Mitigation of Traffic-induced Ground Vibrations

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Abstract — **Ground vibration problems have increased in populated and industrialized areas and effective mitigation measures are needed. Different methods which can be used to reduce traffic-induced vibrations are discussed. Particular emphasis is placed on rail-bound traffic and the application of wave barriers. These can be installed between the vibration source and affected structures. Open or gas-filled trenches achieve the highest isolation effect. Experience from a recently developed vibration isolation method, the gas cushion screen, is presented. Based on results from field measurements it can be concluded that the gas cushions provide long-term isolation effect and that the isolation effect is similar to that of open trenches.**

Keywords — **Barriers, environment, gas cushions, traffic, railway, vibration isolation, vibrations.**

INTRODUCTION

Traffic intensity has increased on roads, highways and railway lines and in many countries, major investments are being made to make transportation systems more efficient. Modern communication requires higher train speeds, while at the same time trainloads have increased. Because of the special requirements of highway and rail-bound transportation systems, which usually need to pass through densely populated areas, new technical and environmental challenges have to be dealt with. These include noise and vibration emission, which can affect buildings, installations and cause nuisance to inhabitants. Under unfavorable conditions, ground vibrations can also damage sensitive structures and installations in and on the ground. Due to the increasing importance of vibration problems and the enforcement of stricter environmental regulations, there is a need to protect buildings or installations on or in the ground against ground-borne vibrations.

Ground vibrations and their propagation from the source to the surroundings is a complex process, which is affected by several, interrelated problems. Therefore, in the past, the risk of vibration problems has rarely been considered at the planning stage. However, once disturbing or damaging vibrations occur, it is usually more difficult and expensive to apply vibration-reducing measures. Therefore, the prediction of vibrations and the implementation of vibration-reducing measures should be part of the planning process. This paper discusses measures to reduce ground vibration, which are caused by railway traffic. However, the presented concepts and solutions can also be applied to other sources of ground vibrations.

In the first part of this paper, different measures to reduce rail-bound traffic are discussed. Thereafter, efficiency of rigid and flexible barriers and trenches is discussed. Finally, the recently developed gas cushion method is presented, which can be used as a permanent vibration isolation screen. The practical implementation of isolation barriers using the gas cushion screen will be discussed. Finally, the vibration isolation effect, as determined from several field applications, will be presented.

MITIGATION MEASURES

The Federal Railroad Administration of the US Department of Transportation [1] has prepared recommendations for noise and vibration impact assessment. Three different types of mitigation measures are considered to reduce ground vibrations: a) at or below the vibration source (active vibration isolation), b) screening of wave propagation in the ground between the source and the exposed object (vibration isolation barriers), or c) measures at the object, for instance changes of the dynamic properties of the structure (passive vibration isolation).

Measures to reduce ground-borne vibrations from railway traffic can be divided into the following categories: maintenance procedures, location and design of special track-work, vehicle modifications, operational changes, changes in the track support system, modification of the embankment foundation conditions, wave barriers such as trenches and walls, buffer zones and building modifications. These measures will be discussed briefly.

Maintenance

The importance of adequate wheel and rail maintenance in controlling levels of ground-borne vibration cannot be overemphasized. Problems with rough wheels or rails can increase vibration levels, negating the effects of even the most effective vibration control measures. When ground-borne vibration problems are occur at rails and rolling stock, often the best control

Keynote Lecture, 11th Intern. Conf. on Soil Dynamics and Earthquake Engineering and 3rd on Earthquake Geotechnical Engineering, Berkeley, January 7 – 9, 2004.

measure is to implement new or improved maintenance procedures. Grinding rough or corrugated rail and implementing wheel truing to restore the wheel surface and contour may reduce vibration more than completely replacing the existing track system.

Location and Design of Special Track-work

Most vibration impact from a new train system is caused by wheel impacts at switches, turnouts and crossovers. Careful review of their locations during the preliminary engineering stage is an important step in minimizing potential for vibration impact. When feasible, the most effective vibration control measure is to relocate the special track to a less vibration-sensitive area. It is also important to investigate the soil and foundation conditions in areas where switches, crossovers or turnouts are planned. Sometimes this requires adjusting the location by several hundred meters, which usually does not have a significant adverse impact on the operation plan for the system.

Vehicle Suspension

The ideal rail vehicle, with respect to minimizing ground-borne vibration, should have a low "unsprung weight", a soft primary suspension, a minimum of metal-to-metal contact between moving parts, and smooth wheels that are perfectly round.

