduces by one. Hence only the boundary of the domain needs to be discretized. Beskos et al (1985, 1986), Emad and Manolis (1985) appear to be the first group of people to utilize BEM for studying this problem. They used a constant element based BEM algorithm and presented some results for vibration screening using open and infilled trenches.

In order to develop design methods for vibration isolation by open or infilled trenches, a systematic detailed parametric investigation was undertaken. Details of this investigation have been reported by Ahmad and Al-Hussaini (1991), Al-Hussaini and Ahmad (1991). Isolation of vertical ground vibration by rectangular open and infilled (Stiffer than soil) trenches in a homogeneous isotropic viscoelastic half-space were studied. Reduction of the horizontal ground motion was investigated for the case of infilled trenches. In addition, layering effects have been examined by considering open trenches in a double layered soil profile.

A rigorous 2-D Direct Boundary Element method based on the infinite-plane fundamental solution (in frequency domain) is used for this study. The BEM algorithm incorporates quadratic (or higher order) elements, is capable of handling multiple regions and has a self-adaptive numerical integration scheme.

PROBLEM DEFINITION

The problem of passive isolation under plane-strain condition using rectangular open and infilled trenches is considered. As shown in Fig. 1, a trench of depth d and width w is located at a distance ℓ from a rigid surface footing which is subjected to a vertical or horizontal time harmonic load. Since vibration isolation by a trench is primarily achieved by screening of surface (Rayleigh) waves, the depth, width and the distance of the trench are normalized with respect to the Rayleigh wavelength ($D = d/L_r$, $W = w/L_r$, $L = \ell/L_r$; where L_r = Rayleigh wavelength). The presence of a trench causes reduction in the vibration amplitude in an area after the trench. The screening effect may be expressed by the two parameters A_{rv} (vertical amplitude reduction ratio) and A_{rh} (horizontal amplitude reduction ratio);

$$A_{rv} = \frac{\text{Vert. Displ. Ampl. of Ground Surf. with trench}}{\text{Vert. Displ. Ampl. of Ground Surf. without trench}}$$

$$A_{rh} = \frac{\text{Horztl. Displ. Ampl. of Ground Surf. with trench}}{\text{Horztl. Displ. Ampl. of Ground Surf. without trench}}$$

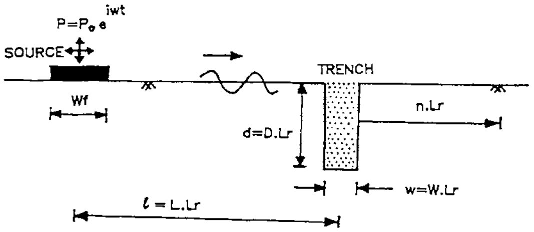

Fig. 1: Schematic diagram of the problem studied: Passive vibration isolation by rectangular trenches in a viscoelastic half-space.

In order to represent the amplitude reduction over an area of extent nL_r after the trench, the average amplitude reduction ratio in that area is computed:

$$\bar{A}_{rv} = \frac{1}{nL_r}\int_0^{nL_r} A_{rv}\,dx_t \quad \text{and} \quad \bar{A}_{rh} = \frac{1}{nL_r}\int_0^{nL_r} A_{rh}\,dx_t$$

where x_t is the distance after the trench.

COMPARISON WITH PUBLISHED RESULT

Result obtained using the present methodology is compared with that of Haupt (1978) in Fig. 2. Haupt (1978) used the FEM employing his influence matrix concept and boundary conditions developed by Lysmer and Kuhlemeyer (1968). In this problem, an in-plane steady state Rayleigh wave is considered incident upon a rectangular concrete infilled trench having normalized dimensions of W = 0.2 and D = 1.5. The vertical amplitude reduction after the trench obtained by the two different methods agree reasonably well.

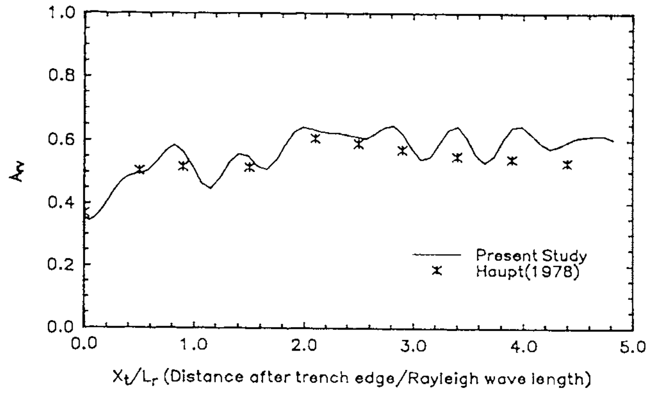

Fig. 2: Comparative study for Rayleigh wave screening by a concrete trench (W=0.2, D=1.5).

