Vibration Isolation using Gas-filled Cushions

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Abstract

Parameters which affect the propagation of waves in the ground are discussed. A simple method is proposed to assess the zone of vibration focusing due to wave bending. Theoretical investigations and model tests suggest that an open trench is the most efficient vibration isolation barrier. Parameters which influence the effectiveness of open trenches are discussed and design recommendations are given. The gas cushion method, which was developed thirty years ago, is presented and practical applications in full-scale projects are described. The effectiveness of the gas cushion method in different soil conditions is evaluated and design recommendations are given. Recent improvements of the gas cushion method are described.

Introduction

In populated and industrialized regions, the importance of ground vibration problems has increased. Various factors have contributed to this development, such as heavier traffic and increased speed as well as expansion of the transportation infrastructure in densely populated areas. Especially in Europe and Japan, railway lines are being expanded, linking city centers by high-speed railway lines. Heavy manufacturing equipment is used in industrial processes. Due to the high cost of land, areas with poor ground conditions are developed, requiring construction activities often in the proximity of sensitive, historical buildings. Vibration-sensitive electronic equipment and precision manufacturing processes are used more frequently. Modern buildings have become susceptible to vibrations as they are often constructed of light-weight material, to optimize the size of construction elements, such as building floors and walls. At the same time, the awareness with respect to noise and building vibrations has increased. In many European countries, stringent environmental regulations have been introduced, which make the producer of disturbing vibrations responsible for remedial measures. Municipal and governmental organizations are enforcing environmental regulations more rigorously.

Vibration problems are often neglected in the case of major projects. One reason is that reliable analysis and prediction methods are not available to, or too sophisticated for, practicing engineers. While extensive research efforts have been made in the area of earthquake engineering, many aspects of traffic- and construction-induced vibrations are still not fully understood. In particular, measures to reduce vibrations are needed in order to meet the environmental requirements of modern society. In many cased, vibration problems are recognized so late that it is difficult to adapt the initial design. As practical measures to reduce ground vibrations are not generally available, vibration problems are frequently solved in court, rather than by engineering measures.

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Ground Vibration Propagation

Wave Propagation

Ground vibrations and their propagation from the source through geological formations, and their interaction with structures in or on the ground, is a complex problem. The fundamentals of wave propagation in soils have been described extensively in the literature and reference is made to relevant publications, (Richart et al. 1970, Haupt, 1995). Soil stratification, the ground water, and the dynamic properties of soils 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 consists of vertical and horizontal vibration components, Figure 1. The amplitude decays quickly with depth and the depth of influence is about one wave length, L_R.

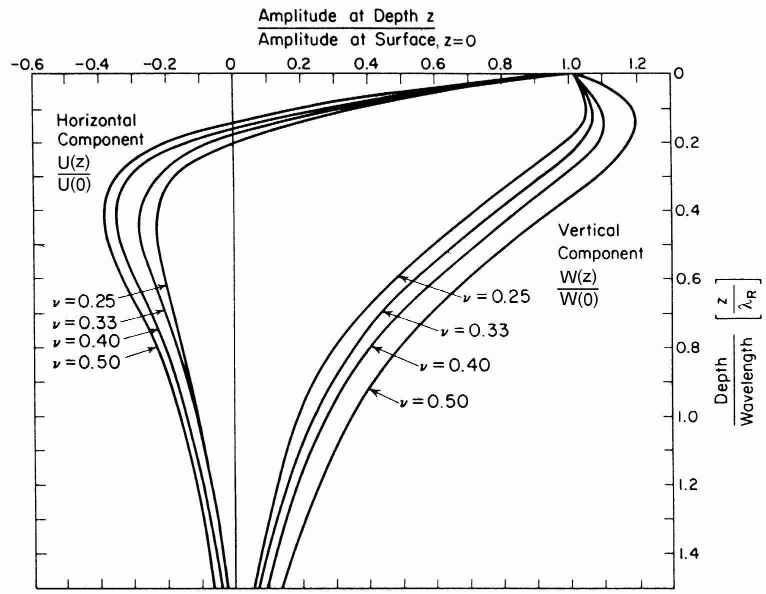

Figure 1. Variation of normalized horizontal and vertical vibration amplitude with depth, normalized by wave length (Richart et al., 1970).

At the surface, the horizontal component is about 0.6 – 0.8 of the vertical component. 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.

Vibration Isolation using Trenches

Vibrations in buildings 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 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.

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 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, the 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 2 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.