Special Track Support Systems

When the vibration assessment indicates that vibration levels will be excessive, it is common to modify the track support system to reduce the vibration levels. Floating slabs, resiliently supported ties, high resilience fasteners, and ballast mats have been used to reduce the levels of ground-borne vibration. To be effective, these measures must be optimized for the frequency spectrum of the vibration. These measures have been used successfully on urban transit subway projects, but applications on "at grade" and elevated track are rare because vibration problems are less common for these conditions. Ballast mats are frequently used to reduce high-frequency vibrations, typically above 25 to 30 Hz. A ballast mat consist of a rubber or other type of elastomer pads, that is placed under the ballast. The mat generally must be placed on a thick concrete or asphalt pad to be effective. It will not be as effective if placed directly on the soil or the sub-ballast.

A resiliently supported tie system consists of concrete ties supported by rubber pads. The rails are fastened directly to the concrete ties using standard rail clips. The frequency range over which this type of track support system can reduce ground-borne vibrations depends on the pad stiffness and the interaction between the pads, ties, and rails.

Floating slabs can be very effective at controlling ground-borne vibration and noise. They consist of a concrete slab placed on resilient elements, usually rubber or a similar elastomer. Floating slabs are effective at frequencies higher than their single-degree-of-freedom vertical resonance frequency. The primary disadvantage of floating slabs is that they tend to be the most expensive of the track-related vibration control treatments.

Other measures include the use of heavier rail, thicker ballast, heavier ties, or resilient elements beneath the tracks. There also is some indication that vibration levels are lower when using wood ties compared to concrete ties. However, there is little confirmation that any of these approaches will make a significant change in the vibration levels.

Operational Changes

The most obvious operational change is to reduce the vehicle speed. Reducing the train speed by a factor of two will reduce vibration levels by approximately 50%. Another alternative is to use the equipment that generates the lowest vibration levels during the night-time hours, when people are most sensitive to vibration and noise. While there are benefits from reducing speed and limiting operations during the most sensitive time periods, these measures are usually not be practical from the standpoint of travel time and service frequency requirements. Furthermore, vibration reduction achieved through operating restrictions requires continuous monitoring and will be negated if the signal system does not enforce compliance with the speed restriction.

Modification of Embankment Foundation Conditions

An alternative method of reducing vibrations from railway traffic is to modify the foundation conditions in and below the embankment. It is useful if the dynamic response of an embankment is analyzed already at the planning or design stage and to anticipate remedial measures. It is usually easier and thus cheaper to improve the foundation conditions during the construction phase. However, in most cases, modification of the embankment foundation must be carried out below existing embankments. When train traffic is already in operation improvement measures are often difficult to implement and associated with high costs.

One way of increasing the stiffness of an embankment is by compaction of the embankment material. This method is usually only applicable when new embankments are constructed. Another alternative is to install a stiffening element (e.g. concrete beam or box-structure) horizontally along the alignment of the embankment. Installation of stiffening beams, consisting of concrete elements, can be effective. However, this alternative can be difficult to implement in the case of existing railway lines.

In Sweden and other Nordic countries, railway tracks are often founded on soft soil deposits (clay, organic clay and silt) with high ground water level. These foundation conditions can give rise to ground vibrations at low frequencies, which results in large displacements of the track. The problem becomes even more pronounced in the case of high-speed trains, when the train speed can approach the critical wave propagation velocity of the embankment-foundation system.

When the stiffness of the embankment and of the foundation is increased, static and dynamic displacements decrease. The most common method in the Nordic countries to improve cohesive soils is by deep mixing, using dry stabilizing agents (primarily unslaked lime and cement). The so-called “lime column” (LC column) method can increase the shear wave velocity of soft clays from typically 40 – 80 m/s to around 200 – 400 m/s, depending on the geotechnical conditions. Thus, the impedance (product of material density and wave velocity) of individual columns can be increased by a factor of about 5 and the shear modulus by a factor of 25. However, as LC columns are installed in groups (clusters, panels or grids) and cover usually 25 to 50% of the soil volume, the overall dynamic stiffness is lower. Thus, it can be difficult to predict the dynamic response of the embankment-foundation system without detailed site investigations or field measurements. Fig. 1 shows as an example two different applications of lime cement columns for vibration mitigation: as reinforcement below an embankment and as a barrier between the embankment and a building. The experience from using narrow rows of lime-cement columns as vibration barriers has been inconclusive. Numerical analyses were used by [2] to predict embankment vibrations and the results were compared with field measurements. The study presented by [2] focused mainly on the stiffening effect of lime-cement columns below the embankment.

Typical vibration records prior to and after improvement of the soft clay below the railway embankment are shown in Fig. 3. The peak particle velocity was about 52 mm/s before remedial measures were implemented. After installation of the about 10 m deep LC columns with a diameter of 0.60 m, which covered approximately 35 percent of the soil volume, the peak particle velocity decreased to about 6 mm/s.

