Ground Vibration Isolation Using Gas-filled Cushions

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ABSTRACTS: Ground vibrations are of increasing importance, especially in industrialized countries. Aspects of importance for wave propagation in soil deposits are presented. The effect of wave bending due to increasing wave velocity with depth is discussed. The vibration effectiveness of open trenches is reviewed, based on theoretical studies and model tests. The concept of the gas cushion screen for permanent ground vibration isolation is described. The boundary element method was used to compare the vibration isolation effect of an open trench with that of a gas cushion screen. The analytical results are compared with field tests. Design recommendations for ground vibration isolation measures are given.

1. INTRODUCTION

The importance of ground vibrations from man-made activities has increased during the past decades, especially in densely populated areas and industrial zones. This is due to various factors, such as more intense and heavier traffic and the expansion of the transportation infrastructure in urban areas. Especially in Europe and Japan, the high-speed railway network is being expanded, between city centers. Also the use of heavy manufacturing equipment and industrial processes can cause disturbing vibrations. Due to the high cost of land, sites with poor ground conditions are now being developed, where construction activities often must be carried out in the close proximity of existing buildings. Major problems can arise in the vicinity of vibration-sensitive historic monuments. Ground vibrations can also have negative consequences in residential areas and industrial zones, where vibration-sensitive equipment and manufacturing process can be negativley affected. Modern buildings have become increasingly susceptible to vibrations as they are often constructed of light-weight material, with an effort to minimize construction costs. At the same time, the awareness with respect to noise and building vibrations has increased. In many industrialized countries, stringent environmental regulations are being introduced and enforced.

In the following sections, fundamental aspects of ground vibration propagation are discussed. The effectiveness of different vibration isolation measures is reviewed, based on theoretical considerations, model tests and field trials. A new method of permanent ground vibration isolation, the gas cushion screen is presented. The results of extensive field studies are compared with theoretical investigations.

2. GROUND VIBRATION PROPAGATION

2.1 Wave Propagation

The propagation of ground vibrations from the source and through geological formations, as well as their interaction with structures in or on the ground, is a complex problem. The fundamentals of wave propagation in soils have been treated extensively in the literature and reference is made to two important publications, (Richart et al. 1970, Haupt, 1995). The geological conditions, the location of the ground water and the dynamic properties of soils (wave velocity and damping) are of great importance.

Special phenomena can occur at geometric irregularities or across inhomogeneities. At the interface between two elastic bodies, body waves are partly reflected and partly refracted. The angles of reflection and refraction are determined by Snell's law. The wave amplitudes depend on the angle of incidence and the ratio of the wave propagation velocity of the two materials. At a free surface, full reflection occurs.

For vibration problems, the surface wave (Rayleigh wave, R-wave) has greatest practical importance. The R-wave propagates along the free surface of the half space and is composed of vertical and horizontal vibration components, Figure 1. The amplitude decays quickly with depth and the region of influence is about one wave length, L_R. At the surface, the horizontal component is about 0.6 – 0.8 of the vertical component.

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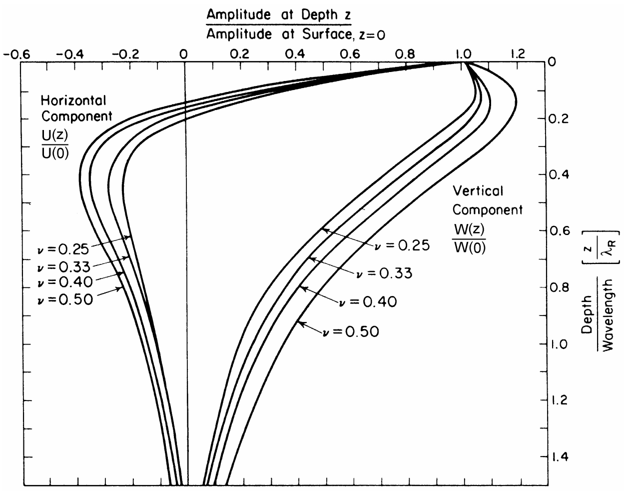


Figure 1. Variation of normalized horizontal and vertical vibration amplitude with depth, normalized by wave length (Richart et al., 1970).

The velocity of the R-wave is slightly slower than that of the shear wave, S-wave (87 – 96 % for Poisson's ratio ν varying between 0 and 0.5). The wave length L can be calculated from the following equation:

$$L = \frac{c}{f} \tag{1}$$

where c is the wave propagation velocity and f is the vibration frequency.

2.2 Vibration Amplification due to Wave Bending

In a half-space, where the wave velocity increases with depth, body waves radiating from an oscillating source at the surface are bent upwards towards the surface. There, superposition occurs with the surface waves. This results in a distinct interference pattern. Figure 2 shows the measured vibrations on the ground surface from tests in moist sand with gradually increasing wave velocity with depth, (Haupt, 1995). The vibration attenuation curve exhibits zones of vibration amplification. When the distance is normalized by the wave length, a distinct amplification pattern can be observed, which is superimposed on the monotonically decaying vibration attenuation curve. This effect can be attributed to wave bending.

A critical condition of wave bending occurs when wave rays are focused towards a zone on the ground surface, where vibrations are amplified. This situation occurs when the wave velocity increases with depth according to a hyperbolic cosine function, Massarsch (1993). The practical significance of this problem is illustrated in Figure 3. Theoretically, all vibration energy is refracted to an area located a distance x_f from the vibration source.

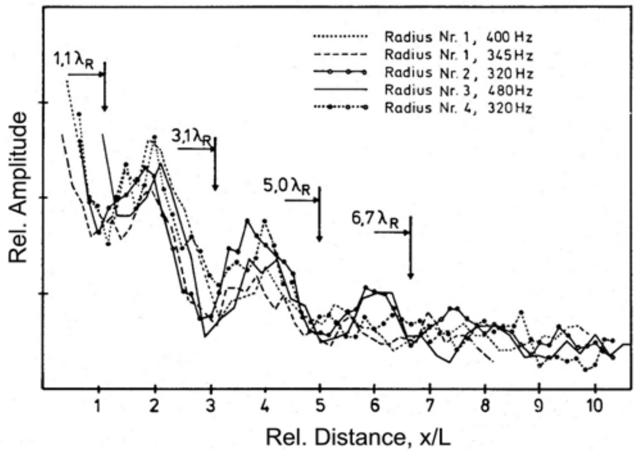


Figure 2. Interference pattern of vibration attenuation curve on the ground surface due to wave bending (from Haupt, 1995).

It is possible to calculate this critical distance x_f from the vibration source by the following equation

$$x_f = \frac{\pi z}{\operatorname{arc\,cosh}\left(c / c_0\right)} \tag{2}$$

where z is the depth, c is the wave velocity at depth z and c_0 is the body wave velocity on the ground surface.

