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Ground Vibration Isolation Using Gas Cushions

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SYNOPSIS: A new ground vibration isolation method is described, which uses inflated, flexible cushions. The isolation cushions have therefore a low impedance and act as vibration reflectors in the ground.

Practical aspects, such as the production of the gas cushions screen, the installation method and the gas-tightness of the gas cushions are discussed. The screen can be installed to great depth, using the well-proven slurry trench technique. After installation, the trench is filled with a self-hardening cement-bentonite grout, which creates a plastic, water-tight protection layer around the cushions and assures the long term stability of the screen. The gas cushion screen can thus be used for permanent installations in the ground.

The paper describes the theoretical concept of the gas cushion screen. The isolation efficiency is analyzed, using the boundary element method. The theoretically predicted isolation effect is compared with field tests and data published in the literature.

The test results suggest that the isolation efficiency of the gas cushion screen is comparable to that of an open trenches.

INTRODUCTION

Ground vibration problems occur frequently in built-up areas and they have become increasingly important as a result of the use of vibration-sensitive electronic equipment, and due to the awareness of the public for environmental problems. However, only in few countries exist codes or regulations which regulate the vibration limits. This has led to the unsatisfactory situation where many vibration problems result in legal action, instead of engineering solutions. One contributing factor is that there exist only a limited number of practical measures to solve ground vibration problems.

WAVE PROPAGATION IN SOIL

Vibrations propagate in the ground as body waves (compression- and shear waves) or as surface waves (mainly Rayleigh waves). **Figure 1** shows the deformations caused by a stationary wave field as determined by finite element analysis, (Haupt, 1986). In the calculations it was assumed that a vertically oscillating foundation is located at the surface of an isotropic, elastic medium. Theoretically, surface waves (R-waves) account in this case for 67 %, shear waves (S-waves) for 26 %, and compression waves (P-waves) for only 7 % of the total energy. Thus surface waves are most important in the case of ground vibration problems.

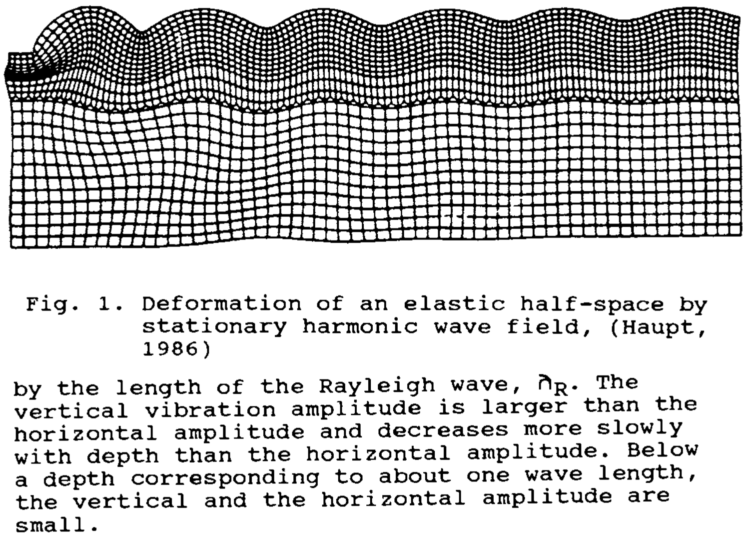


Fig. 1. Deformation of an elastic half-space by stationary harmonic wave field, (Haupt, 1986)

Figure 2 shows the variation of the horizontal and the vertical vibration amplitude as a function of depth, for Poisson's ratio of 0,25 and 0,5, respectively. The vibration amplitude is normalized by the horizontal amplitude at the ground surface and the depth is normalized by the length of the Rayleigh wave, λ_R. The vertical vibration amplitude is larger than the horizontal amplitude and decreases more slowly with depth than the horizontal amplitude. Below a depth corresponding to about one wave length, the vertical and the horizontal amplitude are small.

VIBRATION ISOLATION METHODS

Three different methods can be used to reduce ground vibrations: restrictions at the source of vibrations, screening of the waves propagating through the soil, or changes at the structure affected by the vibrations.

An effective vibration isolation measure is often to change the conditions at the source of vibrations (active isolation), e. g. by limiting the speed of traffic, by modifying the operating frequency of machines or by improving

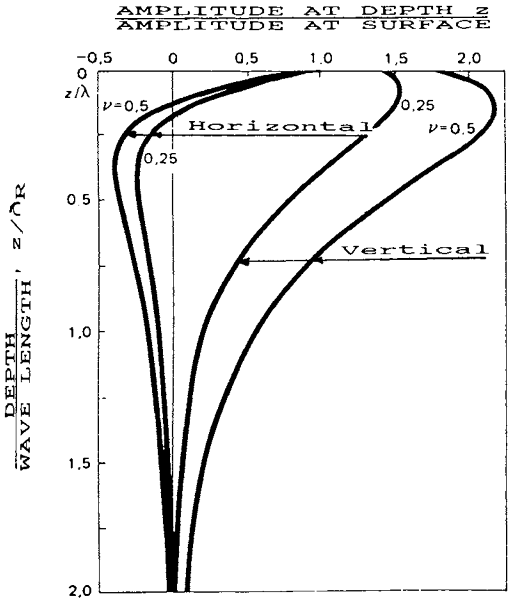


Fig. 2. Amplitude ratio vs. dimensionless depth for Rayleigh wave, assuming different values of Poisson's ratio

the dynamic response of the foundation of vibrating machines. However, this solution is not always possible. Another effective and often cheap measure is to increase the distance between the vibration source and the affected structure (passive isolation). This implies, however, that vibration problems are anticipated during the planning stage of a project.

Ground vibrations can also be reduced by isolation barriers in the ground. The concept of wave barriers is based on reflection, scattering, and diffraction of wave energy. Different types of isolation barriers have been used, such as open or slurry-filled trenches, sheet piles and concrete walls (Barkan, 1962, Woods, 1968, Richart et al., 1970 and Haupt, 1980).