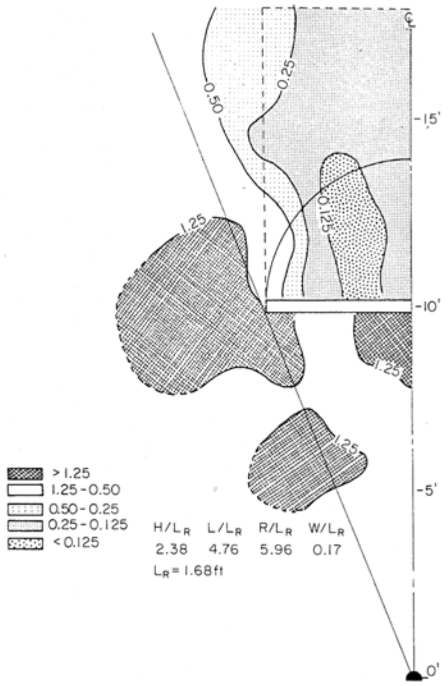

Figure 2. Passive isolation test: vibration amplitude reduction contours, (from Woods, 1968). H = trench depth, LR = length of Rayleigh wave, L = trench length. i = trench width.

These results are shown in Figure 3. 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. A limited test series confirmed the conclusions by Barkan (1962), that sheet pile barriers are not efficient in reducing vertical ground motions.

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 with a trench distance of 3 m from the vibration source. The results by Dolling have been reviewed and analyzed by Haupt (1978a). It was found that trenches are efficient isolation barriers when the trench depth is at least 0.8 $L_{R.}$

Haupt (1981) performed 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 3 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 %).

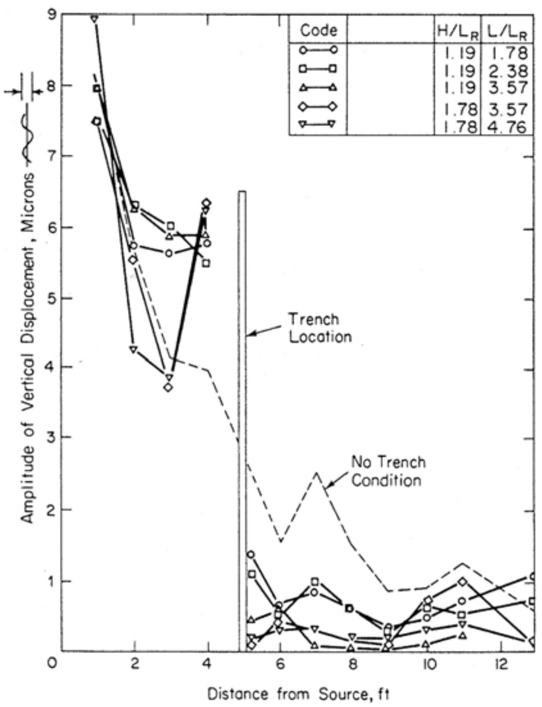

Figure 3. Amplitude of vertical vibration amplitude vs. distance from the source for five tests, (from Woods, 1968).

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.

Design Aspects

In the literature, different methods have been used to assess the isolation effect of barriers. Often, subjectively chosen “typical 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, see Figure 4. The amplitude reduction factor can be determined for different frequency intervals and plotted as a function of the normalize barrier depth, see Figure 8. 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.

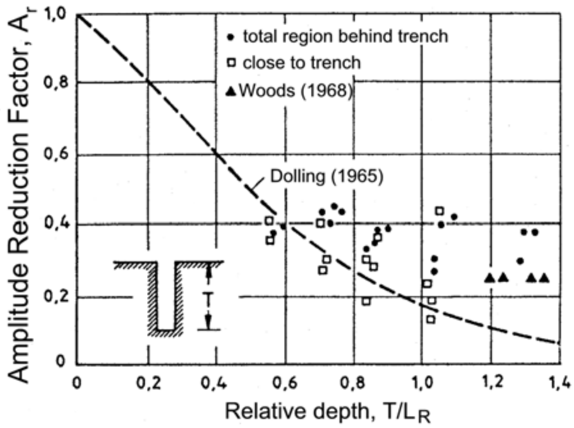

Figure 4. Results of vibration isolation model tests with open trench (Haupt, 1981). Results from tests by Woods (1968) and reduction curve suggested by Dolling (1965).

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

$$A_r = \frac{A_{fa}}{A_{fb}} \tag{2}$$

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

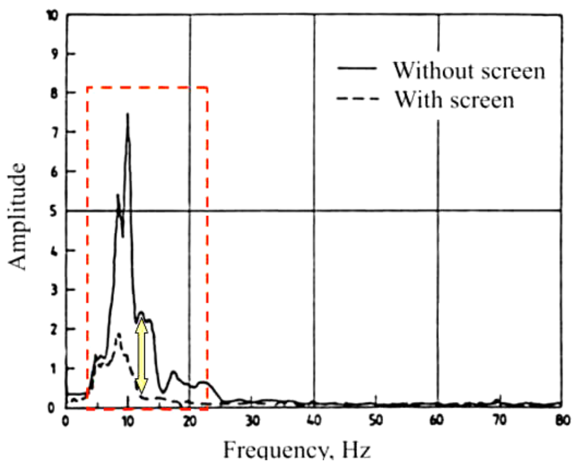

Figure 5. Determination of vibration isolation effect from the frequency spectrum of vibration signal. The dashed zone indicates the frequency range of interest.