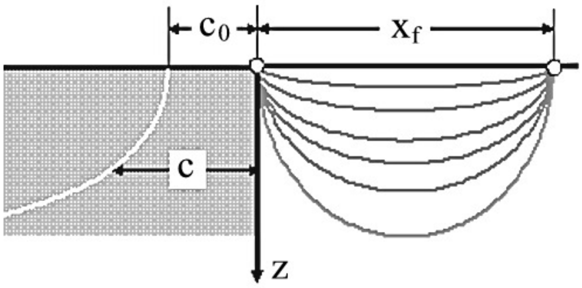


Figure 3. Bending of waves in soil deposit with wave velocity increasing according to cosh function.

Figure 4 shows six wave velocity profiles as a function of the depth, normalized by the distance x_f from the vibration source, at which vibration focusing occurs. Eight different shear wave velocity profiles were chosen, which are not unrealistic in naturally occurring geological formations. The diagram can be used to assess the risk of wave bending and to identify risk zones, by assuming different S-wave (or P-wave) velocity profiles.

In order to illustrate this point, Figure 5 shows the variation of wave velocity with depth for different wave velocity values on the ground surface, increasing according to Eq. 2. All the shown curves cause wave focusing at a distance of 30 m from the vibration source.

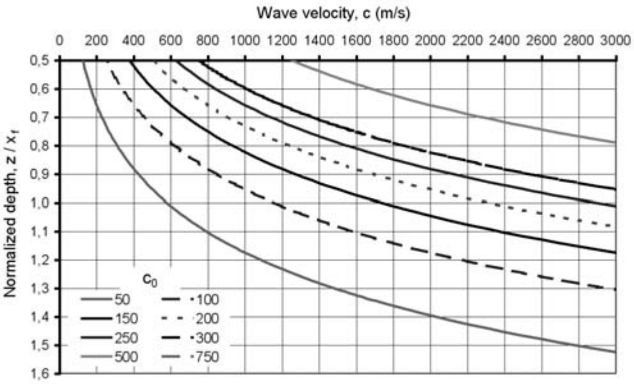


Figure 4. Variation of body wave velocity, c_0 with depth normalized by the critical distance, x_f for different values of wave velocity at the ground surface.

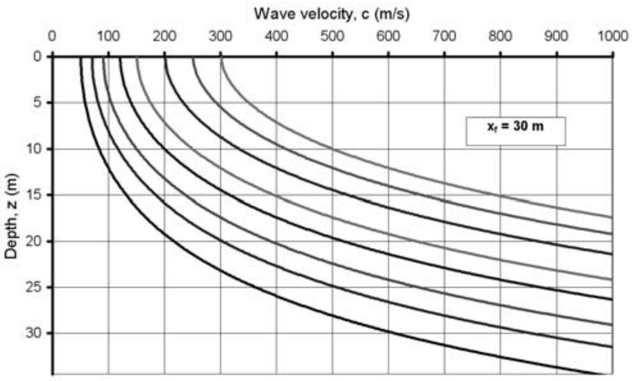


Figure 5. Variation of shear wave velocity with depth, resulting in vibration focusing at 30 m distance, cf. Eq. 2. Note value of shear wave velocity at ground surface for respective curve.

The wave velocity variation of many geological formations does at least partly fit the shown curves. Wave bending can explain the fact that vibrations can be higher at locations further away from the vibration source than in the vicinity.

3. VIBRATION ISOLATION USING TRENCHES

Ground vibrations can be reduced by barriers between the source and the affected structure. A comprehensive discussion of different vibration isolation measures was presented by Haupt (1995). The literature comprises many theoretical investigations regarding the efficiency of vibration isolation barriers, using the Finite Element and/or the Boundary Element Method, (Ahmad and Al-Hussaini, 1991, Beskos et al., 1986, Beskos et al. 1990, Haupt, 1978a). Dolling (1965) performed a theoretical analysis of energy partitioning for Rayleigh waves across a trench. He proposed an isolation factor, A_r, as a function of the normalized trench depth, T/L_R, where T is the trench depth and L_R is the wave length of the Rayleigh wave. He concluded that soil type (Poisson's ratio) does not appear to have a major influence on the isolation effect. More sophisticated theoretical analyses were performed by Haupt (1981), Beskos et al. (1986, 1990) and Ahmad and Al-Hussaini, (1991) on the isolation efficiency of open trenches have confirmed the findings by Dolling.

For a detailed discussion of these investigations and the work by Haupt (1978a, b) and others, reference is made to Haupt (1995). Only a limited number of experimental investigations have been reported, mainly model tests in the field and/or in the laboratory. However, there is a lack of well-documented case histories of full-scale applications. In many cases they lack important information about the geotechnical and dynamic soil properties. Probably the most important pieces of information, which often are missing, are actual vibration measurements before and after implementation of the isolation measures. Thus it is difficult to assess the efficiency of such measures.

3.1 Isolation Efficiency of Trenches

The first scientific investigations on the isolation effect of barriers at large scale were reported by Barkan (1962). He studied the screening effect of open trenches and of sheet piles in loess (silt). The wave velocity of the soil was about 150 - 200 m/s. A heavy vibrator was located 1.8 m from a trench. The length of the trench was varied (8m, 11m) and the depth was increased gradually to 4 m. Tests were performed at frequencies ranging between 12 and 17 Hz. The isolation effect increased with trench depth but also with the length of the trench. The screening efficiency was higher when the vibration frequency was increased (wave length decreased). Vibrations were lowest directly behind the screen and increased with increasing distance. In front of the screen, vibrations amplitudes were larger. The isolation effect of open trenches was better than that of sheet piles. Also, sheet piles had no effect on horizontal amplitudes.

Woods (1968) carried out tests in silty sand on a model scale and distinguished between near-field and far-field isolation conditions. The maximum depth of the trench was 1.2 m. The vibration source was a vertically oscillating vibrator and the wave length was varied between 0.34 and 0.7 m. Tests with straight and partial circular trenches were performed at different distances from the vibration source. Figure 6 shows amplitude reduction contours behind a straight trench in the far-field (passive isolation test). The length, *L,* and width, *W,* of the trench were varied. Tests were performed at two distances between the vibrator and the trench. It was found that the most important isolation parameter is the relative depth of the trench compared to the wave length, H/L_R. Woods (1968) measured vertical displacement amplitudes are shown as a function of the distance from the vibration source for the case of passive isolation.

These results are shown in Figure 7. The isolation effectiveness increases with increasing relative trench depth (H/L_R) The isolation effect is largest directly behind the trench along the center line. In this location, the average isolation effect is 75% (amplitude ratio: 0.25). Vibrations were magnified in front of the trench, indicating that the trench acts as a reflector of wave energy.