The isolation effect of a wave barrier depends on the impedance I,

$$I = C \rho \qquad (1)$$

where C is the wave velocity and ρ is the density. The energy reflection ratio R_n is a function of the differences of impedance

$$R_n = (I_2 - I_1)^2 / (I_2 + I_1)^2 \qquad (2)$$

where I_1 is the impedance of the soil and I_2 is the impedance of the wave barrier. From this relationship it is apparent that an open trench (with an impedance close to zero) is more effective than a stiff barrier.

OPEN TRENCH

Several investigators have performed vibration isolation studies using open trenches, (Barkan, 1962, Woods and Richart, 1967, Dolling, 1970, Woods, 1977, Haupt, 1981). They found that the isolation effect depends on three main factors: the depth of the trench in relation to the wave length of the surface wave, the geometry of the trench and the relative distance between the source of vibration, the trench and the measuring point.

Figure 3 compares the results of model tests in the field with theoretical calculations by Dolling (1970). The isolation effect is expressed as amplitude reduction factor, R_A (ratio of vibration amplitudes after and before installation of the trench), and is shown as a function of the dimensionless depth of the screen. Theoretical calculations agree well with field measurements, obtained immediately behind the screen (near-field). On the other hand, open trenches appear to be less effective at a distance of several wave length behind the trench (far-field). This effect can be attributed to the limited length of the open trench in the field tests, compared to the infinitely long trench, which was assumed in the theoretical analysis by Dolling (1970).

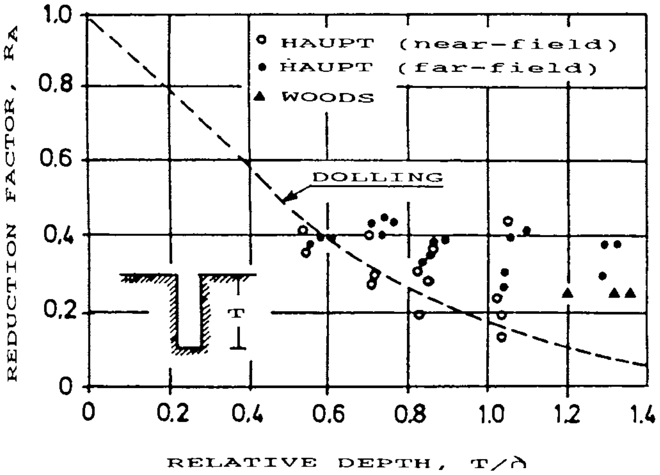


Fig. 3. Vibration isolation effect behind an open trench, after Haupt (1981)

The influence of trench geometry on the screening effect was investigated in the field and by holographic model test, (Woods, 1968 and 1977). Straight as well as circular trenches were studied. **Figure** 4 shows that the isolation effect is largest in a zone in the centre behind the trench (shadow zone). Vibration amplification can occur in front of the trench and demonstrates the reflection of wave energy.

Richart et al (1970) have made the following recommendations concerning the design of open trenches for ground vibration isolation. If the trench is located close to the vibration source and completely surrounds the source, an amplitude reduction factor of 0.25 can be expected, provided that the trench has a depth of at least 0.6 λ. For a partially surrounding trench the isolation efficiency and the size of the affected zone depend on the trench geometry and on the distance between the source of vibrations and the trench.

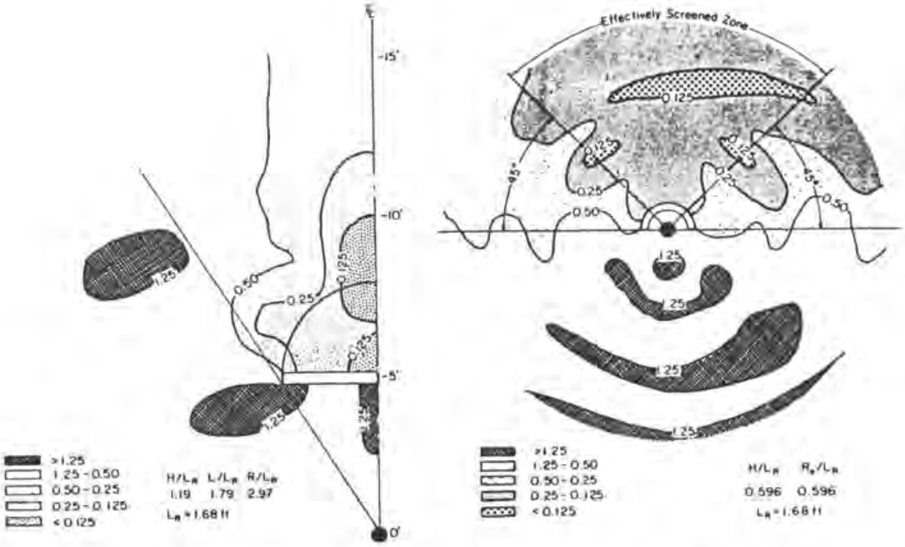


Fig. 4. Amplitude reduction contours behind a straight and a circular trench, (Woods, 1968)

GAS CUSHION SCREEN

Open trenches have found only limited practical application. It is often difficult to install permanent trenches in populated areas. Stability considerations limit also the maximum depth of excavation and thus the isolation efficiency. In order to overcome the problems associated with open trenches, a new ground vibration isolation method, the gas cushion screen, was developed, (Massarsch and Ersson, 1985). The gas cushions can be installed in the ground to great depth, between the source of vibrations and the affected building, **Fig. 5**.