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

$$t = \frac{d}{\lambda} \tag{3}$$

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 determined vibration frequency and the wave velocity, the critical wave length can then be established. As discussed above, the isolation barrier shall have a depth corresponding 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 (1981) are useful to estimate the isolation effect of open trenches.

Isolation Efficiency of Barrier Material

When analyzing 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

$$Z = c\rho \tag{4}$$

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:

$$E_n = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2} \tag{5}$$

where Z_1 and Z_2 are the impedances of the soil and of the barrier, respectively. Equation (6) is shown in Figure 6 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.

Gas Cushion Method

Light-Weight Material

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.

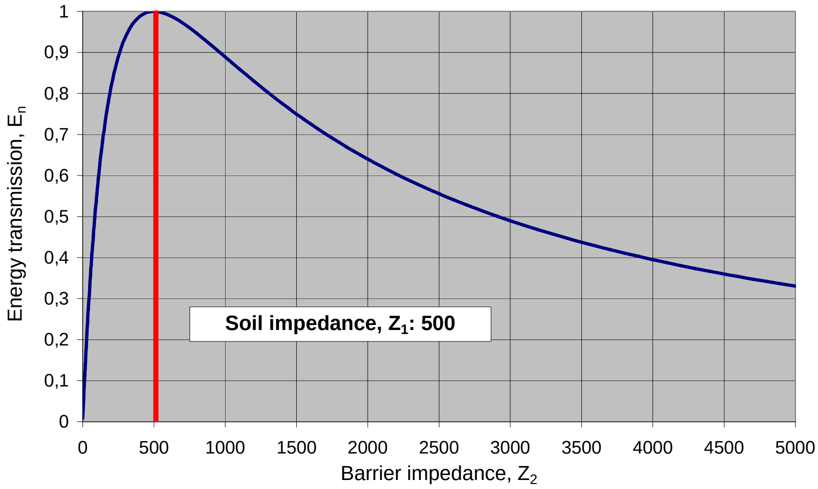

Figure 6. Energy transmission in soil with impedance Z1, across a barrier with variable impedance Z2, cf. Eq. 5.

Gas Cushion Concept

The objective of the gas cushion barrier 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. Thus, gas cushions fulfill the requirements of an efficient barrier according to Figure 5. 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 to great depths even in very soft soils. The gas-tightness of the gas cushions is an important aspect for permanent isolation barriers. Gas cushions are manufactured of a thin flexible film, composed of plastic aluminum laminate, similar to that used in the food packaging industry. An important design aspect is the gas pressure in the cushions, which can be illustrated by the following experiment. If a rubber balloon is inflated by gas, its volume increases with increasing pressure, Figure 7a. 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 7b. 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 7c. At high pressure, the membrane of the balloon and of the aluminum foil are completely unloaded and no tensile stresses act upon the membrane.

Tests with Rubber Panels

The initial development of the gas cushion method took place in early 1980 when tests were performed with water- and gas-inflated rubber cushions in clay. Rubber panels mounted in a steel frame were installed in soft clay to 4.3 m depth (Massarsch and Ersson, 1985). After installation, the cushions were inflated with gas and water, respectively. Vibration measurements were carried out, using a drop hammer (63 kg), which impacted on a steel plate. The vibration isolation effect of the cushions was determined by sensors aligned along the center line in front and behind the screen. Extensive field measurements demonstrated the isolation efficiency of the gas-filled cushions. (Massarsch, 1986, Massarsch and Corten, 1998). An example of the frequency spectrum before and after installation of a gas-filled rubber panel is shown in Figure 5.

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 7. Illustration of gas cushion principle.

First Generation of Gas Cushions

Vibration Isolation Project Gnarp, Sweden

Based on these encouraging results, it was decided to manufacture vibration isolation panels of plastic-aluminum laminate. The cushions consisted of flexible tubes with a diameter of 20 mm and a length of 0.6 m. The individual cells were welded to create laterally overlapping cells. These welded cushions were inflated in the factory and surrounded by a protective layer of tough polyethylene.

The first full-scale application of the gas cushion method was to protect a residential building from railway-induced vibrations. Vibration problems were cause by floor resonance in the range of 15 – 20 Hz. The soil consisted of loose silty sand down to a depth of about 7m. The ground water level was located about 2 m below the ground surface. The shear wave velocity of the loose sand was about 120 m/s. A 6.5 m deep and 50-m, long screen was installed between a railway track and a residential building. The depth of the screen corresponded to one wave length. A timber frame was used to push the screen into a bentonite-filled trench, Figure 8.

After installation of the gas cushion screen, the building floor vibrations were reduced by more than 70%, which was considered very successful, as all other alternative solutions would have been very costly or not practical. Figure 9 shows vibration records on the building floor before and after installation of the gas cushion screen.

Figure 8. Installation of gas cushion screen in Bentonite slurry, using timber frame, Gnarp, Sweden 1984. First generation of gas cushion system.

