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A REVIEW OF STRATEGIES TO CONTROL MANMADE INDUCED GROUND VIBRATIONS

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Abstract

Ground-transmitted waves generated by machine foundation, traffic, or blasting may result in ground vibrations, causing distress to adjacent structures and disruption to the operation of nearby sensitive machinery. Most of the vibratory energy affecting nearby structures is carried by surface waves that propagate in a zone close to the ground surface. Therefore, it is possible to reduce the ground vibration significantly by placing a suitable isolation system beneath the surface of the ground. This paper presents the findings of an investigation of different vibration isolation systems including floating slab tracks (FST), wave impending barriers (WIB) and trenches, which have been used to reduce the effects of machine foundation and traffic induced vibrations on nearby structures.

INTRODUCTION

Railway trains have been a major form of public transportation in the world for more than one and half centuries [1]. A wide variety of railway systems exists in the world, ranging from traditional weight freight and express passenger lines to modern metropolitan subways and high-speed railways. Different types of railway system should meet different safety and environmental requirements. Even though advanced transportation systems, such as airlines, have made rapid progress in the last half-century, the status of railways as a key transportation vehicle remains the same [1].

Unbalanced forces developed in machinery may result in significant foundation vibrations. Waves generated by trains and machine foundations may cause distress to adjacent structures and sensitive machinery. The disturbance introduced into residential and sleeping accommodation by an underground railway. Trains can be more intolerable than that caused by others forms of transport because it is often unexpected and has arisen from an unseen source [2]. One is prepared to tolerate some disturbance from road traffic as one has very likely travelled by road to the residential accommodation and this is remembered. The noise from aircraft is tolerated, except perhaps by those living close to a major airport, because there is something inevitable about it and the aircraft is rather remote. When an underground railway creates sufficient ground vibrations that the occupants in an adjacent building can hear the trains and possibly feel the vibrations, however short the duration may be, an element of the unexpected is introduced. The source of such a disturbance is somewhere below the building, near its foundations and thus close by, not remote as with an aircraft. There is sometimes an element of fear involved in that it is thought the vibrations may cause structural damage. The trend towards lightweight and framed structures with continuous floor slabs means that buildings are becoming dynamically more “alive” and hence there is a greater possibility of a resonant response.

Vibrations can be amplified by the passage of trains due to the surface irregularities of wheels and rails, by the rise and fall of axles on rails resting on sleepers and by the propagation of deformation patterns in the track and ground. Such vibrations are transmitted through the track structure, including the rails, sleepers, ballast and sub-layers, and propagate as wave through the soil medium, after which they can be sensed by the people living alongside the railway or over a tunnel through which a railway passes. Four phases in the process of the transmission of vibrations are: generation, transmission, reception and interception. During each phase, various factors can affect the final vibration levels to different degrees. The main factors involved include the train type, train speed, embankment design, ground condition, building foundation, building type, and the distance between the railway and buildings [1].

ISOLATION OF VIBRATION

To isolate ground vibrations a number of methods have been developed during the past few decades. The most common methods include floating slab tracks for railway vibrations, wave impeding barriers and the installation of trenches. Other possible methods include in the case of tunnels, increasing the tunnel depth and, in the case of railway, using ballast layers and resilient wheels.

Floating Slab Track

Floating slabs, which consist of concrete slab tracks supported on resilient elements, have been widely used in modern rail transit systems [3]. It is well known that greater effectiveness can be achieved in reducing ground vibrations when the vibration frequency exceed 1.414 times the resonance frequency of the floating slab system. Resilient pads support the floating slab system. However, when the frequency is equal or close to the resonant frequency, vibrations will be greatly amplified. Designs which employ floating slab tracks assume the existence of a single-degree-of-freedom system, in which the lumped mass includes that of the floating slab and the unsprung mass of the train, and in which the spring stiffness is determined by the supporting resilient pads. In order to increase the effectiveness of the floating slab track, that is, to lower the resonant frequency, the mass of the floating slab should be made as large as possible, as the resilient pads have to maintain a minimum level of rigidity to ensure rail stability under full axle loads [1].