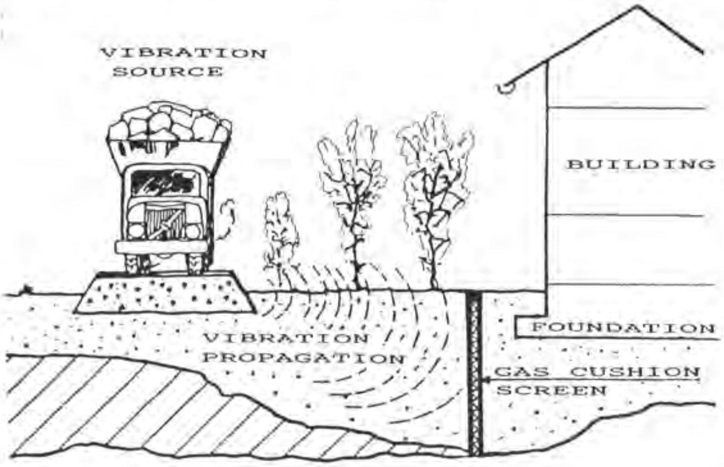


Fig. 5. Ground vibration isolation using the gas cushion screen

The present paper describes the theoretical concept on which the gas cushion concept is based, the construction principle of the gas cushions and the installation procedure. Finally, results from field tests are presented and compared with theoretical analyses.

The first generation of the gas cushion screen was developed in Sweden some 10 years ago and was successfully applied on several projects, (Massarsch, 1986, Carlsson, 1987, Massarsch and Corten, 1988 and Massarsch, 1989). However, the manufacturing of the isolation cushions was time-consuming and the installation method limited to soft ground conditions. The second generation of gas cushions was developed in Belgium, adopting the system for mass production of the cushions and using an installation method which is applicable to a variety of ground conditions.

The objective of the gas cushion screen is to create a permanent, vertical barrier with low impedance in the ground. This can be achieved by installing a continuous wall of flexible, gas-inflated cushions. The impedance for P-waves depends on the density and the wave velocity of the inflated cushions. The density of air at 10^{o} C is about $1.3\ 10^{-3}$ t/m^3. The P-wave velocity is independent of the pressure and is for air at 10^{o} C about 338 m/s, resulting in an impedance of 0.438 t/m^2s^1. Assuming a typical P-wave velocity for soil of 600 m/s and a density of 1.8 t/m^3, the corresponding impedance is 1080 t/m^2s^1. The reflection coefficient R_n of gas cushions according to Equ. (2) is theoretically about 0.99, which means that practically all energy of the incident P-wave is reflected. Shear waves can not be transmitted through gas and are thus theoretically completely reflected.

The gas cushions consist of horizontally placed, flexible tubes, which are overlapping in the vertical direction, Fig. 6. They are manufactured of a thin-walled, flexible plastic laminate, which consists of two layers of polyethylene film, surrounding a thin metal foil. The composition of the laminate assures complete gas tightness and high mechanical as well as chemical resistance, (de Cock and Legrand, 1990). The balloons are inserted into pockets of a woven geotextile fabric and then inflated through a valve. The valve can be permanently sealed. The diameter of the geotextile pockets is slightly smaller than that of the fully inflated gas cushions, thus keeping the walls of the gas cushions completely unloaded (similar to an inflated bicycle tube). The gas cushion panels can be assembled to about 2 m wide sections of any required length.

During the short period after inflation and before installation in the ground, there exists an overpressure in the gas cushions, compared to the external air pressure. However, because of the low diffusion coefficient of the metal foil in the plastic laminate, the diffusion rate is very small. The gas diffusion process can be analyzed by Ficks's law

$$\Delta M = (D \cdot S \cdot A) \cdot \Delta_p \cdot [t - (L_m^2 / GD)] / (L_m) \quad (3)$$

where ΔM is the mass of the gas, D is the diffusion coefficient, S is the solution coefficient of the gas, A is the diffusion surface, Δ_p is the differential gas pressure, t is the time, L_m is the membrane thickness and (L_m^2 / GD) is the induction coefficient. For the present case the induction coefficient can be neglected. The differential gas pressure depends on the difference of the molecular gas concentration on either side of the membrane.

The gas cushion concept is based on the fundamental principle that after installation in the ground, the external pressure acting at the outside of the membrane is in balance with the internal gas pressure. Then, as a result of the pressure equilibrium the diffusion rate is reduced to a very low value. The inflation pressure of the cushions must be chosen lower than the liquid pressure in the trench or the earth pressure at the respective depth in the soil after installation. Theoretical calculations suggest a life time of at least 40 years.

The gas cushions are installed in a slurry-filled trench, Fig. 6. As a result of the buoyancy of the gas cushions, the screen is subjected to high temporary up-lift forces, which have to be compensated either by an anchor or by a heavy weight at the lower end of the screen. After screen installation, the bentonite slurry is replaced by a self-hardening cement/bentonite grout, similar to that used for ground water cut-off walls. The plastic cement-bentonite material forms a flexible, water-tight layer on either side of the gas cushions, providing the screen with a watertight protection.

After installation, the surface of the trench above the gas cushion screen must be properly protected by a layer of styrofoam (for temperature isolation) and by a cover of plastic cement/bentonite.

THEORETICAL ANALYSIS OF THE GAS CUSHION SCREEN

Beskos et al (1986) have analyzed the screening efficiency of stiff and flexible isolation barriers in an elastic medium, using the boundary element method. They came to the conclusion that an open trench has the highest isolation effect. **Figure 7** shows the vibration isolation effect of an open trench. The isolation efficiency is expressed in terms of the amplitude reduction factor R_A, as a function of the relative trench depth T/λ. A trench length of 5 m was assumed and the width was varied between 0.1 and 1.0 m. The trench width appears to have little influence on the isolation efficiency. At a trench depth corresponding to one wave length, the amplitude reduction factor is about 0.2 and does not decrease very much when the trench depth is further increased (minimum value of R_A = 0.1). The results by Beskos et al. (1986) are in good agreement with the relationship proposed by Dolling (1970), cf. Fig. 3.