The effect LC column stabilization on the frequency content is shown in Fig. 3. The vibration-reducing effect is highest at lower frequencies, where the largest vibration amplitude occurred.

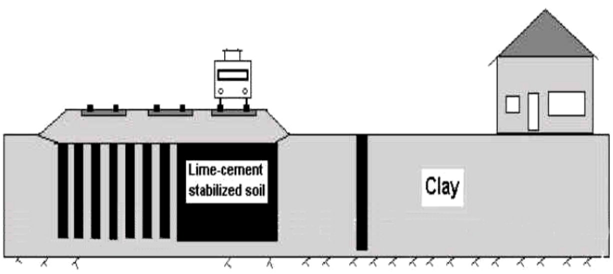
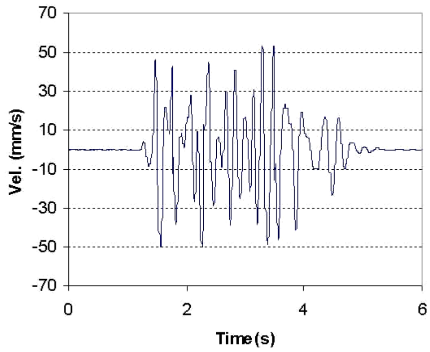
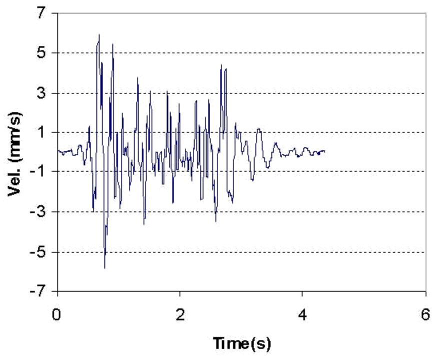


Fig. 1. Vibration reduction at Ledsgård, using lime-cement stabilized soil [2].



a) Before ground improvement



b) After ground improvement

Fig. 2 Time history of particle velocity at 7.5 m from the midpoint of the track, before (a) and after (b) Lime-Cement Column stabilization, train X 2000, train speed 190 km/h [2].

The isolation effect depends on the frequency and a marked increase of embankment response can be observed in the frequency range from 12 to 25 Hz. The resonance frequencies of many structural elements, such as building floors, are within this frequency interval. Thus, increasing the stiffness of the soil below the embankment may have a beneficial effect on the track displacements but be less effective to reduce ground vibrations propagating into the sourroundings. This aspect should be considered when planning to reduce vibrations by ground improvement measures.

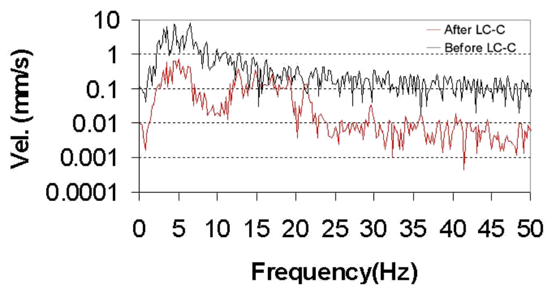


Fig. 3. Particle velocity in frequency domain at 7.5 m from the track, before and after Lime-Cement Column (LC-C) stabilization, train X 2000, train speed 190 km/h [2]. Note the logarithmic amplitude scale.

Foundation stabilization can be difficult to apply at existing railway lines, as they require the removal of the existing embankment. However, this method can be cost-effective when planning new railway lines.

Buffer Zones

Creating buffer zones at the planning stage is the most economical method of controlling the vibration impact. A similar approach is to negotiate a vibration easement from the affected property owners. However, this aspect of vibration mitigation can usually be applied only during the planning stage of projects or be used when establishing zoning (land use) plans. Developing buffer zones requires knowledge of how vibrations from railway traffic are emitted and in which way they affect buildings, installations and humans residing in buildings. Unfortunately, consequences of vibration problems are generally taken into consideration only when claims or complaints have already occurred. At that stage, when conflicts already exist, remedial measures or alternative solutions are often difficult to find and more costly, as if they were taken into consideration at the planning stage.

Building Modifications

The dynamic response of buildings and building elements depends on a complex chain of interacting factors, including the dynamic characteristics of the vibration source, the wave propagation (and thus geotechnical and soil dynamic) conditions between the source and the affected building, the foundation situation of the building and the dynamic characteristics of the building and of structural elements (floors, walls and installations).