SCREENING OF VERTICAL VIBRATION

A vertical harmonic load is considered in the problem of Fig. 1 and the influence of various parameters on the amplitude reduction due to an open or concrete (stiffer than soil) infilled trench is studied. Here only the key parameters that govern the screening process will be presented, followed by the simple models developed. Unless otherwise stated, $\ell = 5L_r$, width of the footing $w_f = 0.5L_r$, frequency of vibration $f = 50$ Hz and soil properties were those corresponding to medium dense sand: Rayleigh wave velocity V_r = 250m/sec, unit weight $\gamma_s = 17.5$ KN/m^3, Poisson's ratio $\nu_s = 0.3$, and material damping $\beta_s = 5\%$. For the case of concrete-infilled trenches, the properties of concrete were chosen as: Young's Modulus $E_c = 11316$ MN/m^2, Poisson's ratio $\nu_c = 0.25$, unit weight $\gamma_c = 24$ KN/m^3 and material damping $\beta_c = 5\%$. The average amplitude reduction ratio is computed over an area extending to a distance of $10L_r$ after the trench.

The functional difference between an open trench and an infilled trench is mainly due to the ability of the trench material of an infilled trench to act as a transmission path for the incident wave energy to the zone of screening. As a result, for the same trench dimensions an infilled trench is always less effective than an open trench.

OPEN TRENCH

The normalized depth D is varied from 0.4 to 2.0 and the normalized width W is varied from 0.1 to 1.0. As shown in Fig. 3, the normalized depth D appears to govern the screening efficiency of an open trench. W is of very little importance except for shallow depths (D<0.8). For shallow depths, increase in width, in general, results in better performance of the trench. This could be due to more mode conversion (to body waves) from the wider base of the trench. For shallow trenches, significant amount of Rayleigh wave energy is allowed to pass below the trench and the relative contribution of this width effect is large.

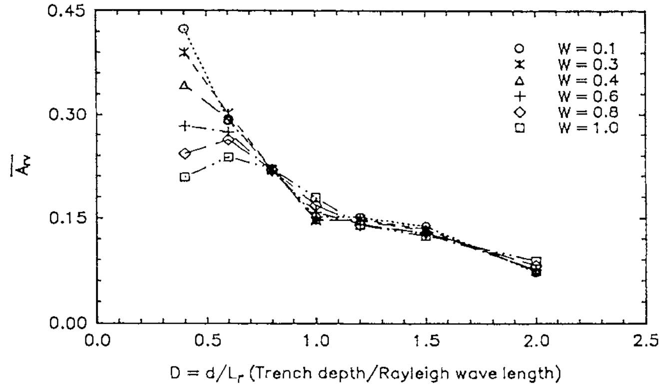

Fig. 3: Influence of normalized trench depth and width for an open trench.

Simple Model

For open trenches, the normalized depth D is the primary parameter, except for shallow depths (D<0.8) when the width has significant influence. The latter effect is somewhat irregular and cannot be incorporated in a simple model. However, considering narrow trenches (W=0.1 to 0.3), the simple expression

$\bar{A}_r \cong \frac{1}{6}(D)^{-1.07}$ ...(1) maybe used to represent the screening effectiveness of open trenches in the entire depth range of D=0.4 to 2.0. Utility of the simple model is established by comparison with results obtained by the rigorous BEM method as shown below:

G_s (MN/m^2)	γ_s (kN/m^3)	ν_s	f (Hz)	W	D	$\bar{A}_r$(BEM)	$\bar{A}_r$(Model)
60.0	15.0	0.33	25	0.5	1.2	0.18	0.14
200.0	18.0	0.4	150	0.3	1.5	0.07	0.11

INFILLED TRENCH

For an infilled trench, more parameters need to be considered.