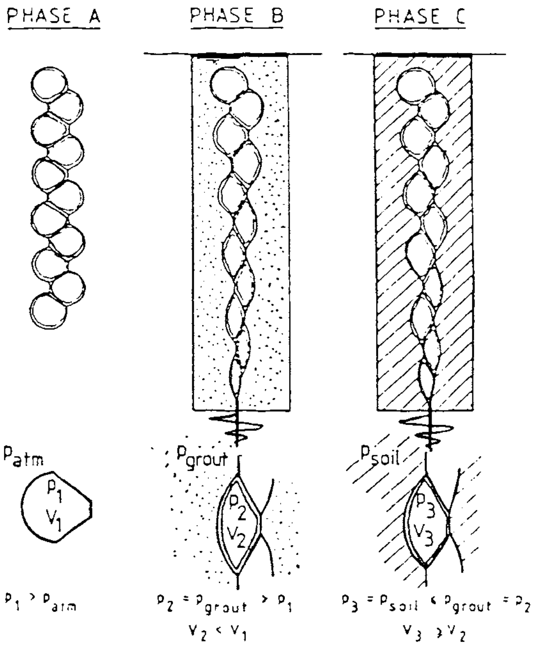


Fig. 6. The principle of the gas cushion system, (de Cock and Legrand, 1990)

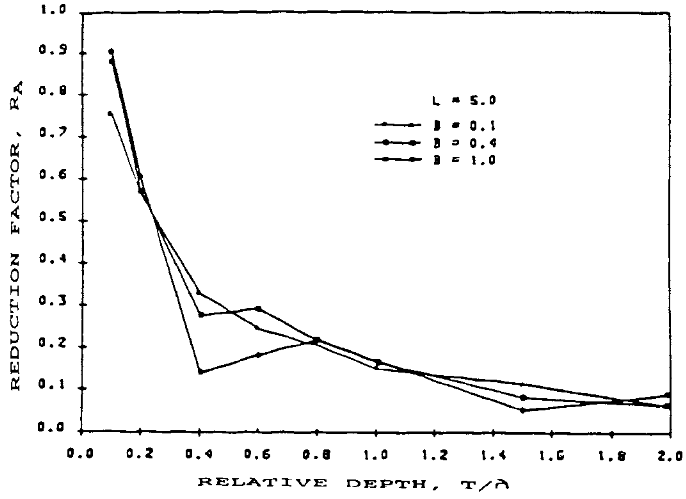


Fig. 7. Influence of relative trench depth on the amplitude reduction factor as a function of trench width (Beskos et al., 1986)

The boundary element method was also used to analyze the gas cushion screen and to compare its isolation efficiency with that of an open trench, (Vardoulakis et al., 1987). The problem was solved numerically in the frequency domaine under conditions of plain strain. The gas-filled cushions were idealized as a set of springs with stiffnesses equivalent to those of the cushions, which effectively offset the overburden earth pressure. A coefficient of total lateral earth pressure $K_0 = 1.0$ was chosen. The soil was assumed to be homogeneous, isotropic and linearly elastic. For comparison, calculations were performed without a trench, with an open trench and with the gas-cushion screen, respectively.

The soil conditions in the analysis were chosen to simulated field tests reported by Massarsch (1986). The depth of the screen was 8 m and the screen width 0.03 m. The shear wave velocity of the soft clay was 70 m/s, with a density of 1.6 t/m^3. The damping ratio and the Poisson's ratio were 3 % and 0.49, respectively. The vibration source was assumed as a vertically oscillating, massless footing of 0.3 m width, excited at a frequency of 30 Hz. The wave length of the shear wave corresponded to 2.3 m. **Figure 8** shows the variation of the vertical vibration amplitude on either side of the footing, with and without the gas cushion screen.

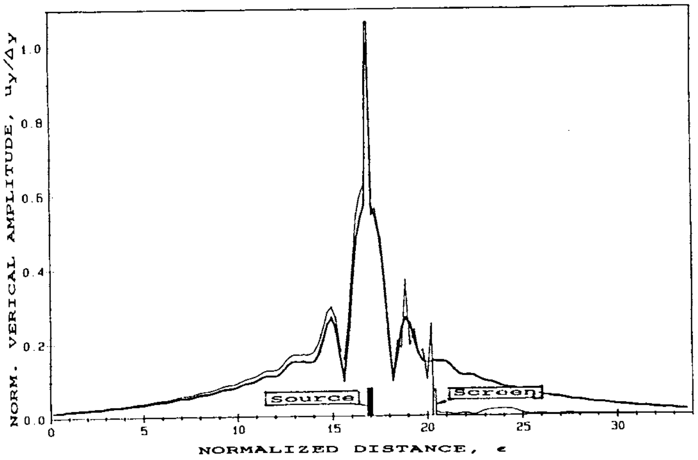


Fig. 8. Vertical vibration amplitude as a function of normalized distance, with and without gas cushion screen, bold line representing conditions without screen, (Vardoulakis et al., 1987)

Fig. 9 and 10 show the normalized vertical and horizontal vibration amplitude as a function of normalized distance for the case of a gas cushion screen. The screening effect of harmonic waves behind the gas cushion screen is evident, and considerable amplification occurs in the zone between the trench and the vibration source, which is due to the reflection from the screen. The isolation effect is somewhat different for the vertical amplitude compared to the horizontal amplitude. The vertical amplitude has the lowest value immediately behind the screen, while the horizontal amplitude decreases gradually with increasing distance behind the screen.

The screening efficiency was defined in terms of the amplitude reduction factor R_A. The ratio of the average normalized amplitude was determined for the open trench and the gas cushion screen, respectively. For the case of an open trench, the amplitude reduction factor of the vertical amplitude was $R_{Av}^{tr} = 0.093$ and of the horizontal amplitude $R_{Ah}^{tr} = 0.121$. The equivalent values for the gas cushions screen were $R_{Av}^{gc} = 0.094$ and $R_{Ah}^{gc} = 0.122$, respectively. It can thus be concluded that theoretically, the gas cushion screen behaves in the same way as an open trench.