Under special circumstances, it can be practical to modify an affected building to reduce the vibration levels. Vibration isolation of buildings consists of supporting the building foundation on elastomer pads similar to bridge bearing pads. Vibration isolation is seldom an option for existing buildings. However, building vibration isolation can be particularly important for vibration-sensitive industrial facilities or office space above a train station or terminal. When vibration-sensitive equipment such as electron microscopes will be affected by train vibration, specific modifications to the building structure may be the most cost-effective method of controlling the impact. For example, the floor upon which the vibration-sensitive equipment is located could be stiffened and isolated from the remainder of the building.

WAVE BARRIERS

Use of trenches and walls to control ground-borne vibration is similar to controlling airborne noise with sound barriers. Although this approach has not received much attention, a trench or wall can be a practical method for controlling ground-borne vibration. Trenches and walls can reduce ground vibrations even at existing railway lines, as their installation does not affect its operation. Extensive theoretical knowledge is available to design walls, infilled (gas-filled) trenches and open trenches [3, 4, 5, 6]. However, few details have been published about their practical application. An important limitation of information presented in the literature is the lack of well-documented case histories, providing sufficient background information to objectively assess the vibration isolation effect of specific measures.

As trenches and walls have a potential for solving vibrations from railway traffic, they will be discussed in detail below. Wave barriers, such as open or infilled trenches or walls, can be installed either in the vicinity of the vibration source (active isolation) or adjacent to the buildings to be protected. Isolation barriers should, if possible, be installed as close to the vibration source. If this is not possible or practical, the barrier should be installed in the close vicinity of the building to be protected. In this case, it may be necessary to extend the screen also along the sides of the building. The length of the barrier needs to be determined based on detailed vibration studies, which should establish the wave propagation path in different directions from the source.

The concept of wave barriers is based on reflection, scattering and diffraction of vibration energy. Different types of isolation barriers have been used, such as open or slurry-filled trenches, sheet piles and concrete walls. Comprehensive descriptions of the theoretical concepts and studies of ground vibration isolation measures have been presented by [3, 4 and 7].

When designing wave barriers, it is important to establish, which frequencies are causing problems. In many cases, resonance effects can amplify vibrations in structural elements or on building floors. Therefore, it is important to establish as a first step these critical vibration frequencies. The next step is to determine the frequency content of the ground 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) must be determined preferably by seismic field measurements (SASW, surface wave, down-hole or cross-hole tests). The depth of the vibration isolation barrier should be sufficient to eliminate the frequency which causes the actual vibration problem. Usually, the isolation barrier shall have a depth corresponding to the wave length of the disturbance.

Isolation effect of infilled trench (wall)

In most cases, solid wave barriers consist of concrete as infill material. Reference [4] conducted studies of stiff isolation barriers, using the Finite Element method. He introduced the normalized dimensions *T, B* and *R,* as shown in Fig. 4. Experience from barriers using ground improvement methods (deep mixing) have until now been inconclusive.

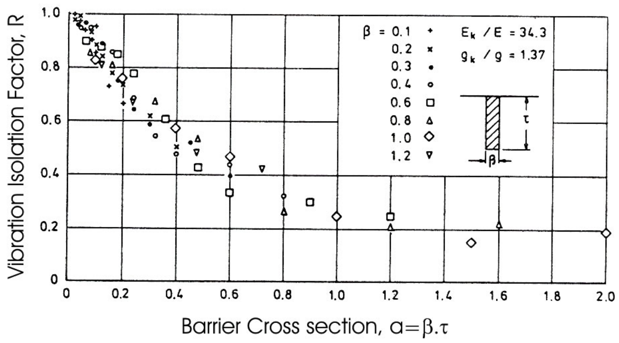


Fig. 4. Calculated vibration isolation (relative vibration amplitude, v/v_{max}) effect for stiff barriers (concrete) with different cross-sections, from [5].

The ratio E_k/E defines the stiffness difference between the barrier material $\underline{E_k}$ and the soil E. Similarly, the ratio g_k/g defines the difference in density between the barrier material and the soil. The values assumed in Fig. 4 correspond to a concrete barrier. References [5, 6] considered also irregular cross-sectional shapes of the barriers and different infill materials. A considerably better screening effect is achieved with active than with passive isolation. An important aspect is the fact, that in the case of stiff barriers, not only the depth T of the barrier is an essential parameter, but also the width B. In the case of stiff obstacles, it has been found that the decisive parameter governing isolation efficiency is the product of width and depth. The barrier width, B and depth T are normalized by the wave length,

$$\beta\,\tau = (BT/\lambda^2) \tag{1}$$

From Fig. 4, it can be concluded that the amplitude reduction depends strongly on the cross-sectional area, $\beta\,\tau$ while the shape of the barrier appears to have less importance. Thus, based on this investigation, a wall with small width, such as steel sheet piles, has only limited effect on the horizontal vibration amplitude but may reduce to some extent the vertical vibration amplitude. The results from the model tests indicate also, that the mass of the obstacle is an important parameter for the isolation effect. This may explain the limited vibration isolation effect of barriers created by ground improvement (deep mixing).