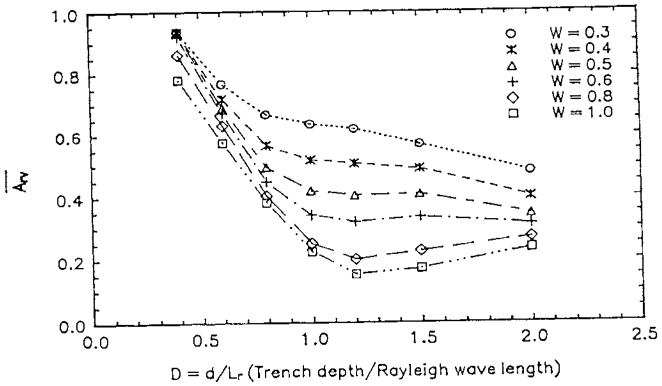

Fig. 4: Influence of normalized trench depth and width for concrete (infilled) trench.

From Fig. 4, Both D and W appear to be equally important. For efficient design D should not be more than 1.2. The amplitude reduction ratio $\bar{A}_{rv}$ is not just a simple function of the normalized cross-sectional area ($A=DW=dw/L_r^2$) as was thought by earlier researchers. Another parameter, the D/W ratio exerts a controlling influence as demonstrated in Fig. 5. The shape factor, I_s is defined as the ratio between the $\bar{A}_{rv}$ value at a particular D/W ratio to the lowest $\bar{A}_{rv}$ value obtainable for the same cross-sectional area. The influence of D/W is probably due to a complex combination of several factors. Wave energy is reflected back and diffracted from the incident face of the concrete trench. The presence of the barrier results in partial mode conversion of the incident Rayleigh wave to body (P&S) waves which travel in all directions from the barrier. Also the waves that are transmitted through the trench and under the trench due to different passage velocity are out of phase by some amount and this can result in partial destructive interference after the trench. The influence of D/W ratio is greater for larger trench cross-sections, because greater amount of wave reflection and mode conversion is associated with larger cross-sections.

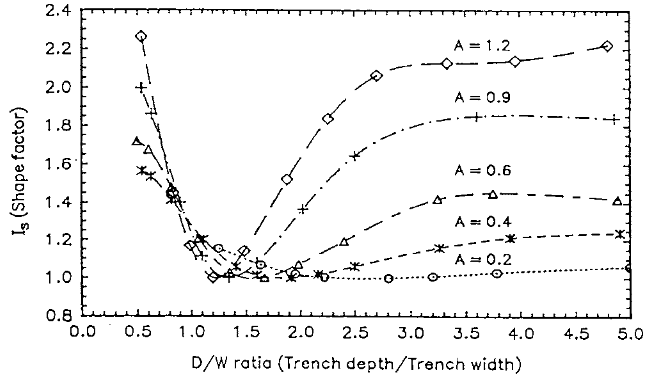

Fig. 5: Influence of D/W ratio on the vibration screening by a concrete trench.

Vibration screening effectiveness of an infilled trench directly depends on the contrast (physical anomaly) in the material properties of the trench material and the soil. Fig. 6 shows the effect of the shear wave velocity ratio (V_{st}/V_{ss}) of the trench material to the soil for various cross-sections. Increase in V_{st}/V_{ss} ratio results in better vibration screening. This means that a material of higher shear modulus provides greater resistance to the incoming wave. At a V_{st}/V_{ss} value approaching one, the $\bar{A}_{rv}$ value is seen to be close to unity. This very fact highlights the importance of this parameter. Based on this figure, it is recommended that the V_{st}/V_{ss} ratio should at least be 2.5.

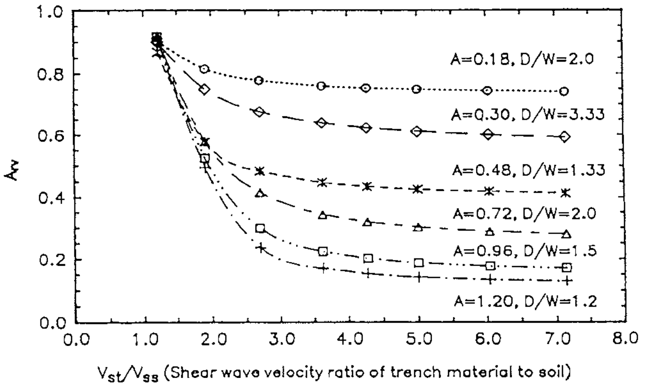

Fig. 6: Influence of the ratio of shear wave velocity of the trench material to that of the soil.