Many devices can be used as resilient elements. These can be: a rubber or steel spring under the rail, the ballast, a resilient element under the sleepers or the plates that support the rail, or a foam rubber under the ballast. The best results are obtained when the resilient elements are made as soft as safety considerations allow them to be, and when the mass between the rail and the resilient element is made as large as space [4].

In the high frequency range, a floating slab track system behaves as an effective vibration isolator [5]. A floating slab track system is also effective for cut-and-cover type of construction. A design approach has also been proposed for a floating slab track inside a bored tunnel without the need to increase the tunnel diameter [2].

High vibration attenuation levels can be reliably achieved with well designed, low-tuned floating track beds, supported on steel springs. Long slabs or troughs provide advantages in terms of construction, installation and performance. The springs are generally accessible. They allow fast and easy re-adjustment of deviated track levels. Being fatigue-proof and provided with a durable anti-corrosion system, the springs are designed for a long lifetime [6].

Floating slabs were effective in isolating train induced ground vibrations in the frequency range above 20 Hz, although floating slabs can be designed to extend the effectiveness to lower frequencies [3].

Wave Isolation Using a Wave Impeding Block

A wave-impeding block (WIB) is an artificial stiff plate installed at a certain depth below a vibration source that acts as artificial bedrock. A WIB can effectively reduce ground vibrations due to trains but wave propagation into the surrounding area cannot be much impeded because the artificial bedrock also vibrates. The effectiveness of the artificial bedrock can be improved by increasing its stiffness. Shielding a building from soil vibrations can also be achieved by installing artificial bedrock directly beneath the building [1], [7], [8].

Wave Isolation by Trenches

Ground vibrations due to man-made sources, such as traffic and machine foundations, and ground vibrations due to TBMs can be a major problem in densely populated urban areas and for structures which are housing sensitive equipment. The environmental effects of vibrations have received considerable attention in recent years owing to the damage they can cause, both to buildings and people. In many countries new rules and regulations have been introduced to control vibrations [9] for example BS 7385 in the UK and DIN 4150 in Germany. Therefore, screening of vibrations induced by traffic and construction activities has become an important issue in recent times and it has been shown that it is possible to reduce the ground vibration significantly by placing a suitable wave barrier in the ground. Wave barriers are often installed in the ground to reduce ground vibrations induced by man-made sources such as traffic and machine foundations [10].

The methods of vibration isolation for soil-structure interaction systems may be classified into two families: active isolation and passive isolation. Active isolation, also known as source isolation, refers to the installation of barriers at a distance so close to the wave source that energy transmitted from it can be directly cut off or to the installation of barriers surrounding the vibration source [11]. Passive isolation, also known as receiver isolation, involves placing suitable barriers in the ground between the source and the structure or surrounding the structure [12]. An active isolation barrier can effectively isolate stationary sources of vibration, whereas a passive isolation barrier is effective for a wide variety of wave generating sources, including moving sources. Different kinds of wave barriers, among them open and backfilled trenches, are the most common in practical applications as they are most effective and their installation cost is low. The ratio of the shear wave velocities of the barrier and the soil is one of the important parameters that govern the screening efficiency of a backfilled trench barrier and a backfill material that is soft with respect to the surrounding soil, generally performs better than a stiffer material [13], [14].

Much research, both experimental and numerical, has been carried out in the past few decades to study the effectiveness of wave barriers for reducing ground vibrations. An analytical approach has rarely been used because closed-form solutions are extremely difficult to obtain, except for very simple geometries and boundary conditions that rarely exist in practice. While full-scale experimentation is expensive to carry out, small-scale model test results can be difficult to extrapolate to prototype situations. An efficient numerical technique, on the other hand, can be an effective alternative method for conducting a thorough investigation into the vibration isolation phenomena [12], [15], [16].

Using field tests, Barkan [17] investigated the screening of waves by means of a trench and found that the amplitude of the waves decreased the depth of the trench was increased. Woods [18] also carried out a series of field test on vibration isolation by installing open trenches from very close to the wave source to the far field and found that reduction in the amplitude of ground vibrations of up to 75% could be achieved.