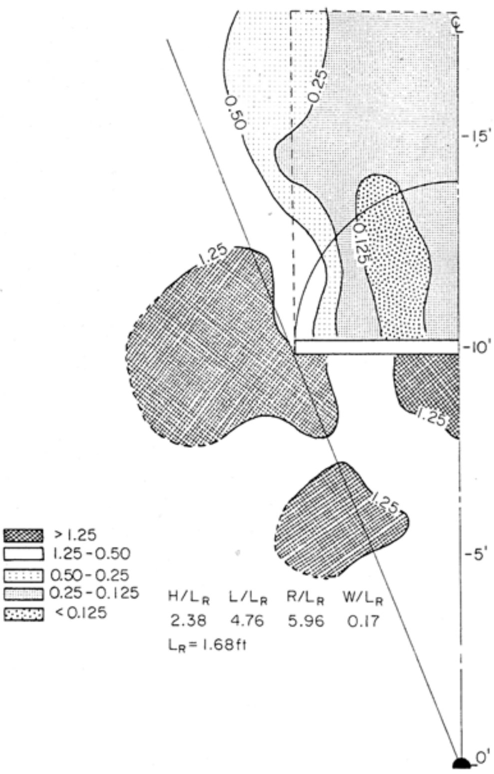


Figure 6. Passive isolation test: vibration amplitude reduction contours, (from Woods, 1968). *H* = trench depth, L_R = length of Rayleigh wave, *L* = trench length.

A limited test series confirmed the conclusions by Barkan (1962), that sheet pile barriers are not efficient in reducing vertical ground motions.

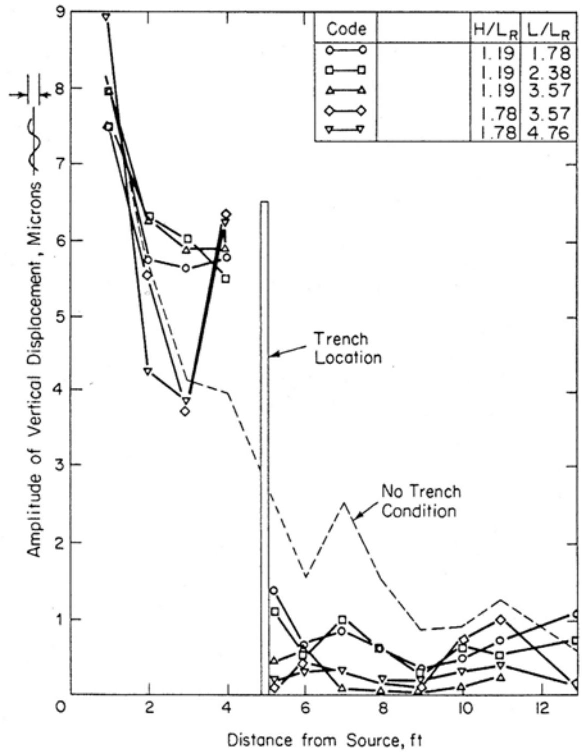


Figure 7. Amplitude of vertical vibration amplitude vs. distance from the source for five tests, (from Woods, 1968).

Dolling (1970) performed systematic field tests in large scale, using a 15 m long and 6 m deep trench, which was filled with bentonite slurry. He varied the wave length between 1.5 and 12 m by changing the vibration frequency. Most of the testes were performed at a trench distance of 3 m from the vibration source. The results by Dolling have been reviewed and analyzed by Haupt (1978a). He found that trenches are efficient isolation barriers when the trench depth is at least 0.8 L_R.

Haupt (1981) reported on laboratory model tests in uniform, artificially densified sand. He investigated open trenches, rows of bore holes and stiff infilled trenches. The wave length was on the order of 0.2 – 0.5 m. The results of the tests are shown in Figure 8 and compared with the results by Woods (1969). The isolation effect measured from model tests is less than that theoretically predicted by Dolling (1965). At a depth of one wave length, the vibration isolation effect, expressed as amplitude reduction factor, A_r is about 0.4 – 0.2 (reduction by 60 – 80 %).

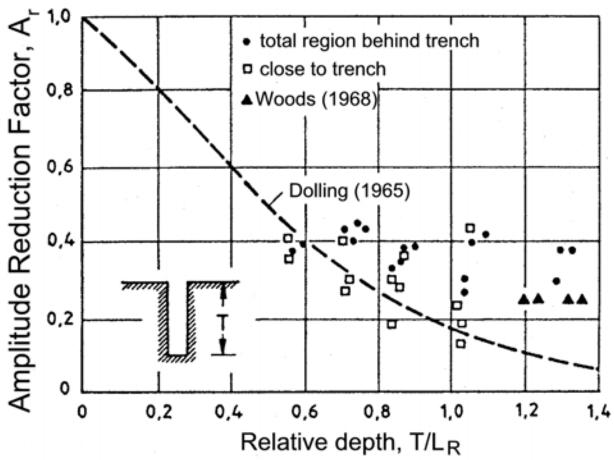


Figure 8. Results of vibration isolation model tests with open trench (Haupt, 1981). Results from tests by Woods (1968) and reduction curve suggested by Dolling (1965).

The following general conclusions can be drawn from studies of the isolation effect of open trenches: 1) trench depth is the most important factor and should correspond to approximately one wave length of the dominating frequency; 2) liquid-filled trenches are effective in reducing vertically propagating waves as water can not transmit shear forces. However, horizontal vibration amplitudes are transmitted across water-filled trenches as compression waves; 3) the trench width has little importance; and 4) in front of the trench, part of the wave energy is reflected and may increase vibration levels.

3.2 Design Considerations

In the literature, different methods have been used to assess the isolation effect of barriers. Often, subjectively chosen "representative values" from vibration records are compared in the time domain. In many cases, vibration measurements for comparable conditions before the implementation of isolation barriers do not even exist and assumptions are made. Such an approach is subjective and does not take into account the influence of vibration frequency (wave length), which is an important factor for vibration isolation measures. A more appropriate method is to evaluate the vibration record in the frequency domain, as shown in the following example. The amplitude reduction factor can be determined for different frequency intervals and plotted as a function of the normalize barrier depth, see Figure 9. It should be noted that due to the often irregular shape of frequency spectra, the calculated isolation effect can show significant fluctuations, especially at the boundary of the frequency spectrum. This is a numerical effect which does not have practical significance.

The relative vibration amplitude (isolation effect A_r) is expressed as the relative vibration amplitude and can be determined from

$$A_r = \frac{A_{fa}}{A_{fb}} \tag{3}$$

where A_{fa} and A_{fb} are the vibration amplitudes after and before the installation of the trench.

