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Guang-Yun Gao

*4th Design and Research Institute, Ministry of Machinery and Electronics Industry, China*

Xian-Jian Yang

*4th Design and Research Institute, Ministry of Machinery and Electronics Industry, China*

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**Guang-Yun Gao**
Senior Research Engineering Assistant Professor, 4th Design and Res. Inst. Min. of Mach. and Elect. Ind., China

**Xian-Jian Yang**
Senior Research Engineering Professor, 4th Design and Res. Inst. of Mach. and Elect. Ind., China

SYNOPSIS: A high sensitive and large semi—anechoic chamber, designed by a new system of isolation is reported in this paper. The combined isolation of a large size elastic plate on sand cushion and pile barriers was used in this system. By properly designing the stiffness of elastic base plate, the amplitude of the anechoic chamber floor under the action of dynamic load of testing vehicle can be controlled within the allowed range of accurcy. This new system has been conformed with the disturbance of outside of vibration on anechoic chamber ( passive vibration isolation)and with that of vehicle testing inside the anechoic chamber (active vibration isolation). The cost of the anechoic chamber designed by the new system has been reduced by 93%, compared with the traditional chamber, and also the period of construction was much shorter. It has been tested by the "Acoustics Research Institute of the China Academy of Science" that the background vibration of the anechoic chamber has met accurate requirement. It has been in use for quite a few years and great econmic benefit has been made.

## INTRODUCTION

A large-sized semi-anechoic chamber was built more recently, it has a net area of $14.2\times16.2m^2$ and requires high sensitivity. The strength of background noise is required less than 15-16 dBA and its background vibration (no areal source) less than the ground pulsation in daytime. In case of a vehicle testing, the amplitude of elastic plate is not more than 20 μm under the action of exciting forces which have different frequency. According to the traditional isolation program, this system is a block foundation on spring absorbers, as shown in Fig.1. If this system were used, it would have cost hundred thousands of dollars and the construction conditions would be very difficult. The performed plan chosen was a combined isolation foundation by elastic base plate and pile barrier, as shown in Fig. 2. The results were satisfactory and the huge funds of the project was cut a good deal and the constrution period was much shortened. Thus we provide some desiging experience, engineering calculating theory and practical designing method.

## PROPERTY OF SOIL AND SAND CUSHION

Soil: the surface layer is filled soil, 0.8～1.5m thick; the second layer is neo-loess, 1.5～6.5m thick, bearing capacity f=60～80 kPa; underneath is the non-collapsing, leoss-like silty clay, f=150～200kPa. the Rayleigh wave velocity was measured $V_R$=154m/s.

Sand cushion: the soil in test box was a dense medium sand, w=4.6%～5.1%, e=0.807, unit weight $\gamma=15kN/m^3$; mechanical composition: (1～0.5mm)30.5%, (0.5～0.25mm)34.3%, (0.25～0.10mm)30.6%, (<0.1mm) 4.6%, $V_R$=185.6m/s. In-situ test, e=0.500～0.540, $\gamma$=17.0～17.3$kN/m^3$, $V_R$=110m/s, the damping ratio was measured in vertical direction $D_z$=0.1755.

## VIBRATION CONTROL OF ELASTIC PLATE

Elementary hypothesis: considering sand cushion was taken under elastic plate, the plate dynamical response was according to Winkler's assumption.

Theoretical analysis and engineering design: as the elastic plate produces dynamical deflection, which must be accompanied by the dynamical deformationof the underlying half-space, at the same time, the steady state force of mass-spring system acts on the plate (see Fig.3), and the disturbing frequency approaches to the natural frequenay of the first three mode shapes. So the dynamical response of the rectangular elastic plate on half- space is more complicated than that of the stiff mass foundation ( Whifaker, W.L., Christiano, P.).