Fig. 7 represents the influence of the density ratio ρ_t/ρ_s. In practice, densities of soils and concrete are not expected to vary much, so the density ratio was varied from 0.75 to 1.5 only. In order to remove the effect of V_{st}/V_{ss} ratio which in turn is a function of the density ratio, the V_{st}/V_{ss} ratio was kept constant. Increased density of the trench material contributes to its screening efficiency.

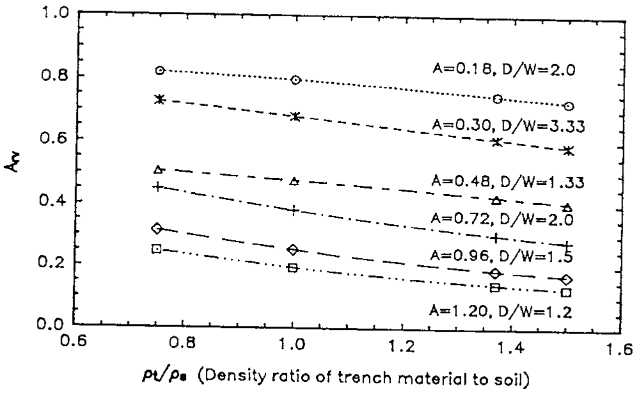

Fig. 7: Influence of the ratio of density of the trench material to that of the soil.

Simple Model

The model developed describes the average amplitude reduction ratio $\bar{A}_{rv}$ due to an infilled trench, for D<1.2, as:

$$\bar{A}_{rv} = I_s I_v I_d I_a$$

where I_s = shape factor, I_v = velocity factor, I_d = density factor, and I_a = area factor.

The shape factor I_s (Fig 5) is a function of both D/W and A.

The velocity factor I_v, for $\frac{V_{st}}{V_{ss}} > 2.5$, is approximated as $I_v = \left[\frac{V_{ss}}{V_{st}}\right]^n$ where n = 0.54 A. When A = 0, $I_v = 1.0$, which is, indeed, logical.

The density factor I_d is represented as $I_d = \left[\frac{\rho_s}{\rho_t}\right]^m$ where m=0.94A.

The model implies that the density and wave velocity effect increases with larger trench cross-sections, as should be expected.

The area factor I_a is given as $I_a = 0.57(A)^{-0.25}$.

Predictions with the simple model are compared first with results obtained by the BEM method.

G_s (MN/m^2)	γ_s (Kn/m^3)	ν_s	f (Hz)	$\frac{V_{st}}{V_{ss}}$
60.0	15.0	0.33	25	3.5
200.0	18.0	0.4	150	3.0

$\frac{\rho_t}{\rho_s}$	W	D	$\bar{A}_{rv}$(BEM)	$\bar{A}_{rv}$(Model)
1.5	0.5	1.2	0.39	0.41
1.2	1.2	1.0	0.3	0.32

Comparisons are also done with the laboratory test results of Haupt (1978):

$\frac{V_{st}}{V_{ss}}$	$\frac{\rho_t}{\rho_s}$	A	D/W (assumed)	$\bar{A}_{rv}$(Haupt)	$\bar{A}_{rv}$(Model)
8.0	1.34	0.23	2.57	0.51-0.57	0.60
8.0	1.34	0.33	2.05	0.41	0.48

OPEN TRENCHES IN LAYERED SOIL

Effects of layering are studied by considering in the problem of Fig. 1, a two-layer soil profile (single layer over half-space) replacing the half-space. Isolation of vertical vibration by various depths of open trenches (w =0.5) is studied. A layered soil problem differs from the corresponding half-space problem principally in two aspects. First, significant wave energy can be reflected from the layer interface back to the upper layer (which cannot occur in the case of half-space). Secondly, if the bottom layer is close to the ground surface, a dispersive type (frequency dependent) Rayleigh wave exists, a significant part of which travels in the bottom layer. The influence of parameters H (Top layer depth/Rayleigh wave length) and V_{S1}/V_{S2} (shear wave velocity ratio of top to bottom layer), which are expected to have a controlling role, are investigated.