In the previous few decades, many researchers have used several numerical techniques to study the vibration isolation problem. Ju [19] used three-dimensional finite element analyses with absorbing boundary conditions to investigate the isolation of structures from train-induced vibrations by means of soil improvement and open and infilled trenches. As a result of this research it was found that soil improvements near bridges did not significantly reduce low-frequency vibrations. Open and backfilled trenches could reduce vertical vibrations but their efficiency seemed disproportionate to their cost. Yang and Hung [11] carried out a parametric study of the use of open and backfilled trenches and elastic foundations for the reduction of train–induced vibrations and found that all three-wave barriers are suitable for screening vibrations associated with waves of higher frequencies. Segol et al. [20] used the FEM along with special non-reflecting boundaries to study vibration isolation by means of open and backfilled trenches in layered soils. They concluded that the width of the trench is insignificant. Lysmer and Wass [21] applied the lumped mass method to investigate layered soil systems as a means of reducing vibrations. Aboudi [22] carried out a combined perturbation-finite difference method analysis of the screening effect due to a thin barrier in a half space and suggested that an open trench barrier will yield the best results for screening purposes. Ju [23] applied the 3-D finite element method to simulate soil vibrations due to a high-speed train moving across bridges and investigated the screening of vibrations by means of open and backfilled trenches. Ju found that these trenches could not provide a barrier against low-frequency waves. Yang and Hung [24] proposed a 2.5D finite/infinite element procedure to model ground vibrations induced by moving loads. Besides the two in-plane degrees of freedom per node conventionally used for plane strain elements, an extra degree of freedom is introduced to account for out-of-plane wave transmission. The profile of the half-space was divided into a near field and a semi-infinite far field. The near field, containing loads and irregular structures, was modelled by the finite elements, while the far field, covering the soils extending to infinity, was modelled by the infinite elements, with due account taken of the radiation effects produced by the moving loads.

In recent decades, the boundary element method (BEM) has emerged as a very efficient numerical technique for solving a wide class of engineering problems. This method is especially well suited for wave propagation problems in soils involving a semi-infinite domain. A number of researchers have carried out 2-D and 3-D numerical analyses using the BEM to investigate the screening of vibrations by means of open and backfilled trenches and the use of different types of foundations to screen the vibration due to machines [12], [14], [15], [16], [25]. However, the BEM is not well suited for the modelling of irregular geometries. To overcome this problem, several procedures for coupling finite elements with boundary elements or finite elements with infinite elements have been proposed by a number of researchers [13].

CONCLUSIONS

A review has been carried out of different techniques to impede the vibrations due to trains and machines. The disturbance due to vibrations caused by a railway running through a residential area can be eliminated by boxing the railway in and by providing a floating track slab. However, care has to be taken to avoid slab resonance.

An open trench or a backfilled trench barrier are most effective for providing active isolation from vibrations due to a machine foundation. The reduction in the amplitude of ground vibrations depends not only on the depth of the trench, but also on the size of the foundation and the distance of the barrier from the source. The ratio of the shear wave velocities of the barrier and the soil is one of the important parameters that govern the screening efficiency of a backfilled trench barrier. Softer backfill materials yield a better screening effect than stiffer materials.