Isolation effect of open trench (stationary source)

Several analytical investigations of the isolation effect of stiff and flexible barriers have been reported in the literature. References [3, 4, 5, 6] have presented results from model tests using stiff and open trenches. Vibration isolation tests were also performed by [7], using slurry-filled trenches. Since shear waves cannot propagate through this fluid, these trenches, if located in the far field of a wave source, are to be considered as open trenches rather than solid barriers. Reference [3] has obtained almost identical holographic isolation patterns at an open trench and also when using trenches filled with bentonite slurry. The highest isolation effect is obtained in a zone, immediately behind the open trench, which decreases with increasing distance behind the screen. Reference [4] compared model tests in sand with the theoretical determined isolation effects. Fig. 5 shows the reduction in vibration amplitude as a function of the relative trench depth, where d is the trench depth and L is the wave length. In the experimental investigations carried out by [5], most of the tests were performed at a distance of 3 m from the wave source to the barrier. The relative trench depth τ is defined by the ratio of the trench depth and the wave length, λ. The amplitude reduction of the harmonic vibration was measured at small intervals along the radius of symmetry. Reference [8] reported that the normalized amplitude was always much lower immediately behind the trench than at a greater distance. This nearby region obviously represents the wave shadow of the trench [3].

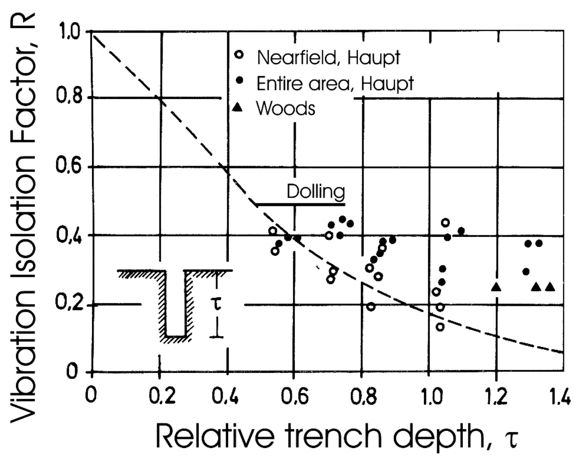


Fig. 5. Comparison of theoretical isolation effect of open trench and results of model tests, by [3, 4 and 8]. Isolation effect expressed as relative amplitude, v/v_{max}.

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 reference [8] are frequently used to estimate the isolation effect and required depth of an open trench. The relative vibration amplitude (isolation effect R_A) is expressed as the relative vibration amplitude and can be determined from

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

where A_{fa} and A_{fb} are the vibration amplitudes after and before the implementation of the vibration isolation measure. 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. The wave length λ is calculated from:

$$\lambda = \frac{c}{f} \quad (4)$$

where c is the wave propagation velocity in the ground of the predominant wave, for instance the Rayleigh wave and f is the predominant frequency, determined for the vibration measurements.

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 the wave length corresponding to 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 isolation effect of gas-filled cushions is similar to that of open trenches. 4) the trench width has little importance. 5) at the front face of the trench, part of the R-wave energy is reflected and may give rise to increase vibration levels.

Determination of Vibration Isolation Effect

In the literature, different methods are used to express the isolation effect. Frequently, an arbitrarily chosen amplitude value (vibration velocity or acceleration) is compared with an equivalent value after implementation of isolation measures. In the time history of a vibration record, a “peak value” or an arbitrarily chosen “average value” of the vibration amplitudes can be difficult to define. In many cases, well-documented vibration measurements do not exist for comparable sources (same train at same speed), thus vibration records can be difficult to analyze and compare. Such an approach is subjective and does not take into account the influence of vibration frequency (wave length).

A more appropriate method is to evaluate the vibration isolation effect in the frequency domain. The following example illustrates how the vibration isolation effect can be determined in the frequency domain. From the vibration record before and after installation of an isolation barrier, the respective frequency spectra are calculated, cf. Fig. 6.

The frequency range, which is of concern for the affected structure(s) (e.g. floor frequencies), is identified. The ratio of the vibration amplitude after and before isolation can readily be determined from the frequency spectra, and is called the relative vibration amplitude, cf. Fig. 4 and 5. It is important to note 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.

GAS CUSHION METHOD

In order to achieve vibration isolation, it is necessary to create an abrupt change of impedance in the ground.