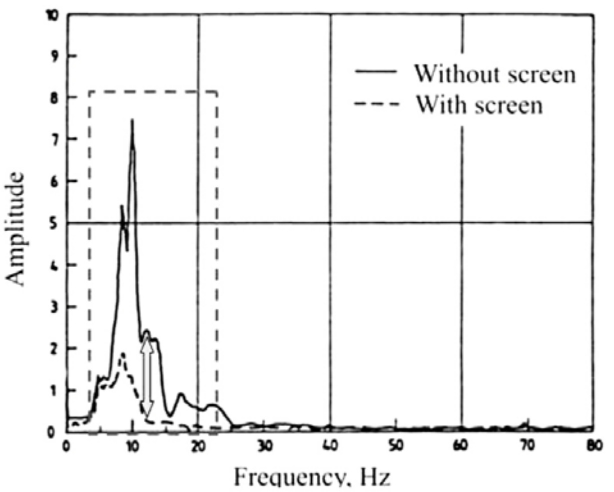


Figure 9. Determination of vibration isolation effect from the frequency spectrum of vibration signal. The dashed zone indicates the frequency range of interest.

The depth ratio t (relative trench depth) is determined from,

$$t = \frac{d}{\lambda} \tag{4}$$

where d is the trench depth and λ the wave length. When designing wave barriers, it is important to establish which frequencies are causing problems and need to be isolated. In many cases, resonance effects in structural elements or building floors cause vibration amplification and need to be controlled. Therefore, it is important to determine as a first step these critical vibration frequencies. The next step is to measure the frequency content of the vibrations, which are propagating in the ground and affect the foundation of the building. This can be accomplished by vibration measurements between the source and the affected structures.

The wave propagation velocity of the disturbance (often the Rayleigh wave or surface wave) should be determined, preferably by seismic field measurements (SASW, surface wave, down-hole or cross-hole tests). From the critical vibration frequency and the wave velocity, the design wave length can then be established. As discussed above, the isolation barrier shall have a depth equalt to one wave length. Even if the trench depth corresponds approximately to one wave length, the isolation effect in the centre line behind the trench is limited to about 80 percent. The results published by Haupt (1981a) are useful to estimate the isolation effect of open trenches, cf. Figure 8.

4. GAS CUSHION METHOD

4.1 Isolation Efficiency of Barrier Material

When analyzing the vibration isolation efficiency of different barrier types, the impedance of the barrier compared to that of the soil is important. The impedance Z is defined as

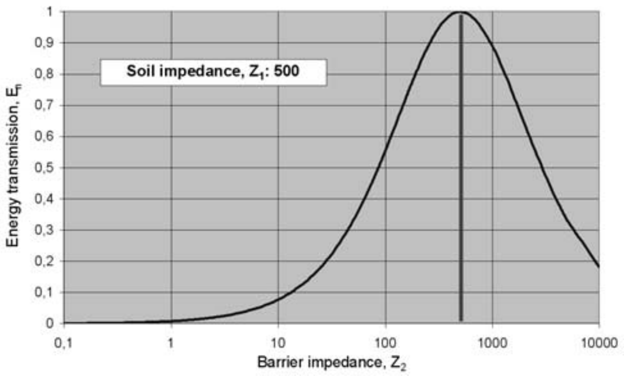
$$Z = c\rho \tag{5}$$

where c is the wave propagation velocity and ρ is material density. The reflection of propagating waves depends on the impedance difference between the soil and the barrier material. Stratified media may be considered as a succession of ideal layers with constant impedance. At each interface with change of impedance, waves will be reflected and/or refracted. The propagated vibration energy can be expressed as an energy transmission coefficient, E_n, which is defined as:

$$E_n = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2} \tag{6}$$

where Z_1 and Z_2 are the impedances of the soil and of the barrier, respectively. Equation (6) is shown in Figure 10 with an assumed soil impedance Z_1 = 500 (c = 250 m/s, ρ = 2 t/m^3). When $Z_1 = Z_2$ all energy is transmitted (E_n = 1). The isolation effect (reflection of energy) is high when the impedance of the barrier is low. On the other hand, it is difficult to achieve sufficiently high impedance values in order to make stiff barriers efficient.

The most efficient isolation screen is an open trench in the ground. However, open or liquid-filled trenches are difficult to use in practice, especially in built-up areas. Tests with light-weight material such as Styrofoam panels, placed in deep trenches, did not achieve a sufficient isolation effect. When this material is subjected to high lateral earth pressure, the initially flexible material is compressed and becomes stiff. Thus, the impedance increases and the barrier material loses its vibration isolation effect.



Fiugre 10. Energy transmission in soil with impedance Z_1, across a barrier with variable impedance Z_2, cf. Eq. 6.

4.2 Concept of Gas Cushions

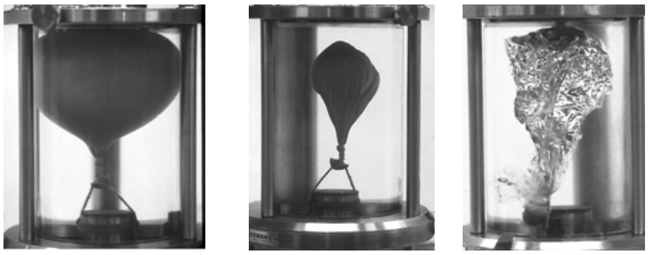
The objective of the gas cushion screen is to achieve an abrupt impedance change in the ground. Vertical panels of gas-filled, flexible cushions with very low impedance can be installed in a trench to great depth without losing its dynamic properties.

The gas pressure in the cushions is chosen to balance the surrounding earth pressure. The P-wave and S-wave velocities in the gas cushions are very low and the density is negligible, compared to that of the surrounding soil.

Gas cushions are installed in a trench and at a pressure which balances the surrounding total earth pressure. In this way it is possible to create permanent, gas-filled trenches extending to great depths even in very soft soils.

The gas-tightness of the gas cushions is an important aspect for permanent isolation screens. This is achieved by balancing the gas pressure in the cushions with the external earth pressure. This concept can be illustrated by the following experiment.

If a rubber balloon is inflated by gas, its volume increases with increasing pressure, Figure 11a. With time, gas will escape from the balloon due to diffusion. When the balloon is surrounded by water and the pressure is increased, its volume will decrease, cf. Figure 11b. The balloon will assume the shape of a water drop. Even when the external pressure is further increased, pressure equilibrium exists on either side of the membrane. Note that there are no tensile forces acting on the balloon wall. As the pressure difference is negligible (between the gas pressure inside the small balloon and the surrounding water), the gas diffusion rate will be very low. In order to further reduce gas diffusion, the membrane can be surrounded by a metal foil (aluminium) which is practically impermeable to gas, Figure 11c.



a) Inflated rubber balloon with excess pressure inside the balloon.

b) Pressure equilibrium between water and gas inside the balloon.

c) Impermeable aluminium foil reduces diffusion rate.

Figure 11. Illustration of gas cushion principle.

At high pressure, the membrane of the balloon and of the aluminium foil is completely unloaded and no tensile stresses act upon the membrane.

4.3 Cushion Material

Gas cushions are manufactured of a thin flexible film, composed of plastic aluminium laminate, similar to that used in the food packaging industry. The specially developed, five-layer plastic-aluminium laminate foil has high mechanical resistance and gas-tightness, Figure 12.