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REFERENCES

[1] H. H. Hung and Y. Yang, “A review of researches on ground-borne vibrations with emphasis on those induced by trains”, Proc. National Science Council, **25**, 1-16 (2001).
[2] P. Grootenhuis, “Floating track slab isolation for railways”, Journal of Sound and Vibration, **51**, 443-448 (1977).
[3] G. P. Wilson, H. J. Saurenman and J. T. Nelson, “Control of ground-borne noise and vibration”, Journal of Sound and Vibration, **87**, 339-350 (1983).
[4] M. Heckl and G. Hauck, Wettschureck, “Structure-borne sound and vibration from rail traffic”, Journal of Sound and Vibration, **193**, 175-184 (1996).
[5] T. Balendra, K. H. Chua, K. W. Lo and S. L. Lee, “Steady-state vibration of subway-soil-building system”, ASCE Journal of Engineering Mechanics, **115**, 145-162 (1989).
[6] H. G. Wagner, “Attenuation of transmission of vibrations and ground-borne noise by means of steel spring supported low-tuned floating track beds”, World Metro Symposium and Exhibition, Taipei, (2002).
[7] H. Antes and O. V. Estorff, “Dynamic response of 2D and 3D block foundations on a half space with inclusions”, International Journal of Soil Dynamics and Earthquake Engineering, **13,** 305-311 (2000).
[8] H. Takemiva and A. Fujiwara, “Wave propagation/impediment in a stratum and wave impeding block (WIB) measured for SSI response reduction, “International Journal of Soil Dynamics and Earthquake Engineering, **13**, 49-61 (1994).
[9] L. Hall, “Simulations and analyses of train-induced ground vibrations in finite element models”, International Journal of Soil Dynamics and Earthquake Engineering, **23**, 403-413 (2003).
[10] T. M. Al-Hussaini and S. Ahmad, “Design of wave barriers for reduction of horizontal ground vibration”, ASCE Journal of Geotechnical Engineering, **117**, 616-636 (1991).
[11] Y. B. Yang and H. H. Hung, “A parametric study of wave barriers for reduction of train-induced vibrations”, International Journal for Numerical Methods in Engineering, **40**, 3729-3747 (1997).
[12] S. Ahmad and T. M. Al-Hussaini, “Simplified design for vibration screening by open and in-filled trenches”, Journal of Geotechnical Engineering ASCE, **117**, 67-88 (1991).
[13] M. Adam and O. V. Estorff, “Reduction of train-induced building vibrations by using open and filled trenches”, Computers and Structures, **83**, 11-24 (2005).

[14] R. Klein, H. Antes and D. L. Houedec, “Efficient 3D modelling of vibration isolation by open trenches”, Computers & Structures, **64**, 809-817 (1997).
[15] S. Ahmad, T. M. Al-Hussaini and K.L. Fisherman, “An Investigation on active isolation of machine foundation by open trenches”, ASCE Journal of Geotechnical Engineering, **122**, 454-464 (1996).
[16] T. M. Al-Hussaini and S. Ahmad, “Active isolation of machine foundations by in-filled trench barriers”, ASCE Journal of Geotechnical Engineering, **122**, 288-294 (1996).
[17] D. D. Barkan, *Dynamics of bases and foundations.* (McGraw-Hill, New York, 1962).
[18] R. D. Woods, “Screening of surface waves in soils”, ASCE Journal of Soil Mechanics Foundation Division, **SM4**, 951-979 (1968).
[19] S. H. Ju, “Three-dimensional analyses of wave barriers for reduction of train-induced vibrations”, Journal of Geotechnical and Geoenvironmental Engineering”, **130**, 740-748 (2004).
[20] G. Segol, P. C. Lee and J. F. Abel, (1978), “Amplitude reduction of surface waves by trenches”, ASCE Journal of Engineering Mechanics, **104**, 621-638 (1978).
[21] J. Lysmer and G. Wass, “Shear waves in plane infinite structures”, ASCE Journal of Engineering Mechanics, **98**, 85-105 (1972).
[22] J. Aboudi, “Elastic waves in half-space with thin barrier”, ASCE Journal of Engineering Mechanics, **99**, 69-83 (1973).
[23] S. H. Ju, “Finite element analyses of wave propagations due to high-speed train across bridges”, International Journal for Numerical Methods in Engineering, **54,** 1391-1408 (2002).
[24] Y. B. Yang and H. H. Hung, “A 2.5-D finite/infinite element approach for modelling viscoelastic bodies subjected to moving loads”, International Journal for Numerical Methods in Engineering, **51**, 1317-1336 (2001).
[25] S. E. Kattis, D. Polyzos and D. E. Beskos, “Modelling of pile wave barriers by effective trenches and their screening effectiveness”, Soil Dynamics and Earthquake Engineering, **18**, 1-10 (1999).