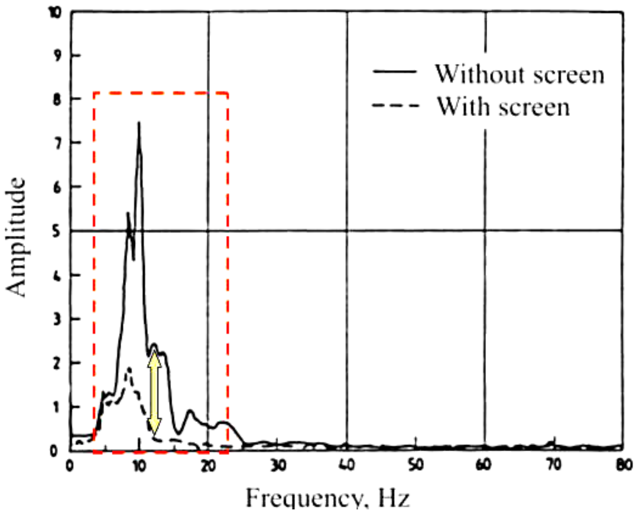


Fig. 6. Determination of vibration isolation effect from frequency spectrum of vibration signal. Gas cushion screen in soft plastic clay, [9].

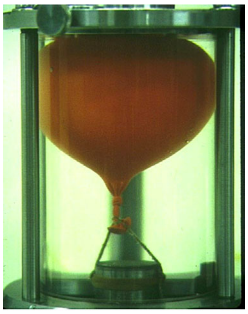
The most efficient isolation screen is an open trench in the ground. However, open or liquid-filled trenches are difficult to use in practice, and in particular in built-up areas. Initially, tests were carried out with light-weight material, such as styrofoam panels. However, when subjected to compressive stresses comparable to the lateral earth pressure which exists after installation in the ground, even light-weight material changed its dynamic properties and lost much of its vibration isolation effect. The density as well as the stiffness (wave velocity) increased with increasing pressure. Thus, a screen had to be developed which can resist the high lateral earth pressure without changing its damping properties (impedance).

The gas cushion method offers makes it possible to create a flexible barrier to great depths, which has a very low impedance (low density and low wave velocity), and can resist the later earth pressure. Such a flexible barrier has a vibration isolation effect which is comparable to an open trench. The first generation of the gas cushion screen was developed in Sweden about 20 years ago. References [9, 10, 11 and 12] describe the initial tests and practical applications.

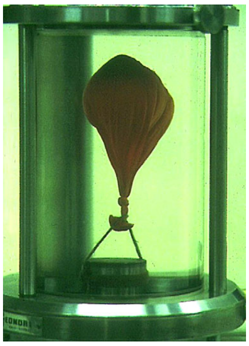
The objective of the gas cushion system is to create a permanent vertical barrier with low impedance. This is achieved by installing panels of flexible, gas-inflated cushions vertically in the ground. The gas cushion screen consists of horizontally arranged, gas-inflated tubes, which consist of a thin-walled plastic-aluminium foil. In order to provide a continuous gas-filled screen, two layers of vertically overlapping gas cushions are placed adjacent to each other.

The principle of the gas cushion concept can be illustrated by the following experiment. If a rubber balloon is inflated, its volume increases with increasing pressure, Fig. 7a. When the balloon is surrounded by water with a higher pressure than the initial gas pressure in the balloon, its volume will decrease, cf. Fig. 7b.

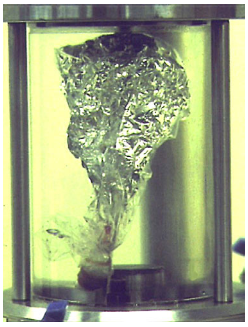
The balloon will assume a water drop shape and pressure equilibrium exists on either side of the rubber membrane. When the external pressure is further increased, the volume of the balloon shrinks but pressure equilibrium remains. As the pressure difference is small between the surrounding water and the gas inside the balloon, the diffusion rate will be very low. In order to further reduce the gas diffusion, the membrane can be surrounded by a metal foil (aluminium), Fig. 7c. As can be seen, the membrane of the balloon and the aluminum foil are completely unloaded due to the reduced volume of the balloon.



a) Inflated rubber balloon with excess pressure.



b) Due to water pressure, the volume of the inflated rubber balloon decreases and pressure equilibrium exists. The membrane is completely unloaded.



c) Aluminium foil surrounding inflated balloon for diffusion reduction

Fig. 7. Illustration of gas cushion principle.

The gas cushion is manufactured of a thin, multi-layered plastic-aluminium foil, similar to material used in the food packaging industry. 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. 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.

An important aspect of the gas cushion screen is that the pressure inside the gas cushions must always be lower than the ambient pressure after installation, resulting in a volume reduction of the cushions.