Several soil-profiles with H varying from 0.5 to 8.0 have been studied; Figs. 8 and 9 correspond to H=0.5 and H=8.0 respectively. The conclusions based on this investigation may be summarized as follows:

> If the lower layer has a lower stiffness than the upper layer, the effect of layering can be ignored.
>
> If the lower layer has a higher stiffness then the layering effect needs to be considered because it reduces the screening effectiveness. However, at a H value of 8.0 (or more), as can be seen from Fig. 9, the effect of layering is zero. In fact, the effect gets diminished drastically at a H value of around 6.0. Compared to a corresponding half-space problem, trenches need to be built deeper. Especially for V_{S1}/V_{S2} values smaller than around 0.7-0.75, trenches may have to be built deep down (D≅H+1.0) into the lower layer to achieve a good isolation effect ($\bar{A}_{rv}$ value of 0.25 or less).

When the top layer is shallow (in terms of the Rayleigh wavelength), such as H≅0.5, and the lower layer is much stiffer ($V_{s1}/V_{s2} \cong 0.25$), one needs to consider the trench depth in terms of the wavelength for the lower layer. This can be noted from Fig. 8.

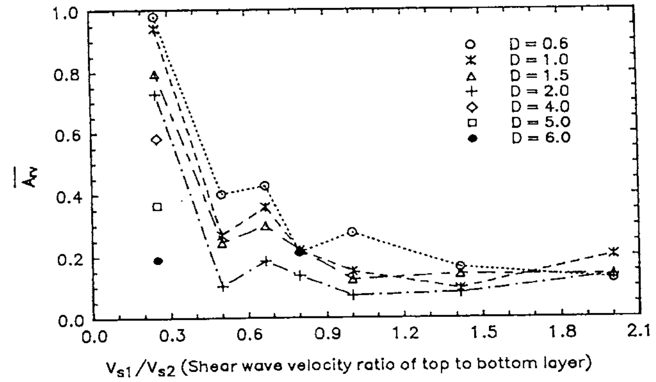

Fig. 8: Effect of the shear wave velocity ratio of two soil layers for different depths of an open trench (W=0.5) in a two layered soil profile with H=0.5.

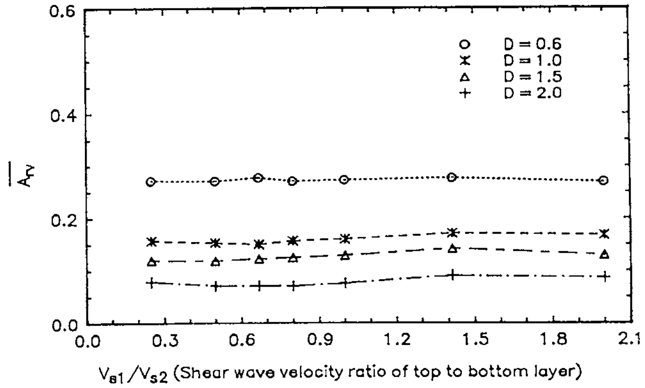

Fig. 9: Effect of the shear wave velocity ratio of two soil layers for different depths of an open trench (W=0.5) in a two layered soil profile with H=8.0.

SCREENING OF HORIZONTAL VIBRATION

A horizontal harmonic load is considered in the problem of Fig. 1 and the effectiveness of concrete infilled trenches in reducing the horizontal ground vibration is studied. The material properties for the soil and the concrete is the same as stated earlier. However, a Poisson's ratio of 0.4 is used for the soil. $\overline{A_{rh}}$ is computed over an area of 5 L_r after the trench.

In Fig. 10, the amplitude reduction achieved by a concrete trench (W=0.6) with respect to the horizontal motion is compared to that corresponding to the vertical motion. Wave barriers appear to be more effective for screening of vertical vibration than that of horizontal vibration. This may be explained as follows: in case of vertical vibration screening, the particle motion within the barrier in the vertical direction can send wave energy deep into the halfspace. Whereas, for horizontal vibration screening, the horizontal particle motion within the barrier tends to transfer energy to the right of the barrier (screening zone).

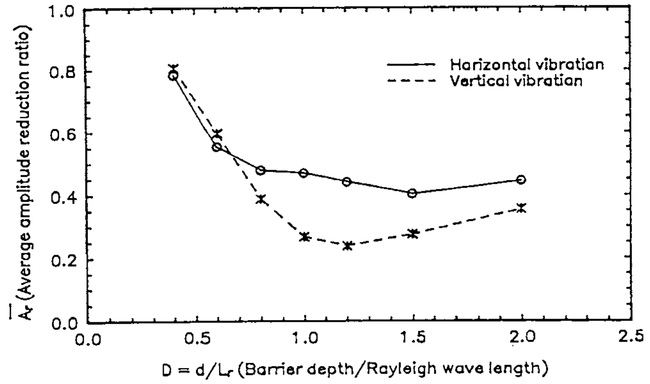

Fig. 10: Comparison of vibration screening in the horizontal and vertical modes by a barrier (W=0.6).