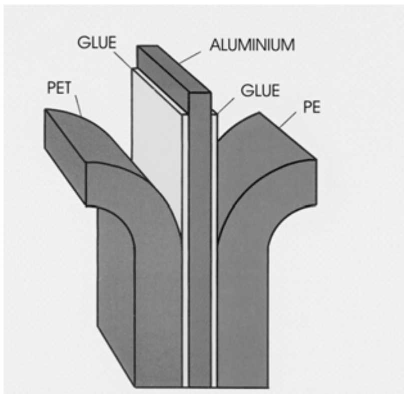


Figure 12. Laminate membrane used for gas cushions. Components: PTE (Polyester, Oriented, Primed + Polyethylene), Glue layer, Aluminium foil, Glue layer; PE (Polyethylene, Low Density Polyethylene).

Extensive tests have been performed to evaluate the strength and gas tightness of different polymer laminates, (Gedde and Bereket, 2004). Four different polymer laminates for the intended use in vibration isolation were studied with mechanical tests. The data were based on approximately 10-fold single experiments and analyzed by statistical methods. All the laminates showed excellent performance. The tensile strength of the unwelded laminate films ranged between 40-70 MPa and the strain at break ranged between 41-78 %. The weld strength expressed in force at first break ranged between 5.6 and 13.0 N. This corresponds to a strength of approximately 15 -20 MPa and approached the strength of the laminate film itself.

The high mechanical strength of the film is beneficial considering point loads, which potentially can cause puncturing of the aluminium layer. The gas cushions are composed of individual, laterally overlapping cells, Figure 13.

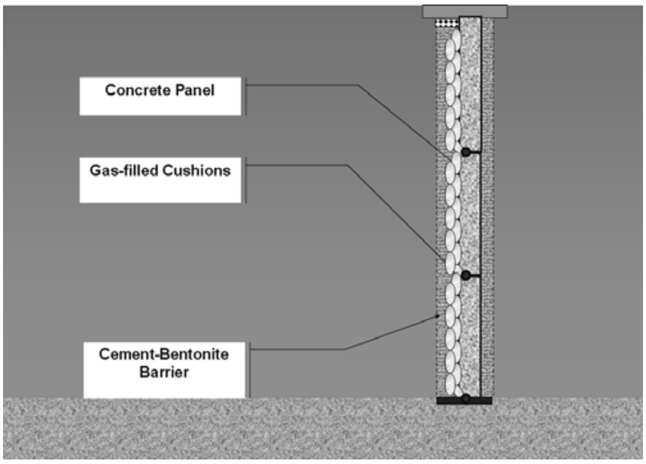


Figure 13. Example of gas cushion screen attached to prefabricated concrete panels.

The diameter of the gas cushion cells can be varied between 0.15 – 0.25 m and the length of the individual cushions ranges typically between 1 and 2 m, and can be adapted to the installation method suitable for the specific project. Due to the multiple screens and the fact that pressure equilibrium exists after installation in the ground, the individual cells are practically gas-tight, even considering long time periods.

In order to further increase the long-term stability of the gas cushion screen, it is installed in a trench which is filled with a self-hardening cement-bentonite slurry. This flexible, clay layer provides a protective layer around the gas cushion screen and makes it possible to install the gas cushion screen in different soil types, even contaminated material. All materials used for manufacturing the gas cushions, and during the installation of the gas cushion screen are environmentally safe.

4.4 Theoretical Analysis of Gas Cushion Screen

The University of Karlsruhe, Germany (Prange, 1985) and the University of Minnesota, USA (Vardoulakis et al., 1987) performed theoretical studies of the isolation effectiveness of the gas cushion screen. The results of the analysis by Vardoulakis are described below, comparing the efficiency of an open trench with that of a gas-filled screen. The problem of dynamic source-soil-trench interaction was solved numerically in the frequency domain under conditions of plane strain, using the Boundary Element Method (BEM). The gas cushions were idealized as a set of springs with stiffness equivalent to those of the cushions, which effectively offset the overburden earth pressure, Figure 14.

Figure 14. Gas-infilled cushion and spring model used in analysis.

The soil medium was assumed to consist of homogeneous, isotropic and linearly elastic or visco-elastic material. The formulation employs the infinite plane fundamental solutions, (Vardoulakis et al., 1987).

The computation for isolation of harmonic disturbances was performed simulating the field tests carried out in Uppsala, Sweden, which are described below; a) Soil properties: Density: ρ = 16.0 kN/m^3; Shear wave velocity: c_s = 70.0 m/s; Poisson's ratio: ν = 0.49; damping ratio: β = 3.0 %; b) Geometric lay-out (Fig. V2): Depth of trench: T = 8.0 m; width of trench: B = 0.03 m; location of foundation: L = 7.5 m; distance of interest beyond trench: D = 30.0 m; Distance left of foundation: L_I = 37.53 m; c) Footing properties: Width of foundation: W = 0.30 m; mass of foundation M = 0 (massless); d) Wave characteristics: Frequency of excitation: f = 30 Hz; e) Pressure of cushion: The pressure corresponds to the overburden pressure; i.e. to at rest conditions of geostatic stress with an earth pressure coefficient at rest, K_0 = 1.

Other data either derived or assumed are: Shear modulus: G = 7840.0 kPa; velocity of pressure wave: c_P = 500.0 m/s; velocity of Rayleigh wave: c_R = 66.8 m/s; vertical load amplitude P_0 = 1.0 kN/m ($P = P_0 e^{i\omega t}$); number of cushion: n_c = 4; Rayleigh wavelength: L_R = 2.23 m; circular frequency ($2\pi f$): ω = 188.5 rad/s. The schematic diagram of the trench foundation system is shown in Figure 15.

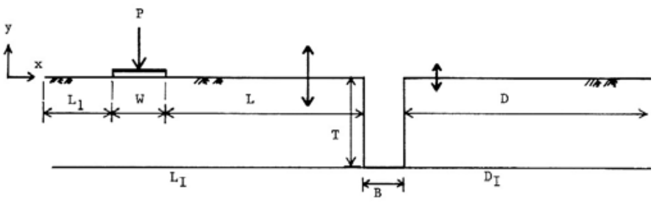


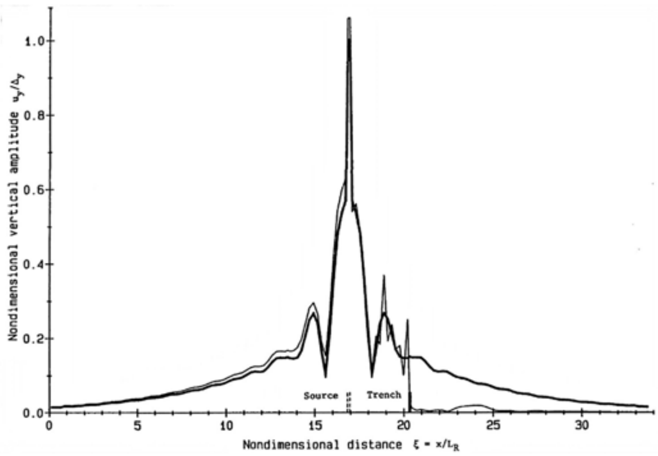
Figure 15. Schematic diagram with definition of parameters used in the analysis.