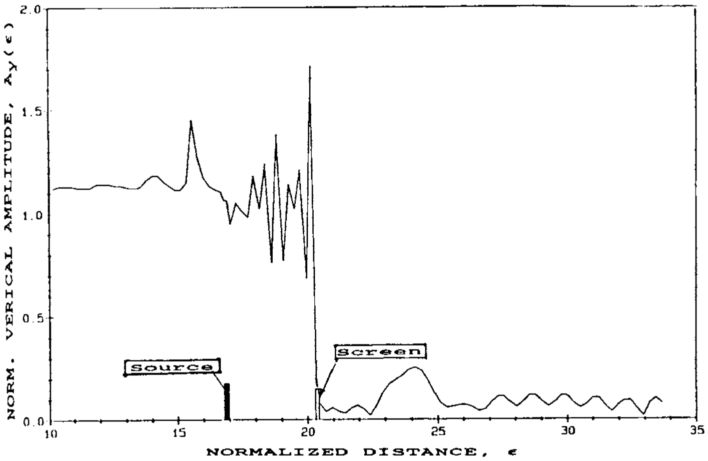


Fig. 9. Normalized vibration amplitude as a function of normalized distance for gas cushion screen, (Vardoulakis, 1987)

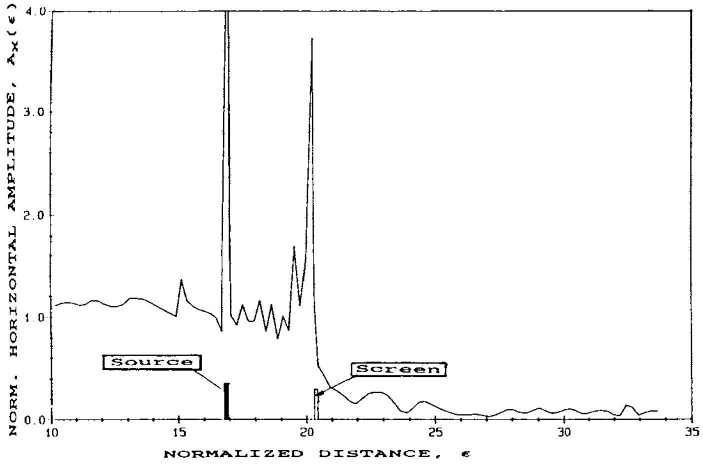


Fig. 10. Normalized horizontal amplitude as a function of normalized distance for gas cushion screen, (Vardoulakis,1987)

FIELD TESTS

The gas cushion screen was extensively tested in Sweden and Belgium. Test results from earlier installations have been reported by Massarsch (1986) and Massarsch and Corten (1988) and Massarsch (1989). In the present report, only tests performed with the gas cushion system developed in Belgium, are presented.

Vibration Tests, University of Gent

The first test serie was carried out at the test field of the University of Gent, where the soil conditions are well known from a large number of previous field tests. The soil consisted of medium dense sand and silty sand. The ground water level was located about 2 m below the ground surface. The surface wave velocity was determined by field tests, using a heavy soil compactor (vibrolance), Fig. 11.

The vibrolance was capable of generating strong ground vibrations within a frequency range of 10 to 30 Hz. The vertical and horizontal vibration amplitudes were measured using geophones, which were placed in the soil layer below the dry crust. **Figure** 12 shows the measured surface wave velocity as a function of the vibration frequency. In the lower part of the figure, the wave velocity is shown as a function of the wave length. The dispersive nature of the surface wave is apparent, suggesting that the soil stiffness increases with depth. The variation of wave velocity has a great effect on the isolation efficiency of the screen and must therefore be determined accurately.

At the test site, a gas cushion screen of 12 m depth and 20 m length was installed. A trench was first excavated using bentonite slurry. Thereafter, the gas cushion panels were lowered into the trench, using heavy concrete weights, attached to the lower end of the screen. The panels were installed laterally overlapping, to achieve a continuous isolation screen. Thereafter, the bentonite slurry was replaced by a self-hardening cement/bentonite grout. The top of the trench was left unprotected to avoid interference of the surface layer on the vibration measurements.

The theoretical investigations reported above suggest, that the isolation screen would be effective for a wave length corresponding to that of the depth of the screen. According to Fig. 12, for a 12 m deep screen and a corresponding wave velocity of 180 m/s, a "cut-off" frequency of 15 Hz was obtained.

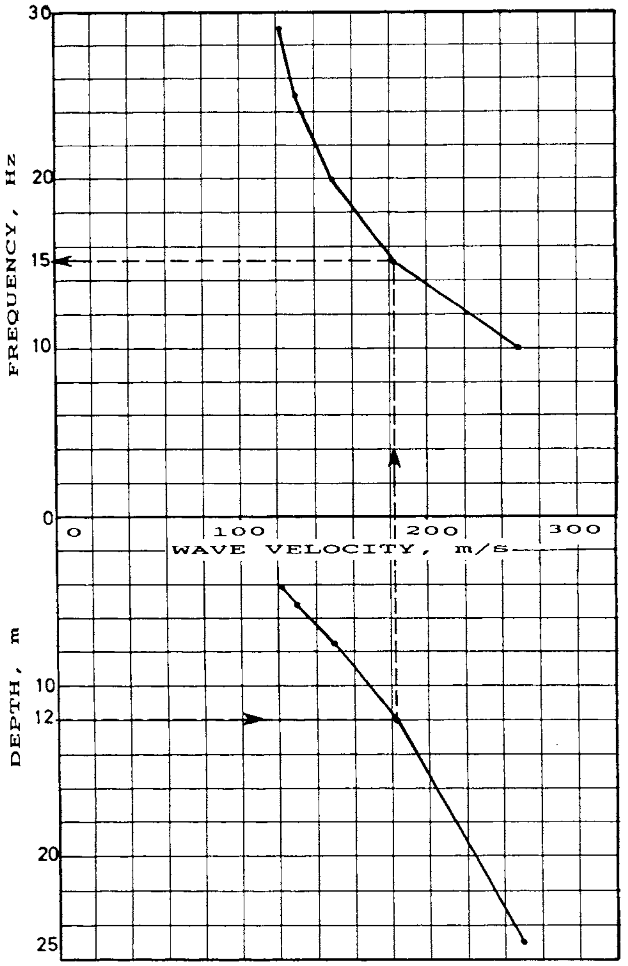


Fig. 12. Measured surface wave velocity as a function of vibrator frequency, and corresponding depth of wave penetration.