Similar to the case of vertical vibration screening, W and D appear to be equally important parameters, as shown in Fig. 11. Except for narrow trenches (W≅0.3), increase in D beyond 1.5 produces no benefit. In Fig. 12 the influence of the dimensionless cross-sectional area A = DW is plotted. Considering design efficiency, depths greater than 1.5 or smaller than 0.6 are not considered. The amplitude reduction ratio can, in this case, be uniquely related to the cross-sectional area by the following expression: $\overline{A}_{rh} \cong 0.4\ (A)^{-0.33}$.

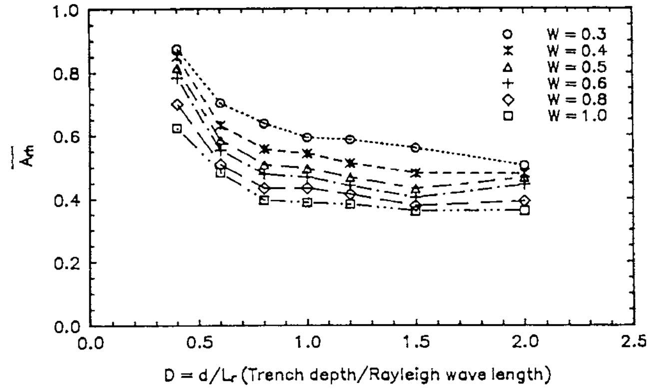

Fig. 11: Influence of the normalized trench depth and width on the screening effectiveness of concrete barriers.

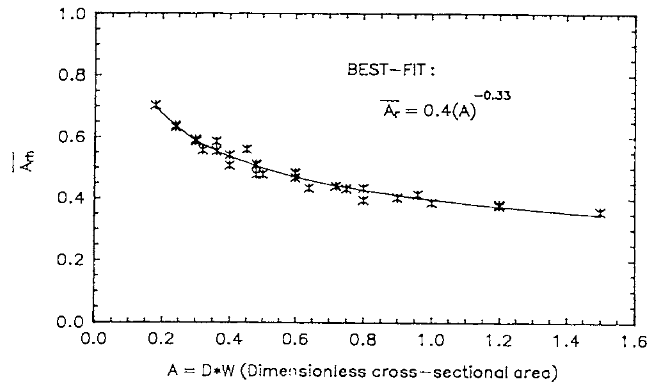

Fig. 12: Influence of the normalized cross-sectional area on the horizontal amplitude reduction ratio for concrete barriers ($0.6 \leq D \leq 1.5$).

Fig. 13 shows the effect of the ratio $\frac{V_{rt}}{V_{rs}}$ of the Rayleigh wave velocity of the trench to that of the soil for different trench cross-sections. Increase in $\frac{V_{rt}}{V_{rs}}$ ratio results in better screening. This is the most important material parameter, since as $\frac{V_{rt}}{V_{rs}}$ ratio approaches unity, the screening effectiveness reduces to almost zero. The influence of the density ratio $\frac{\rho_t}{\rho_s}$ of the trench material and the soil is studied, while maintaining $\frac{V_{rt}}{V_{rs}}$ ratio constant. The amplitude reduction ratio appears to decrease linearly with density ratio, maintaining more of less similar slopes,

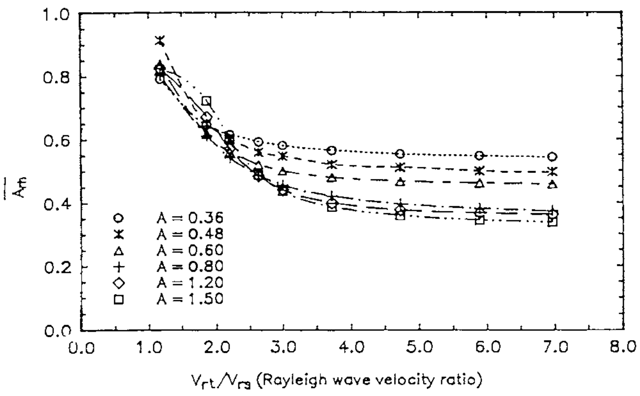

Fig. 13: Influence of the ratio of the Rayleigh wave velocities of the wave barrier and soil on the amplitude recuction ratio.