The surface was discretized with 71 elements along L_I, 5 elements along the width of the foundation W, 15 elements along L, 60 elements along the depth of the trench T, 1 element along the width of the trench B, and 55 elements along the distance D. Along the sub-region interfaces, L_I (= 45.33 m) was discretized into 204 elements and D_I (= 30.0 m) 135 elements. The dimensionless displacements for this configuration were computed without trench. It should be noted that all the coordinate distances are non-dimensional such that $\xi = x/L_R$ and $v = y/L_R$ where L_R is the Rayleigh wave length (L_R = 2.23 m) and displacements u_x and u_y are made dimensionless by dividing them with vertical displacement of the foundation Δ_y.

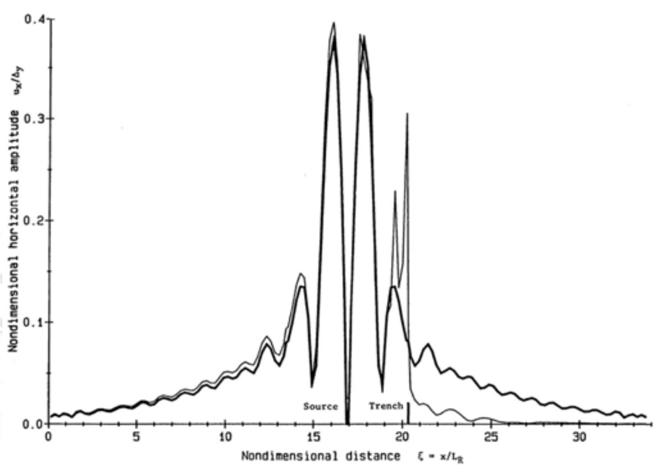
At first, the isolation effectiveness of an open trench was studied. The results were then compared with the isolation effect of gas cushion supported trench (Vardoulakis et al., 1987).

4.5 Isolation Effect of Open Trench

Reference calculations were performed without a trench to assess the isolation efficiency of the barrier. The isolation effectiveness of the open trench and the trench with gas cushions were compared. The displacement profile of the vibration with and without trench along the free surface is shown in Figure 16a for the vertical amplitude and in Fig. 16b for the horizontal amplitude, respectively. The bold lines in the Figure 16 and in subsequent figures represent the amplitudes without trench.



a) Vertical amplitude.



b) Horizontal amplitude.

Figure 165. Comparison of vibration amplitude on ground surface for cases without open trench and with open trench. Amplitudes without a trench are shown in bold lines.

Figure 17 shows the normalized vertical amplitude A_y (ξ) as function of dimensionless distance $\xi = x/L_R$. The normalized amplitude $A_i(\xi)$ is defined as the ratio of the amplitude in the i^{th} direction when the trench is present to the amplitude in the absence of the trench.

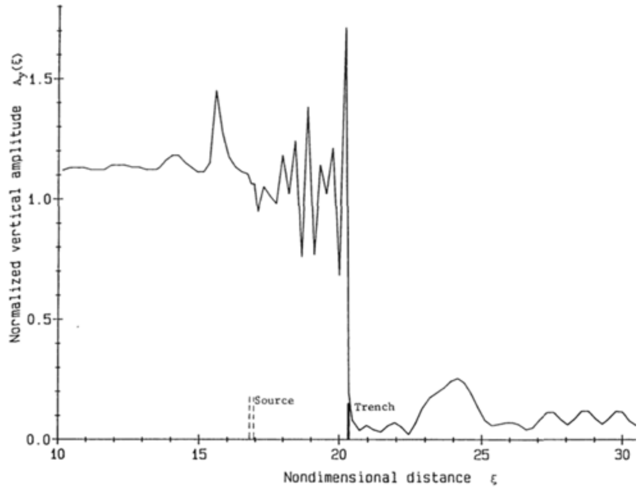


Figure 17. Normalized vertical amplitude on ground surface for open trench.

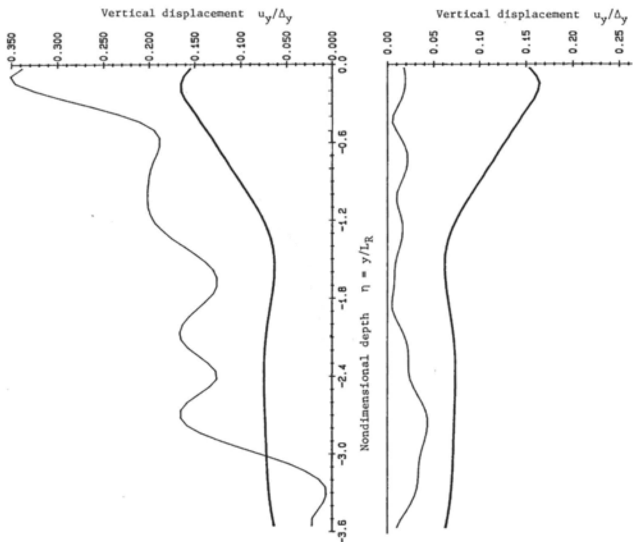
It should also be noticed that the origin of the coordinate axes is at a distance L_1 to the left of the foundation (Fig. 16a) and the location of the source and the trench are indicated in the figures. The screening of a harmonic wave beyond the trench is evident from Figure 17, and there is a considerable amplification between the trench and the foundation due to the reflection from the trench. The amplitude reduction factor A_{RY}, defined as the average normalized vertical surface amplitude behind the trench, is a measure of isolation effectiveness of the trench. For the open trench A_{RY} = 0.094. This means that the average amplitude behind the trench is reduced by about 90 % with trench compared to the amplitude without trench.

For the case of the normalized displacement in the horizontal direction, the amplitude reduction factor is A_{RX} = 0.122. Thus the trench with the chosen dimensions is an effective surface wave barrier for vertical and horizontal ground vibration screening.