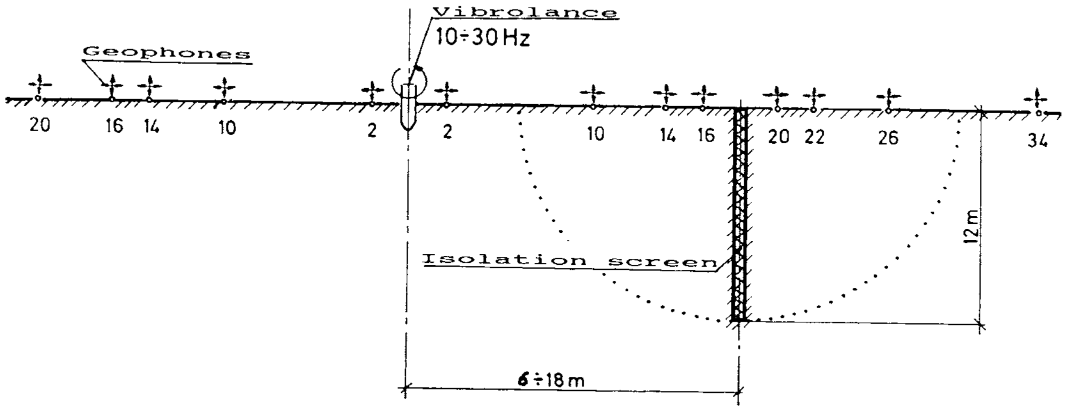


Fig. 11. Test arrangement for for vibration measurements at the test site of the University of Gent

The vibration tests were started about 3 months after installation of the screen. The vibrolance was placed at varying distances (6 to 18 m) from the screen, and the ground vibration velocity was measured in a section perpendicular to the screen, cf. Fig. 11. **Figures 13 and 14** show the measured vibration amplitudes with and without screen, for different vibration frequencies. In order to facilitate comparison of the test data, the vibration amplitudes were normalized by the value at 2 m distance from the source.

In spite of some scatter of the test data, the isolation efficiency of the gas cushion screen is apparent. The average amplitude reduction factor was for the frequency range 10 to 14 Hz, R_A = 0.25, and for the frequency range 21 to 29 Hz, R_A =0.20. The zone of vibration isolation behind the screen extended to a distance of approximately 1.5 times the depth of the screen.

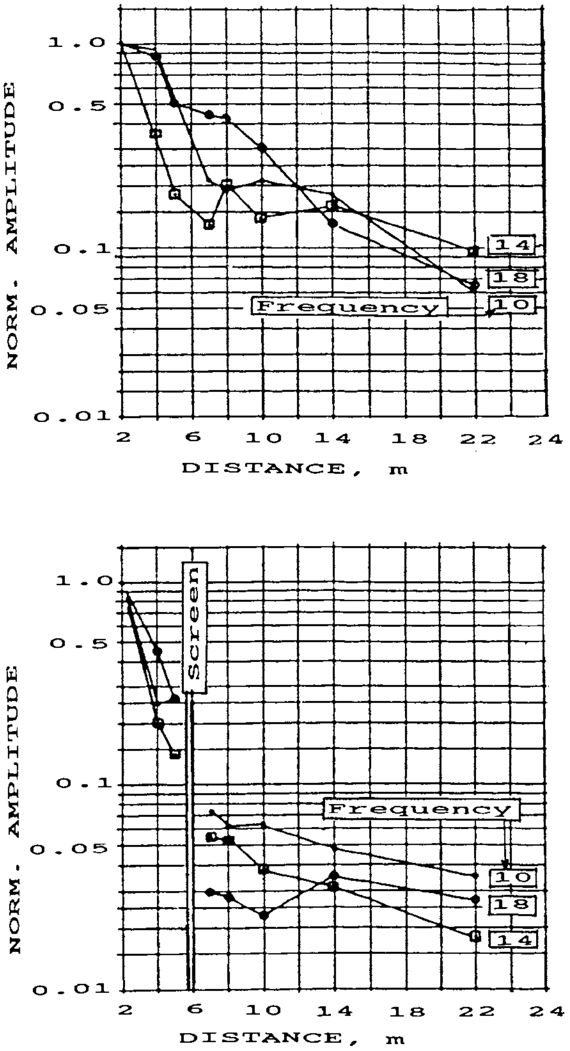


Fig. 13. Normalized vertical vibration amplitudes (logarithmic scale) as a function of the distance from the vibrator, with and without screen, for frequency range 10 to 18 Hz

Variations in temperature during the following winter caused the gas cushions to shrink and surface water started to penetrate into the void between the cushions and the grout layer. Vibration tests during that period showed a marked reduction of the isolation efficiency of the screen. This underlines the importance of adequate surface protection of the gas cushion screen, when they are used for long-term applications.