The gas cushion screen was used successfully on several projects in Sweden, Belgium and Germany, [10, 13, 14, 15].

Fig. 8 shows the installation of the first generation of the gas cushion screen in Sweden. A residential building had to be protected from railway-induced vibrations. The soil consisted of loose silty sand and the ground water level was close to the ground surface. A 6.5 m deep screen was installed between a railway track and a residential building. The depth of the screen corresponded to one wave length.

The first generation of the gas cushions used a timber frame, which was pushed into a bentonite-filled trench. Following installation of the gas cushion screen, the building floor vibrations could be reduced by more than 70% and was considered very successful, as all other alternative solutions would have been very costly. This first project was carried out in 1984 and is the oldest, still functioning isolation project using gas cushions.

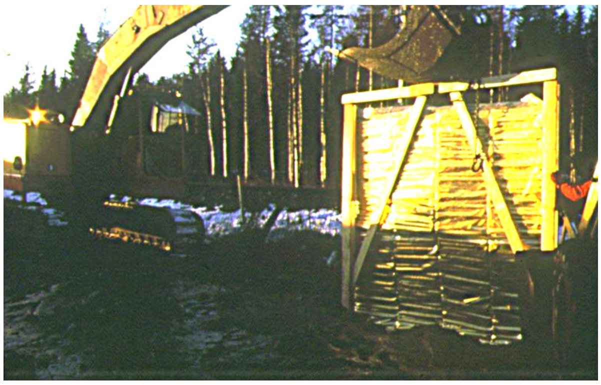


Fig. 8. Installation of the first generation of the gas cushion screen at Gnarp, Sweden (1984) [9, 10].

In the second generation of the gas cushion screen, which was developed in Belgium from 1986 to 1990, the gas-filled cushions were inserted in pockets of a woven geotextile, Fig. 9.

Fig. 9. Installation of gas cushion screen in Ghent, Belgium, using a woven geotextile (1988) [11, 14].

Each cushion was provided with an inflation valve, in order to assure that the cell pressure could be varied depending on the installation depth of the panels. Thus, the cell pressure was always lower than the ambient pressure in the ground. The cushions were assembled into panels and installed according to the slurry trench method, cf. Fig. 9. The panels can either be 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, provided a protective layer and assured chemical protection and long-term stability.

The most recent development of the gas cushion screen (third generation), is based on experience from a previous isolation projects, and is shown in Fig 10.

The gas cushions are manufactured of a specially developed, five-layer plastic-aluminium laminate foil, which has high mechanical resistance and gas-tightness. Inflation of the individual cells is achieved using a patented process, which does not require valves in the individual cells. This simplifies manufacturing and installation of the gas cushion screen.

An important new development is that the gas cushion panels are attached to prefabricated concrete panels. Attaching the gas cushions to concrete panels has several advantages: the weight of the concrete compensates the buoyancy of the gas cushions during insertion in the slurry-filled trench; the panels provide a stiff vertical barrier with an additional impedance change; the concrete panels can carry vertical loads, for instance when installed in areas with heavy traffic; 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).

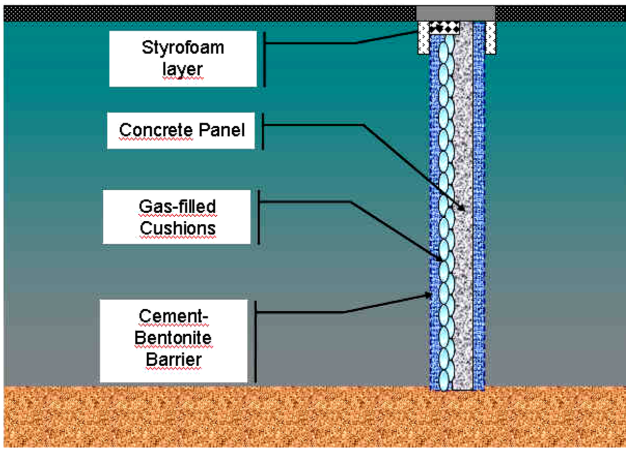


Fig. 10. Third generation of gas cushion system, with flexible cushions attached to stiff, prefabricated concrete panel.

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.

Field experience and laboratory tests have shown that the gas cushion panels, when properly designed and installed, can have a life length in excess of 20 years.

Case History

The gas cushion screen was used on a project north of Düsseldorf, Germany to protect two-story residential buildings against excessive 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) [11]. 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 proposed by [5] were used to establish the required depth of the isolation screen, cf. Fig. 5.