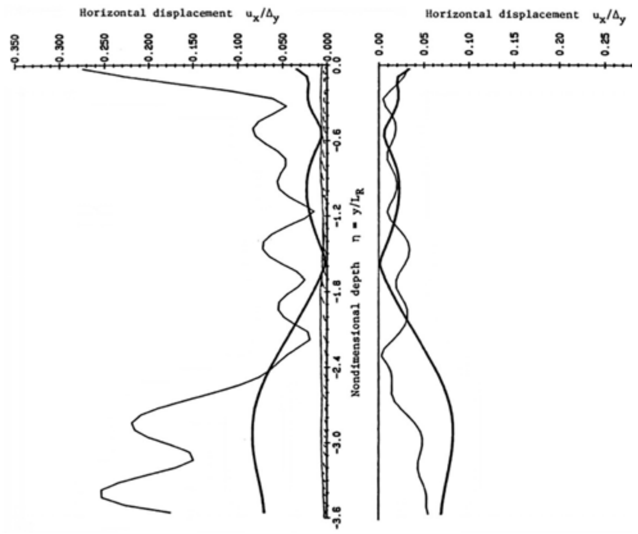
The vertical and horizontal displacements as a function of trench depth are presented in Figures 18. The calculated displacements are divided by the vertical displacement of the foundation, Δ_y without the presence of a trench. It is apparent that the amplitudes of the vertical and horizontal displacements due to the trench amplify on the left side of the trench (direction towards the source), if compared to the ones without a trench. The analysis shows that vibration amplitudes are reduced along the vertical perimeter of the trench.

4.6 Isolation Effect of Gas Cushion Trench

The screening effectiveness of gas-infilled cushion was studied next. The surface and the normalized displacement show very little change if compared to the open trench results (Vardoulakis et al., 1987).



a) Vertical displacements.



b) Horizontal displacements.

Figure 18. Vertical and horizontal displacements along the vertical perimeter of the trench. Amplitudes without a trench are shown in bold lines.

The calculated amplitude reduction factors for vertical and horizontal vibrations, using the gas cushions as described above, were A_{RY} = 0.094 and A_{RX} = 0.122, respectively. A comparison shows that the reduction factors for the gas cushion-supported trench are very close to those of an open trench.

The BEM analysis shows that negligible difference can be detected between the isolation efficiency of gas cushion screens and the open trench model. Vardoulakis et al (1987) thus recommend the open trench model could be used for the analysis of vibration isolation using a cushion-supported trench.

It should be noted that the analyzed case gives an upper limit of the isolation effect which can be achieved in the field. The trench is assumed to be infinitely long, thus ignoring the limited isolation efficiency at the boundaries. Also, the soil is assumed to be homogeneous, which usually is not the case in practical applications. Wave reflections can occur at rigid boundaries or when wave velocities increase with depth (wave refraction).

4.7 Application of Gas Cushion Method

Different installation methods have been developed for the gas cushion screen. The method has been applied on projects in Sweden, Belgium and Germany. Details of these projects have been reported by Massarsch and Ersson, (1985), Massarsch (1986), Massarsch & Corten, (1988), Legrand, (1989), de Cock & Legrand, (1990), Schiffer, (1991) and Massarsch (2005).

In the following, the results of the vibration isolation tests performed in soft clay, which were reported by Wikenholm & Ågren (1986), are compared with the BEM analyses described above.

The isolation efficiency of the gas cushion screen was tested in a deep deposit of soft clay in Uppsala, north of Stockholm. The depth of the soft clay deposit exceeded 35 m. The ground water was located 2 m below the ground surface. The surface wave velocity in the soft clay was 72 m/s. Gas cushions were placed inside a steel box, which was driven into the ground using a drop hammer, Massarsch (1986). The cushions were installed to a depth of 8 m. The screen length was approximately 15 m. Vibration tests were carried out with a 4-ton hammer which impacted a steel plate on the ground surface. The drop height was 0.35 m. The predominant vibration frequency was 9 Hz. The distance between the vibration source and the screen was 1.5 m. Figure 19 summarizes the results of extensive vibration measurements. The results were also evaluated independently by the University of Karlsruhe, Germany, (Prange, 1985) and the University of Minnesota (Vardoulakis et al. 1987). The measurements were also compared with theoretical predictions using a 2D BEM analysis, (Beskos et al, 1986). Figure 18 suggests that up to a distance of 5 wave lengths, the measurement results are in excellent agreement with the theoretical predictions.

Figure 19 suggests that the measured isolation effect up to a distance of 5 wave lengths is in good agreement with the theoretical predictions using the Boundary Element Method, (Beskos, 1986) and Vardoulakis (1987).

5. CONCLUSIONS

The factors which influence the propagation of ground vibrations have been discussed. An often neglected aspect is the effect of wave bending, which can occur in soil deposits where the wave velocity increases with depth. His effect will reduce the efficiency of vibration isolation trenches. It can be shown, that if the wave velocity increases gradually with depth (according to a cosine function), vibration focusing can occur at a distance from the vibration source.

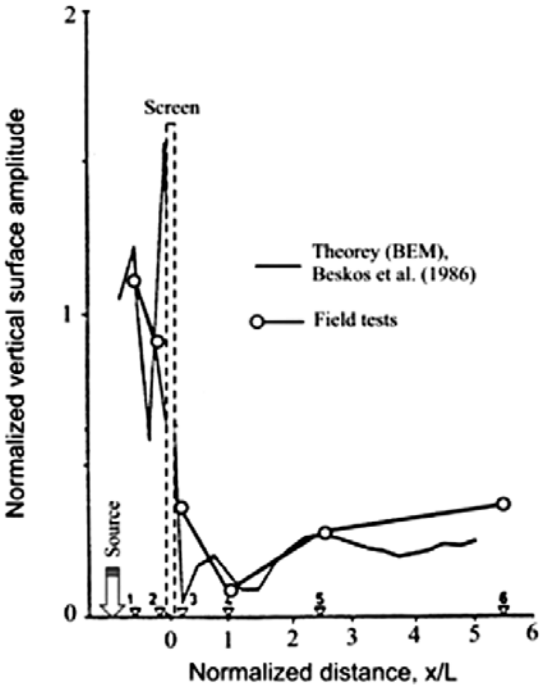


Fig. 19. Results from vibration isolation tests in Uppsala, Sweden. The test results are compared with theoretical predictions using a 2D BEM analysis, Massarsch (1986).

Theoretical analyses and model tests regarding the isolation efficiency of open trenches have been reviewed and reasonably good agreement is obtained from different types of studies. However, theoretical predictions using two-dimensional models overestimate the isolation effect.

It is proposed that the design of isolation screens is based on the predominant vibration frequency and the corresponding wave length of ground vibrations

The gas cushion concept is described. The method uses cushions composed of flexible, plastic-aluminium laminate. The cushions are inflated to a pressure equivalent to the surrounding earth pressure. The gas cushion screen is installed in a trench which is filled with a cement-bentonite slurry, which also acts as a permanent protective layer.

A theoretical study shows that the isolation effectiveness of the gas cushion screen is practically identical to that of an open trench. The theoretical analysis is compared with results from field tests in clay.

Based on a large number of field tests and vibration isolation projects, it can be concluded that a vibration isolation effect of 50 to 80 % can be expected, if the depth of the gas cushion screen corresponds to one wave length, cf. Figure 20.