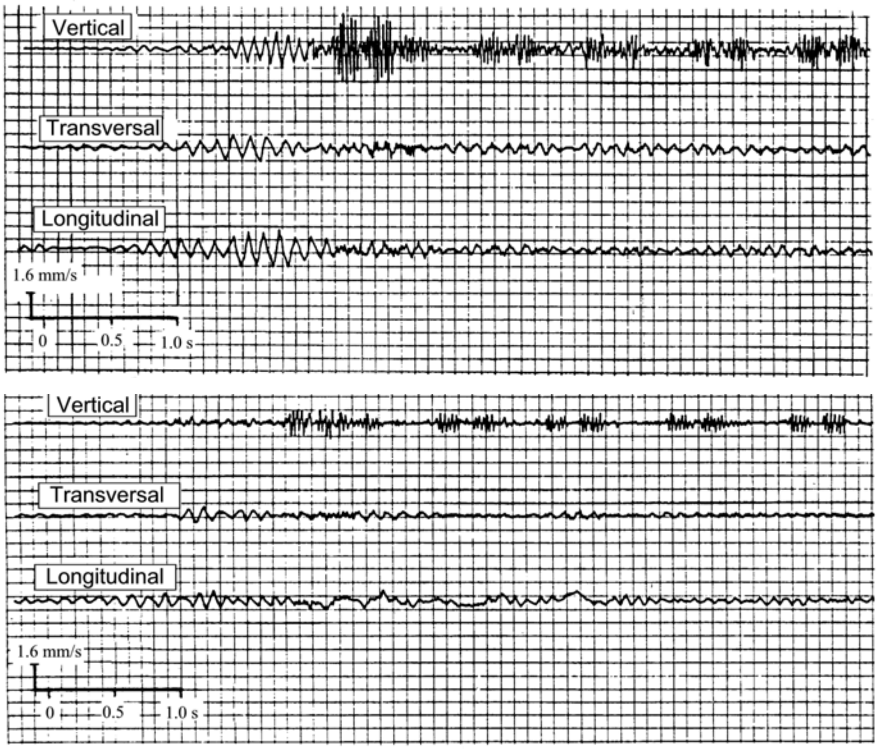

Figure 9. Vibration velocity record before and after installation of gas cushion screen on first building floor.

Mormon Temple Project, Stockholm, Sweden

The second vibration isolation project was the vibration protection of the Mormon temple in Stockholm, which was carried out in 1985. This vibration-sensitive building was constructed in the vicinity of a railway line and experienced strong structural vibrations. As it was impossible to modify the dynamic response of the building (resonance between 30 – 50 Hz), it was decided to implement a gas cushion screen. The foundation soil consisted of medium dense sand over a dense moraine. The shear wave velocity of the medium dense sand to a depth of 8 m was about 200 m/s. The disturbing vibration frequencies were in the range of 25 – 60 Hz, (Massarsch and Corten, 1988). It was necessary to eliminate the resonance effects in building elements around 40 Hz. The depth of the screen was designed, based on extensive vibration measurements. A 95 m long gas cushion screen was installed to a depth of 6.5 m in the stiff moraine about 6 m from the closest railway track. The cushions were mounted inside steel tubes, which were installed by drilling in the close vicinity of the railway track, Figure 10.

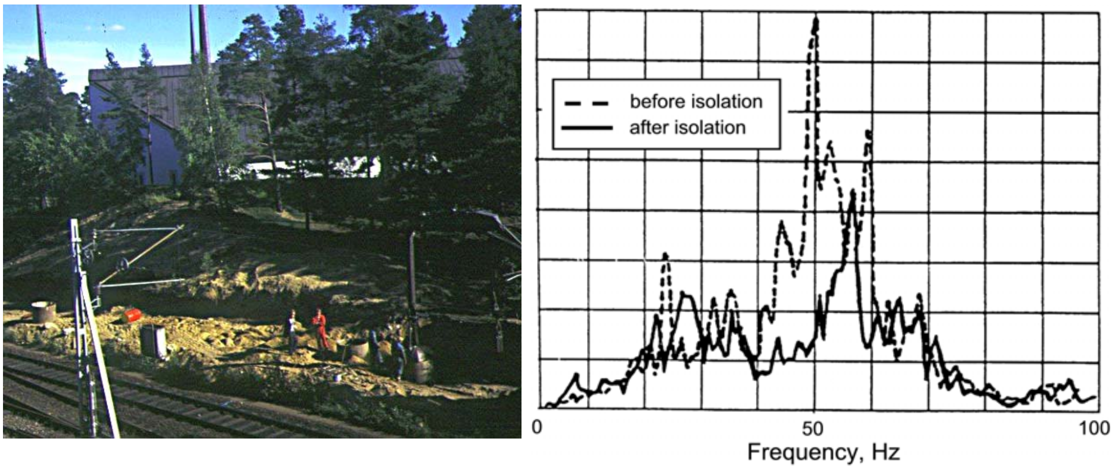

Figure 10. Frequency spectrum of vibration record, Mormon Temple, Stockholm, Sweden.