Simple model

The average amplitude reduction ratio for $0.6 \leq D \leq 1.5$ is expressed as $\bar{A}_{rh} = I_a I_v I_d$........(3)

where I_a = area factor, I_v = velocity factor and I_d = density factor.

I_v and I_d are defined to be 1.0 when $\frac{V_{rt}}{V_{rs}} = 4.72$ and $\frac{\rho_t}{\rho_s} = 1.37$.

Consequently, I_a is given by, $I_a = 0.4(A)^{-0.33}$.

The velocity factor I_v is expressed as:

$$I_v = 1.0 \qquad \text{for } V_{rt}/V_{rs} \geq 4.72$$

$$= 1.0+m(4.72-V_{rt}/V_{rs})/I_a \quad \text{for } 2.63 \leq V_{rt}/V_{rs} \leq 4.72$$

$$= 1.0+[2.09m+0.92(V_{rt}/V_{rs})^{-0.58} - 0.526]/I_a$$

$$\text{for } V_{rt}/V_{rs} < 2.63$$

where, $m = 0.006 + 0.0382(A)$

The density factor I_d is approximated as:

$$I_d = 1.0 - 0.24\ (\rho_t/\rho_s - 1.37)/I_a$$

Results obtained using this model is compared with results obtained by the rigorous BEM code in the table below:

G_s MN/m^2	γ_s (Kn/m^3)	ν_s	W	D
61.5	14.7	0.3	0.6	1.0
8.0	15.2	0.48	1.0	0.6
200.0	18.0	0.4	0.8	1.5

$\frac{V_{rt}}{V_{rs}}$	$\frac{\rho_t}{\rho_s}$	$\bar{A}_{rh}$(Model)	A_{rh}(BEM)
7.14	1.5	0.44	0.38
2.62	0.9	0.69	0.68
4.13	0.85	0.54	0.55

CONCLUSIONS

Based on the results of a rigorous parametric investigation, simple design expressions have been developed for passive isolation systems involving rectangular open and infilled (stiffer material) trenches in homogeneous soil deposits under plane-strain condition. Results predicted by the simple models compare favourably well with those obtained by rigorous numerical methods and available experimental data. Moreover, this study identifies the important dimensionless parameters that controls the effectiveness of a vibration screening system. Finally, some important layering effects have also been identified.

REFERENCES

Ahmad, S. and Al-Hussaini, T.M., 'Simplified design for vibration screening by open and infilled trenches', J. Geotech. Eng. Div., ASCE, (to appear in January 1991), Vol. 117, No. 1.

Al-Hussaini, T.M. and Ahmad, S., 'Design of wave barriers for reduction of horizontal ground vibration; J. Geotech. Eng. Div., ASCE, 1991 (to appear).

Beskos, D.E.; Dasgupta, G.; Vardoulakis, I.G., 'Vibration isoation of machine foundations;, In: Vibration problems in geotechnical engineering ed: Gazetas, G. & Selig, E.T., 1985, pp. 138-151.

Beskos, D.E.; Dasgutpa, G.; Vardoulakis, I.G., 'Vibration isolation using open or filled trenches, Part 1: 2-D homogeneous soil'; Comput. Mech., Vol. 1, 1986, pp. 43-63.

Emad, K. and Manolis, G.D., 'Shallow trenches and propagation of surface waves', J. Eng. Mech., ASCE, Vol. 111, 1985, pp. 279-282.

Fuyuki, M. and Matsumoto, Y., 'Finite difference analysis of Rayleigh wave scattering at a trench', Bull. Seism. Soc. Am., Vol. 70, 1980, pp. 2051-2069.

Haupt, W.A., 'Surface waves in nonhomogeneous half-space', In: Dynamical methods in soil and rock mechanics, ed. Prange B., Balkema, 1978, pp. 335-367.

Lysmer, J. and Kuhlemeyer, R.L., 'Finite dynamic model of infinite media, 'Proc. ASCE, 1969, No. EM4.

Woods, R.D., 'Screening of surface waves in soils', J. Soil Mech. and Found. Div., ASCE, 1968, Vol. 94, SM4, pp. 951-979.