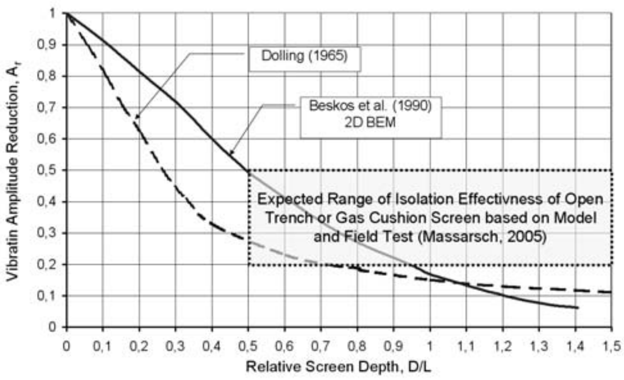


Figure 20. Expected vibration isolation effect of open trench or gas cushion screen, based on theoretical investigations and field measurements.

REFERENCES

Ahmad, S. and Al-Hussaini, T. M. (1991): Simplified design for vibration screening by open and in-filled trenches, *ASCE Journal of Geotechnical Engineering*, Vol 117, Nr 1, pp. 67-88.

Barkan, D. D. (1962): Dynamics of Bases and Foundations, *MacGraw-Hill Book Company, Inc*. pp. 374 - 406.

Beskos, D. E, Dasgupta, B. and Vardoulakis, I. G. (1986): Vibration isolation using open or filled trenches; Part 1: 2-D homogeneous soil. *Computational Mech*. 1990, No. 6, Springer, pp. 43-63.

Beskos, D. E., Dasgupta, B. and Vardoulakis, I. G. (1990): Vibration isolation using open or filled trenches; Part 2: 3-D homogeneous soil. *Computational Mech*. 1990, No. 6, Springer.

Beskos, D. E., Dasgupta, B. and Vardoulakis, I. G., (1987): Vibration Isolation Using Open or Filled Trenches. Part I: 2-D Homogeneous Soil, *Computational Mechanics*, Vol. 1, 1986, pp. 43-63.

de Cock F. and Legrand, C., (1990): Ground Vibration Isolation using Gas Cushions, Proceedings, *4th International Conference on Geotextiles and Membranes*, the Hague, pp. 807-812.

de Cock F. and Legrand, C. (1992): Influence of Underground Gas Cushions on the Wave Propagation of Ground Vibrations, Proceedings, *4th International Conference on the Application of Stress Wave Theory to Piles, the Hague*, pp. 77 - 84.

Dolling, H. J. (1965): Schwingungsisolierung von Bauwerken durch tiefe, auf geeignete Weise stabilisierte Schlitz (Vibration isolation of buildings by means of deep, suitably stabilized trenches). *VDI Bericht* Nr. 88.

Gedde, U and Bereket, N. (2003): Mechanical tests of polymer laminates used for vibration isolation. Research report, Dept. Fibre and Polymer Technology, *Royal Institute of Technology* (KTH), Stockholm, Sweden, 9p.

Haupt, W. A. (1978a): Surface-waves in non-homogeneous half-space, Proc. Dyn. Meth. in Soil and Rock Mech. DMSR 77, Vol. I, A.A. *Balkema*, Rotterdam, pp. 335-367.

Haupt, W. A. (1978b): Verhalten von Oberflächenwellen im inhomogenen Halbraum mit besonderer Berücksichtigung der Wellenabschirmung (Behaviour of surface waves in inhomogeneous halfspace with special consideration of wave isolation), Dr.-Ing. Thesis, Univ. of Karlsruhe, No. 74, pp. 84 -94.

Haupt, W. A. (1981): Model tests on screening of surface waves. Proceedings, *Xth Intern. Conference on Soil Mechanics and Foundation Engineering*, 1981, Stockholm, Vol. 3, pp.215-222.

Haupt, W. A. (1995): Wave propagation in the ground and isolation measures. Proceedings, *3rd Int. Conference on*

Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, State of the art paper. Vol. 3, 985 - 1016.

Legrand, C. (1989): Etudes experimentales condernant les sols et foundations (Experimental studies regarding soils and foundations). Volume 2 – 5. *Convention IRSIA*, No. 5070.

Massarsch K. R. and Corten, F. C. (1988): Bodenvibrationsabschirmung mittels Gasmatten (Ground Vibration Isolation using Gas Cushions). *Deutsche Baugrund Tagung, Hamburg,* Proceedings pp. 161 - 192.

Massarsch, K. R. (1991): Ground Vibration Isolation using Gas Cushions, Proceedings, *Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, St. Louis, Missouri, March 11 - 15, 1991, Vol. 2, pp 1461 - 1470.

Massarsch, K. R. (1993): Man-made Vibrations and Solutions, State-of-the-Art Lecture, Proceedings *Third International Conference on Case Histories in Geotechnical Engineering*, St. Louis, Missouri, June 1 - 6, 1993, Vol. II, pp. 1393 - 1405.

Massarsch, K. R. (2005): Vibration Isolation using Gas-filled Cushions. Soil Dynamics Symposium to Honor Prof. Richard D. Woods (Invited Paper.). *Geo-Frontiers 2005*, Austin, Texas, January 24 – 26, 2005. Submitted for publication. 22 p.

Massarsch, K. R. and Ersson, L-E. (1985): Vibrationsisolering i jord (Vibration Isolation in Soils). *Royal Institute of Technology (KTH)*, Stockholm, Job Report 1985:20, 32 p.

Massarsch, K. R., (1986): Isolation of Traffic Vibrations in Soil, ABTUS Confer., Brussels, *Journl. Tunnels et Ouvrages Souterrains*, No. 74, pp. 67- 72.

Prange, B. (1985): Screening mattress System Massarsch and screening efficiency, *Internal report Franki International*, Liège, Belgium, 35 p.

Richart F. E. (1970): Vibrations of soils and foundations. Prentice-Hall, Englewood Cliffs, NJ. Pp. 244 – 262.

Schiffer, W. (1991): Schlitzwandbauweise mit Gasmatten-Elementen zur Abschirmung von Erschütterungen (Slurry wall method for installation of gas cushion elements), *STUVA-Symposium at Düsseldorf 1991*, Germany.

Vardoulakis, I. G., Dasgupta, B. and Leung, K. L.. (1987): Vibration Isolation of Structures by gas-infilled chushions in 2-D Homogeneous Soil. Task I: Harmonic disturbances. *Research Report to Franki International*, Technology Division. 2nd Revision, April 1987. 57 p.

Wikenholm, G. and Ågren, C. (1986). The air cushion screen, a new method for damping of ground vibrations. Masters Thesis, Report Nr. 2:86, *Royal Institute of Technology* (KTH). Stockholm, Sweden, 134 p.

Woods, R. D., (1968): Screening of Surface Waves in Soils, Journal, *Soil Mechanics and Foundation Division, ASCE* Vol. 94, SM4, July, pp. 951 - 979.