In order to increase the mechanical resistance, the gas cushions were provided with an additional plastic sheet. Before extraction of the steel tubes, fine-grained soil was carefully placed adjacent to the gas cushion panels. Vibration measurements showed a significant reduction of building vibrations, by as much as 65%. The frequency spectrum of two vibration records (vertical vibration velocity measured at the building foundation) is shown in Figure 10. Recent vibration measurements carried out in 2003 suggest that the isolation screen is still working.

Vibration Tests, Uppsala

In 1985 at the test site in Uppsala, Sweden, a modified installation method for the gas cushions was tested in a deep deposit of soft clay. 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 16 summarizes the results of extensive vibration measurements. The results were also evaluated independently by the University of Karlsruhe, Germany, (Prange, 1985) and compared with theoretical predictions using a 2D BEM analysis, (Beskos et al, 1986). Figure 11 suggests that up to a distance of 5 wave lengths, the measurement results are in excellent agreement with the theoretical predictions.

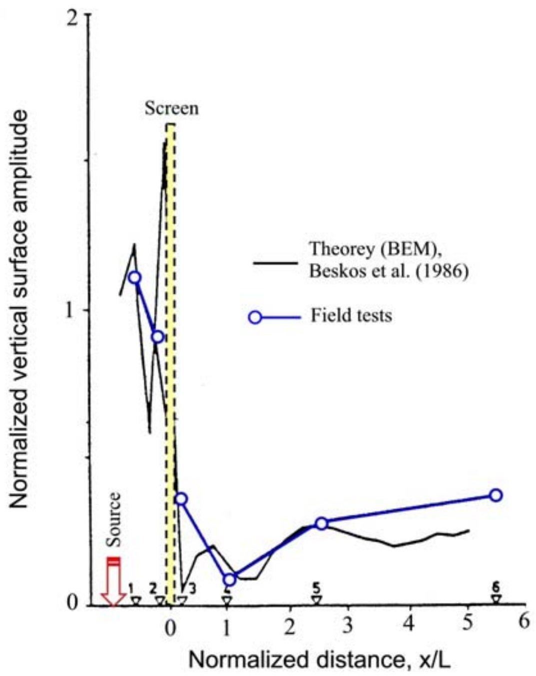

Figure 11. Results from vibration isolation tests in Uppsala, Sweden. The test results are compared with theoretical predictions using a 2D BEM analysis, Massarsch (1986).

Vibration Installation Project, Säffle

Following the successful test in Uppsala, a vibration isolation project was implemented in a deep deposit of very soft clay in 1985. The project concerned the protection of more than 20 residential timber houses from railway vibrations. Passing trains gave rise to strong horizontal vibrations in the timber structure of the buildings. The depth of the very soft clay was in excess of 40 m. The predominant vibration frequency was around 4 Hz. The shear wave velocity in the soft clay was about 60 m/s at the ground surface. As there was no alternative to solve the problem, a 12-m deep and 200-m long gas cushion screen was installed, using a steel box system similar to the system used in Uppsala. The distance of the isolation screen was about 10 m from the closest railway track. The distance from the screen to the affected buildings was in excess of 35 m. During the installation of the screen, great difficulties were encountered. When the steel box was retracted from 12-m depth, the hole collapsed around the box and soft clay was forced into the bottom of the now open steel box. Thus it was difficult to achieve a continuous gas cushion screen. In several instances, the gas cushions were also damaged when the steel box was extracted and pulled to the ground surface. Vibration measurements after installation of the screen showed that the gas cushion screen was not capable of reducing the horizontal building vibrations. The main reasons for the insufficient isolation effect are believed to be in the order of significance: 1) problems encountered when installing the gas cushions with the steel box system to depths larger than 8 m (depth below which the hole collapsed when the steel box was extracted; 2) the excitation mechanism due to the long and heavy trains, which caused the entire clay deposit to oscillate horizontally; 3) the location of the isolation screen, which for practical reasons had to be placed between the source and the affected buildings; 4) the low stiffness of the timber structures, which experienced resonance at about 4 Hz; and 5) insufficient width of the gas cushion cells (2 cm).

Second generation of Gas Cushion Screen

Gas Cushions with Geotextile Panels

Based on the experience from gas cushion projects in Sweden, the manufacturing process of the gas cushions was modified. The objective was to develop a system which can be used in all soil types and to great depth. The same plastic laminate was used to produce the gas cushions. However, the size of the cushion cells was increased from 2 cm to 15 cm diameter. Mattress of woven geotextile fabric were manufactured, consisting of overlapping with tubular pockets. The gas cushion tubes were placed into the pockets and thereafter inflated, Figure 12. Each tube was provided with an inflation valve, in order to assure that the cell pressure could be varied depending on the installation depth of the respective panels. The cushions were assembled into panels and installed according to the slurry trench method. The slurry trench method was adopted for the installation of the gas cushions. The panels were either anchored to the bottom of the trench or provided with a counter weight to resist buoyancy. After installation, the bentonite slurry was replaced by self-hardening cement-bentonite. This about 0.25 m thick clay layer, which surrounded the gas cushions on either side, provides a protective layer and assures chemical protection and long-term stability.