<u>Vibration Tests, Limelette</u>

The gas cushion screen was also studied in detail by the Belgian Scientific and Technical Research Centre for Construction (CSTC). The investigations were conducted at the test field of the institute at Limelette, south of Brussels. The soil consisted of partially saturated, medium dense silty sand to great depth. The surface wave velocity was measured by dropping a mass of 700 kg on the ground

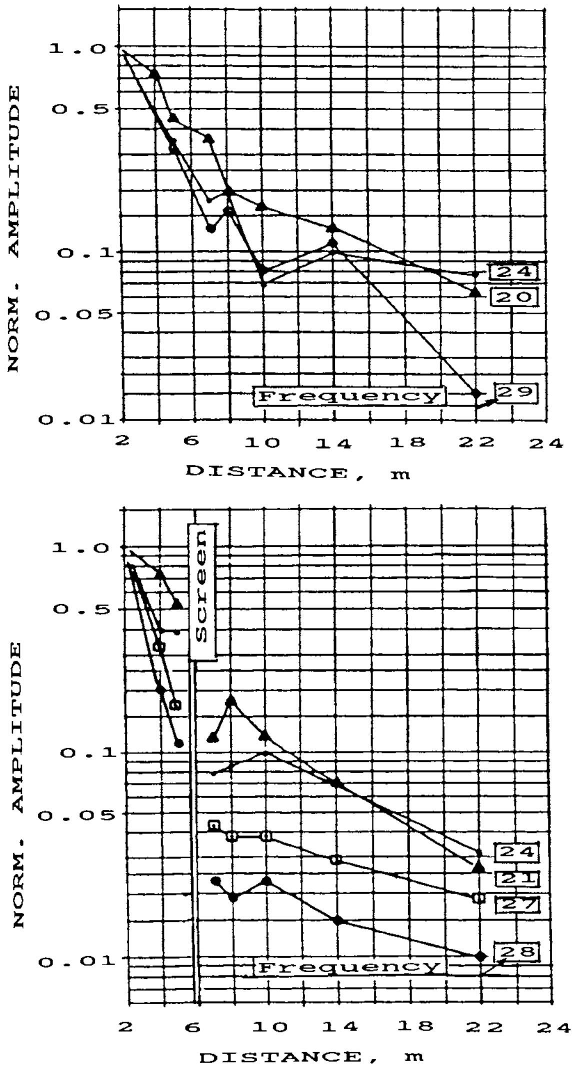


Fig. 14. Normalized vertical vibration amplitudes (logarithmic scale) as a function of the distance from the vibrator, with and without screen, for frequency range 21 to 28 Hz

surface, and recording the travel time intervals between an array of geophones, placed at distances from 2 to 22 m. The surface wave velocity ranged between 110 and 125 m/s, with a dominant frequency of about 25 Hz.

A 6 m deep and 10 m long gas cushion screen was installed in a similar way as at the Gent test site. However, instead of a dead weight, ground anchors were installed at the bottom of the trench to counteract the buoyancy of the gas cushions in the slurry-filled trench. After screen installation, the bentonite slurry was replaced by the self-hardening cement/bentonite grout. Styrofoam panels were placed vertically from the ground surface to a depth of 0.5 m, (to the top of the gas cushion screen) in order to reduce the transfer of vibration energy across the trench. A panel of styrofoam was also placed horizontally above the gas cushions to provide temperature insulation. On top of the styrofoam a 0.5 m thick layer of stiff cement/bentonite grout was placed.

The tests were started several months after completion of the screen. In order to investigate the isolation efficiency, two types of vibration tests were performed. During the first phase of the investigation, explosive charges (200 and 400 g) were detonated at a distance of 6 m from the isolation screen. The vertical and horizontal vibration velocity was measured by accelerometers and geophones in sections perpendicular to the screen, (Legrand, 1989). The vibration amplitudes were recorded in real time and then transformed into the frequency domaine. In **Figure 15 a** and **b**, typical test results are given, showing the amplitude variation (vertical velocity) with time and the corresponding frequency spectrum.

In the case of the explosive charge, the dominating vibration frequency was around 14 Hz, and thus significantly lower than for the falling weight test. For a frequency of 14 Hz and a wave velocity of 120 m/s, the screen depth corresponded to a wave length of about 0.7 λ.

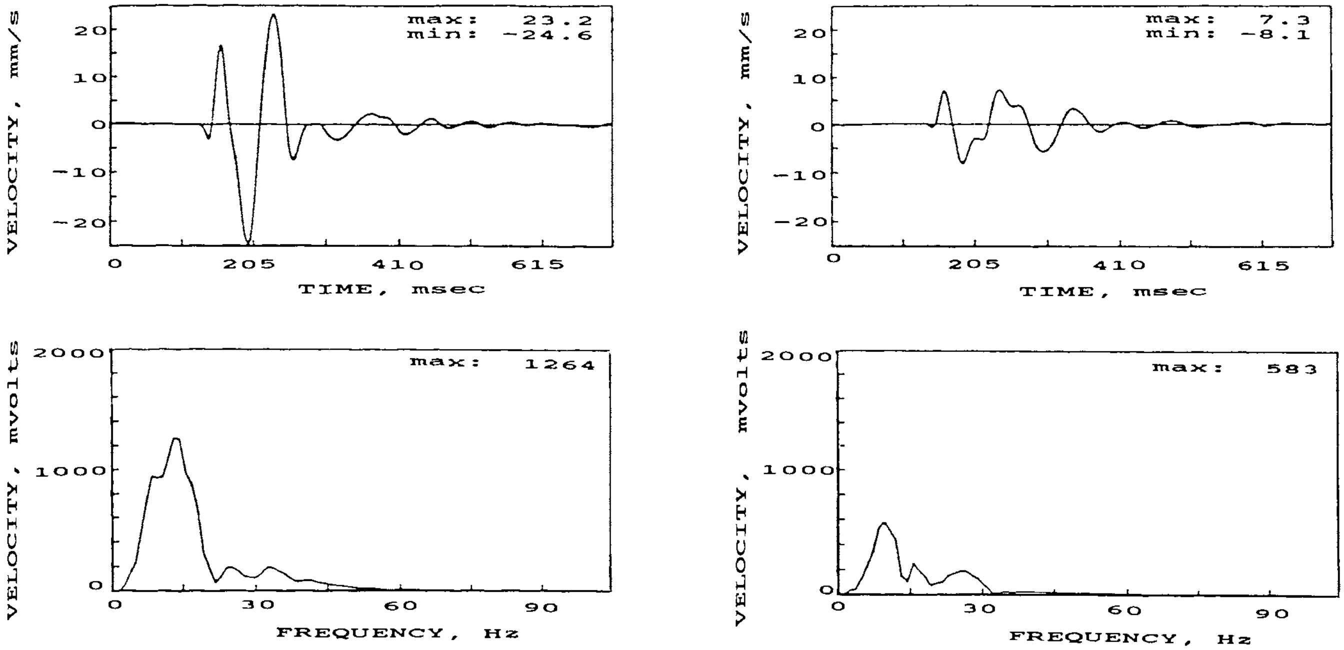
TABLE I summarizes the test results in terms of peak velocity amplitude at different distances from the isolation screen. The amplitude reduction factors could then be calculated for the respective test.