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 10 to 15 Hz and corresponded to the resonance frequencies of the building floors. Thus, the depth of the isolation screen corresponding to one wave length was 12 m. 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 described by [15]. Fig. 11 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.

a) Mounting of the gas-inflated screen prior to installation

b) Covering of hardened cement-bentonite filled trench with styrofoam

Fig. 11. Installation of the gas cushion screen adjacent to a railway track in Düsseldorf, Germany.

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 must be properly protected by a layer of styrofoam, which provides an isolation barrier close to the ground surface and provides temperature isolation of the cushions.

The measured isolation effect after installation of the gas cushion screen corresponded to the amplitude reduction values shown in Fig. 5. 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

The vibration isolation effect of the gas cushion screen has been investigated in different soil types and various applications. It was found that the measured isolation effect is in good agreement with the results reported by [3,4,7, 18] and is comparable to that of an open trenches, [16, 17]. Fig. 12 shows the isolation effect of the gas cushion screen from full-scale projects in different soil conditions. The isolation effect was determined in the frequency domain as illustrated by Fig. 6. The relative vibration amplitude (ratio after and before isolation) is shown as a function of the relative depth. The depth was normalized by the wave length in the same was as the test results presented Fig. 5. In Fig. 12, also the relationship proposed by [7, 18] are shown.

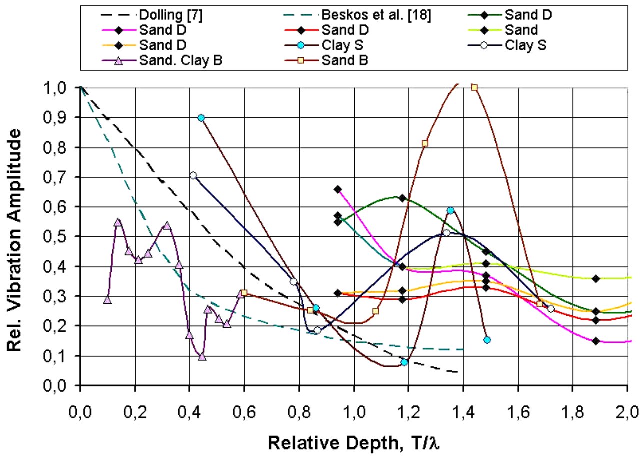


Fig. 12. Isolation effect of gas-filled cushions in different soils and vibration sources, [15, 16, 17].

The measured amplitude reduction (isolation factor) agrees well with the results reported by [4, 7] and the theoretical investigations by [16]. If the screen extends at least to a depth corresponding to one wave length, then an isolation effect between 50 and 80% 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 increasing relative depth, where the vibration frequency and the vibration amplitude are low, and the frequency spectrum shows variations.

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.

It can be concluded that in most cases, the isolation effect is about 60 to 80 % when the screen depth corresponds to one wavelength. At increasing relative depth the frequencies are usually high and the accuracy of the measurements decreases. It can be concluded that the isolation screen depth should be not less than one wavelength, which confirms the investigations reported above.

CONCLUSIONS

Vibrations caused by vehicle and rail-bound traffic can be complex and difficult to analyze. Different mitigation measures can be used at or adjacent to the source, in the ground or in affected buildings. The most efficient mitigation methods are available at the planning phase of a project.

Increasing the stiffness of the embankment and of the foundation material below the embankment can reduce the deformations at the source. However, vibration amplification can occur within a frequency range, which can have negative effects on buildings in the vicinity. Stiff or flexible barriers can be used to reduce ground vibrations.

The most efficient vibration isolation method is to install an open trench close to the vibration source (active vibration isolation). However, open trenches are not practical in populated areas. The gas cushion screen consists of flexible cushions, which are installed permanently in the ground. The isolation effect is comparable to that of an open trench.

ACKNOWLEDGMENTS

Many individuals and organizations have participated in the development of the gas cushion system. Their effort and many contributions are acknowledged. The initial investigations were performed at the Royal Institute of Technology (KTH) in Stockholm and in cooperation with the Swedish Railway Authorities (Banverket). Mr. G. Wallmark of Banverket played an important role during the initial applications of the gas cushion system. Extensive field tests were carried out with support by the Belgian research organization CSTC. The review of railway-induced vibrations was carried out as part of a research project, PrognosVib, funded by the Swedish Railway Administration (Banverket). The valuable contributions of the project team, and in particular the contributions by Dr. A. Bodare, (KTH), R. Rosén (Golder Associates) and A. Smekal (Banverket) are acknowledged. The most recent development of the gas cushion system was financially supported by ALMI Företagspartner and the Stiftelsen Innovationscentrum, SIC. The guidance and encouragement by Prof. K. Mickos and J. Stark was most important and a valuable source of inspiration.

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