Vibration Isolation Project, Düsseldorf

In 1991, north of Düsseldorf, Germany the gas cushion screen was used to protect two-story residential buildings from ground vibrations, which were caused by a high-speed railway line. Different isolation alternatives were considered and the gas cushion isolation method was chosen by the German railway authorities. Detailed vibration measurements were performed to determine the wave propagation velocity and the predominant vibration frequencies (for various train types, passing on different tracks and at different speeds). Vibration measurements were also carried out in different parts of the building (basement, ground floor and first floor) in order to determine the frequency interval which had to be isolated. The design criteria were based on the results published by Haupt (1981), cf. Figure 8. The propagation velocity of the surface wave in the medium stiff sandy soil was approximately 120 - 150 m/s. The ground water level was located approximately 3 m below the ground surface. The dominant vibration frequencies were in the range of 15 - 30 Hz and corresponded to the resonance frequencies of the building floors. The 12-m deep isolation screen corresponded to approximately one wave length. The lateral extent of the isolation screen was established, based on the above mentioned vibration investigations. The total length of the vibration isolation screen was about 75 m, with lateral wings to protect against vibrations propagating parallel to the railway track. The practical application of the gas cushion method has been reported by Schiffer (1991). Figure 13 shows the installation of the gas cushion screen. After excavation of the trench according to the slurry-trench method (using bentonite slurry as a stabilizing fluid), the gas cushions were anchored at the bottom of the trench using a counter weight of concrete.

Figure 12. Installation of the gas cushion screen adjacent to a railway track in Düsseldorf, Germany, 1990. Left: installation of gas cushion screen, Right: placement of surface isolation layer.

As mentioned above, the gas pressure in the individual cells was chosen lower than the ambient ground pressure, thus assuring pressure equilibrium. Thereafter, the bentonite slurry was replaced by a self-hardening cement/bentonite grout, similar to that used for ground water cut-off barriers. In this way, the cement-bentonite creates a flexible, watertight layer on either side of the gas cushions, providing an additional gas-tight layer on either side. After installation of the screen, the surface of the trench above the gas cushion screen was covered by a layer of styrofoam, Figure 12. This layer provides an isolation barrier close to the ground surface and temperature isolation of the cushions.

Figure 13 summarizes the results of vibration measurements, expressed in terms of the amplitude reduction factor, A_r. The measured isolation effect after installation of the gas cushion screen corresponded to the amplitude reduction values suggested by the field tests shown in Figure 4. However, it was found that due to the extended vibration source (long trains) and the limited length of the screen, vibrations could affect the building in the transversal direction. During the past 11 years, the isolation screen has performed as expected.

Effectiveness of Gas Cushion Screen

Extensive measurements from different applications of the gas cushion method (first and second generation) in sandy, silty and clay soils have been reported in the literature, (de Cock and Legrand, 1990 and 1992, Legrand 1989, Massarsch, 1991). The vibration isolation effect of the gas cushion screen has been investigated in different soil types and for various applications. It was found that the measured isolation effect is in good agreement with the results reported by Haupt (1981) and Woods (1968) for open trenches. Figure 14 shows the isolation effect of the gas cushion screen from full-scale projects in different soil conditions.

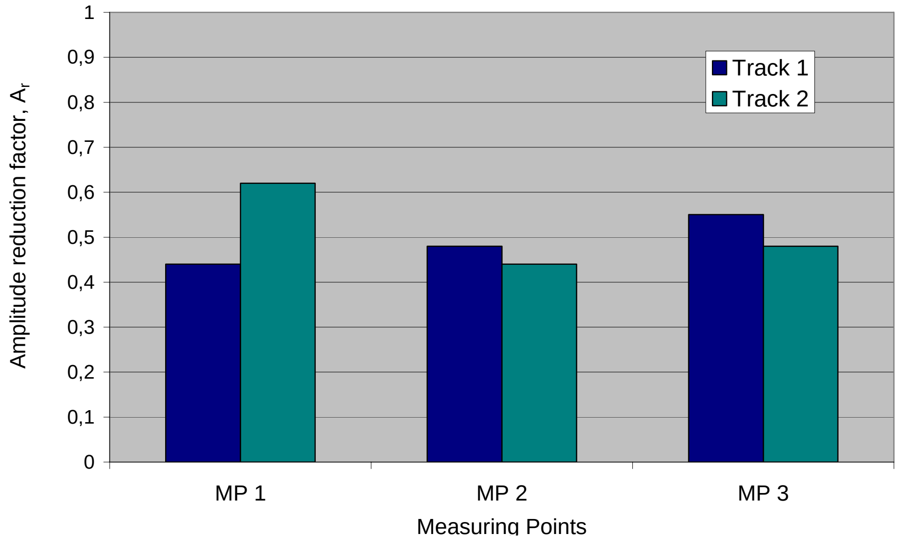

Figure 13. Average values of vibration reduction factor, Düsseldorf, Germany.