The measured amplitude reduction factor, R_A varies between 0.25 and 0.30, and is in good agreement with theoretical calculations, cf. Figs 3 and 7.

For the second test series, a heavy vibrator with variable frequency and variable eccentric moment was installed on a concrete slab, at a distance 6 m in front of the screen. The objective was to determine whether there was a difference in the isolation effect for steady state excitation, compared to impulse excitation.

The operating frequency of the vibrator was varied between 5 and 100 Hz and the measured isolation effect is shown in **Fig. 16**. The measuring point was located 16 m behind the screen. Similar measurements were also performed at 1 and 8 m distance. The average of 20 individual test was determined and is presented in Fig. 16 in a logarithmic scale.

The measurements confirmed the results from the impulse excitation tests. Above a frequency of about 15 Hz, the amplitude reduction factor R_A



a) without screen

b) with gas cushion screen

Fig. 15. Vertical vibration amplitude time history and frequency spectra, measured 14 m from the vibration source (explosive), with and without gas cushion screen Legrand, 1989. Distance between source and screen: 6 m.

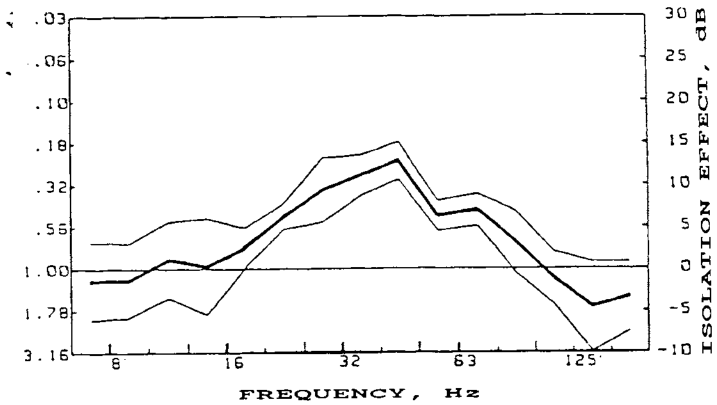


Fig. 16. Efficiency of gas cushion screen for steady state excitation (minimum, maximum and mean value from 20 tests), measured 22 m from the vibration source, (Legrand 1989), distance from screen: 16 m,

TABLE I. Measured vertical vibration amplitudes and amplitude reduction factors, R_A at different distances behind the gas cushion screen, after Legrand (1989).

Test No.	Distance (m)	Vibration Velocity (mm/s) no screen	with screen	R_A (-)
50	1	74.2	12.6	0.17
50	8	93.7	17.0	0.18
50	16	27.7	10.5	0.38
51	1	267.4	19.7	0.13
51	8	67.9	15.7	0.23
51	16	19.7	9.5	0.48
52	1	50.33	14.9	0.30
52	8	42.5	10.5	0.25
52	16	26.7	5.8	0.21
53	1	62.4	21.1	0.34
53	8	53.2	15.1	0.28
53	16	35.4	9.1	0.26
59	1	47.2	29.1	0.61
59	8	24.6	8.1	0.33
59	16	12.9	5.5	0.42
Average	1	-	-	0.31
Average	8	-	-	0.25
Average	16	-	-	0.35

decreases from 0.5 to 0.2. At the cut-off frequency of 20 Hz, the amplitude reduction factor is about 0.3. The isolation effect was higher at the measuring points, located closer to the isolation screen, (Legrand, 1989).

SUMMARY AND CONCLUSIONS

A new ground vibration isolation method, the gas cushion screen is presented. The design of the gas-filled cushions and the installation method assure the long-term stability of the inflated screen in the ground.

The isolation screen is effective when the depth of the screen corresponds to about 0.8-1.0 times the length of the surface wave. Good agreement was obtained between field tests, theoretical analysis using the boundary element method and data for open trench barriers, published in the literature.

The amplitude reduction factor is about 0.2 to 0.5, depending on the distance of the measuring point behind the screen.

It should be noted that the geometry (depth and length) of the screen in relation to the vibration source has great significance for the practical application of an isolation barrier. In order to achieve satisfactory results, the isolation screen should be located as closely as possible to the vibration source. Alternatively, the isolation screen should be placed immediately in front of the building to be protected.

For the determination of the minimum depth of the screen it is necessary to measure the wave propagation velocity in the ground and the cut-off frequency of the structure to be protected.

ACKNOWLEDGEMENTS

The initial development of the gas cushion screen and field tests was carried out at the Department of Soil and Rock Mechanics of the Royal Institute of Technology in Stockholm. The valuable assistance of L-O. Ersson, P-A. Holmberg, B. Carlsson and Dr. A. Bodare is gratefully acknowledged.

The gas cushion screen was further developed while the author was employed with Franki International in Belgium. Many individuals have contributed during the various development phases of the gas cushion project. Mr. F. Corten was responsible for the implementation of the test installations at Gent and Limelette. The assistance of prof. W. Van Impe of the University of Gent is highly appreciated. The field measurements at Limelette were conducted under the leadership of Mr. C. Legrand of CSTC.

The boundary element analysis was performed at the University of Minnesota by prof. Vardoulakis and his staff. Professor B. Prange of the University of Karlsruhe made many valuable contributions and suggestions during the development of the gas cushions system.

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