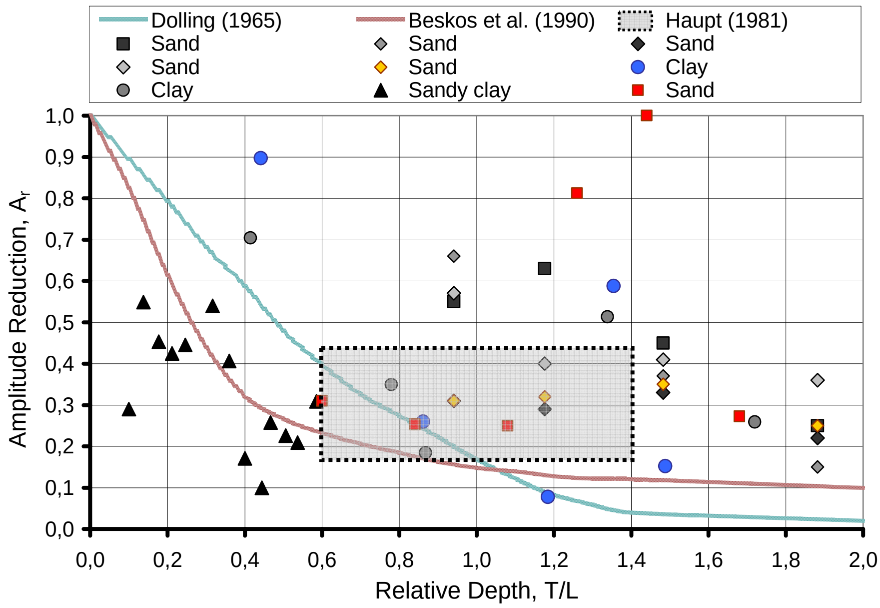

Figure 14. Isolation effect of gas-filled cushions in different soils and vibration sources. The variation of data points is cause by the fluctuation of the frequency spectra, from which the amplitude reduction factors were determined.

The amplitude reduction (ratio of vibration velocity after and before isolation) is shown as a function of the relative depth. The depth was normalized by the wave length. Also the theoretical relationships proposed by Beskos (1990) and Dölling (1970) are shown for comparison. All the data presented in Figure 14 are from actual full-scale applications of the gas cushion system in a variety of soils. Therefore, they take thus into account practical limitations of isolation measures, such as wave bending, limited length of trench compared to length of vibration source, etc. The geometrical configuration of the isolation screen is of great practical importance, especially in the case of railway traffic, where the propagating wave field of a passing train can be complex. The measured amplitude reduction (isolation factor) agrees well with the results reported by Haupt (1981) and Woods (1968), but is less than theoretically predicted. If the screen extends at least to a depth corresponding to one wave length, an isolation effect between 50 and 80% ($A_r \sim 0.5 – 0.8$) can be expected. The fluctuation of the isolation factor, when determined in the frequency domain, is due to numerical effects. This effect is particularly pronounced at short wave lengths, where the vibration frequency and the vibration amplitude are high, and the frequency spectrum shows fluctuations. In order to increase the vibration isolation effect for higher frequencies (short relative depths), it is advisable to create a slot at the ground surface, which prevents transfer of vibration energy in the stiff soil at the ground surface above the screen. This aspect was not recognized in previous applications, but is probably an efficient way to increase the isolation effect at high relative depth factor *T/L*. Field experience and laboratory tests have shown that the gas cushion panels, when properly designed and installed, can have a live length in excess of 20 years.

Third Generation of Gas Cushion Screen

The most recent development of the gas cushion screen is based on experience from past projects. The main objective was to simplify the manufacturing and preparation process and to simplify installation. The most important development was a new cushion inflation method, which avoids the use of valves.

Cushion Material

The gas cushions are now manufactured of a specially developed, five-layer plastic-aluminium laminate foil, which has high mechanical resistance and gas-tightness, Figure 15. 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 causing puncturing of the aluminum layer providing the barrier capacity. The size of the gas cushion cells can be varied between 0.15 – 0.25 m and adapted to the specific project requirements. Due to the multiple barriers and the fact that pressure equilibrium exists after installation in the ground, the individual cells are practically gas-tight, even considering long time periods.

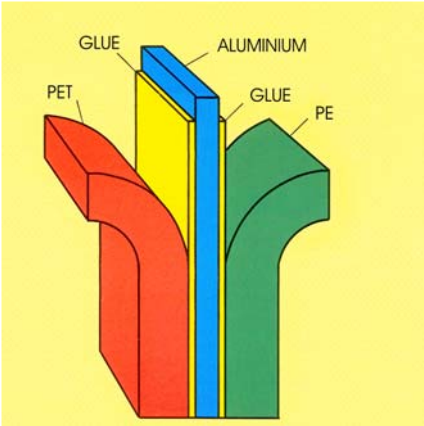

Figure 15. Laminate membrane used for gas cushions. Components: PTE (Polyester, Oriented, Primed + Polyethylene), Glue layer, Aluminium foil, Glue layer; PE (Polyethylene, Low Density Polyethylene).

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.

Inflation of Gas Cushions

The gas cushions are inflated by a newly developed process, where pellets are placed inside the cushion cells. The gas volume can be controlled by the weight and the chemical composition of the pellets. The cushions are inflated after the individual cells are sealed, by triggering the gas inflation process. This new inflation method eliminates the use of valves and thus simplifies the manufacturing, preparation and installation of the gas cushions. The chemicals used for the inflation process are non-toxic and harmless to the environment.

Installation Process

Another important improvement is that the gas cushion panels can be attached to prefabricated concrete panels, Figure 16. The gas cushion screen consists thus of three main components: 1) the bentonite cake, which surrounds the cushions and provides chemical and mechanical protection; 2) two layers of flexible gas cushions (gas pressure corresponding to the ambient ground pressure), which consist of a five-layer plastic laminate (plastic-aluminium foil); and 3) the stiff concrete panel. The gas cushion screen has the advantage, compared to open trenches, that after installation, the screen is no longer visible. Attaching the gas cushions to concrete panels has several advantages: 1) the weight of the concrete compensates the buoyancy of the gas cushions during insertion in the slurry-filled trench; 2) the panels provide a stiff vertical barrier with an additional impedance change; 3) the concrete panels can carry vertical loads, for instance when installed in areas with heavy traffic; and 4) a surface plate can be mounted on top of the concrete panels. The gas cushion screen extends to about 1 m below the ground surface and the top layer is provided with a specially designed temperature and vibration barrier (to avoid transfer of vibration energy close to the ground surface). A careful evaluation of past vibration isolation projects suggests that part of the vibration energy was transmitted along stiff surface layers above the gas cushion screen, and thereby reduced the isolation efficiency.

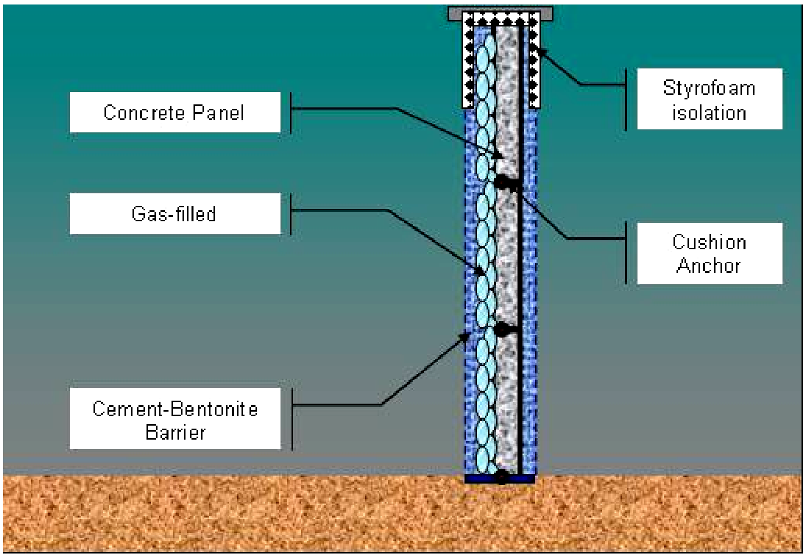

Figure 16. Gas cushion system with flexible cushions attached to stiff, prefabricated concrete panel.

Conclusions

Vibration problems are of increasing importance in many industrialized countries. In the past, research has focused on theoretical investigations while little information is available about full-scale applications of vibration isolation barriers. It is recommended that isolation barriers be installed close to the vibration source to eliminate the effect of wave bending. Alternatively, the barrier should be located close to the structure to be protected. The limited data on ground vibration tests using open trenches are reviewed. 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.

The vibration isolation effect can be expressed in terms of an amplitude reduction factor. The vibration efficiency should be evaluated in the frequency domain, rather than selecting values from vibration records. It can be concluded that the isolation effect, which can be achieved in practice, is less than theoretically predicted. The results obtained from model tests by Haupt (1981) can be used for design purposes. When the trench depth is equivalent to the wave length, the isolation effect is about 0.3 – 0.5 (i.e. a reduction by 50 – 70%).

The development phases of the gas cushion method are described, which was introduced about 20 years ago. The first and second generations of the gas cushion screen have been applied successfully in Europe. The results from full-scale tests in different soil conditions are presented. It can be concluded that the efficiency of the gas cushion screen is comparable to that of open trenches, as determined from model tests performed in the field and in the laboratory.

Observations from gas cushion projects suggest that vibration energy is transmitted across stiff surface layers above the isolation screen and reduce the isolation efficiency. In order to increase the isolation effect at higher frequencies, it is recommended to create a separate slot from the ground surface to about 2 m depth and to avoid rigid contact between stiff elements.

Another important aspect, which is difficult to consider theoretically, is the influence of the length of the vibration source. This aspect is of special importance in the case of vibration problems caused by railway traffic.

Recent improvements of the gas cushion method are described. The most important development is a new cushion inflation process without valves. This makes it possible to seal the cushions before inflation and thereby assures high gas tightness and simplifies the manufacturing, preparation and installation process.

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