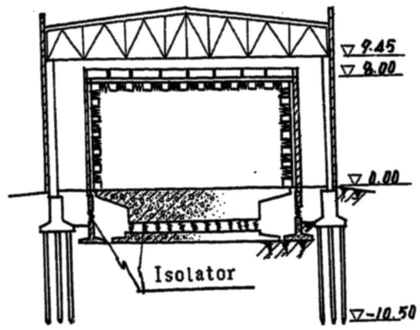



Fig. 1, The Traditional Isolation Programme of Semi-anechoic Chamber

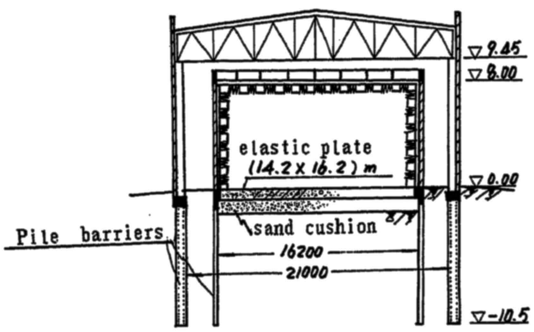



Fig. 2, Performed Isolation Plan of Semi-anechoic Chamber Was Elastic Plate on Sand Cushion and Pile Barrier (The cost of this system is reduced by 93% compared with traditional programme as Fig.1)

1. Relative stiffness of the plate, the proper choice of the stiffness of the plate is the key point in the control of plate vibration in the lab. under the influences of disturbing forces with broad frequency domain. This paper takes the following formula to estimate its relative stiffness (C.J.Qu. and Z.Y.Cao, 1988).

$$Kr=\frac{12\pi(1-\mu_p^2)}{1-\mu_s^2}\left(\frac{E_s}{E_p}\right)\left(\frac{a}{h}\right)^2\left(\frac{b}{h}\right) \qquad (1)$$

Where $\mu_p\approx0.17$; $\mu_s\approx0.30$; $E_s$=7.0MPa; $E_p=2.3\times10^4$MPa; plate length 2a=16.2m; wide 2b=14.2m; thick 0.8m. Then, from Eq.(1), Kr= 1.123>1, hence it is a flexible plate. Although Kr is larger than one, Kr is approximately equal to one, therefore the plate stiffness is still very large.

2. Natural frequency of plate, the plate natural frequency is estimated according to one-dimensional plate which approximates to the dynamic response of Winkler foundation. The error is corrected by the dynamic model testing. The error comes from two-dimensional space effect of the rectangular elastic plate and the selecting of soil dynamical parameter. The plate natural frequency is given by

$$\omega_{ni}=\sqrt{\frac{\Omega_i k_z}{\rho_p}} \qquad (2)$$

in which i=1, 2, 3, ......

$\rho_p$——unit length mass density of one dimensional plate($kNs^2/m^2$)

$k_z=C_zb$——unit length soil stiffness of the plate($kN/m^2$)

$C_z$——soil coefficient of stiffness ($kN/m^3$)

b——unit width of the plate(m)

$\Omega_i$——natural frequency coefficient of the plate for elementary three modes of vibration (G.B.Warburton, 1984).

As shown in Fig.3, the testing vehicle weight is 30kN, taking $C_z=3200kN/m^3$, and m=30/9.81=3.05 ($kN.s^2/m$). The elastic plate is calculated according to the above data and the plate sizes. The first three mode shapes natural frequency coefficient of the plate is $\Omega_1$=0.85, $\Omega_2$=1.50, $\Omega_3$=9.00. Then, from Eq.(2), $f_1$=18.38Hz, $f_2$=24.43Hz, $f_3$=59.85Hz.

3. Amplitude of plate, figure 3 shows that disturbing force $pe^{i\omega t}$ applied on the vehicle with a mass m makes an effort to the plate through the spring K. This exciting force is

$$p=\frac{K|A_i-y_i(o)|}{\beta_i},$$

being borne by the plate. This exciting system applied on the plate is,

$$K|A_i-y_i(o)|=\psi C_zFy_i(o)+M\omega^2_iy_i(o)=P\beta_i$$

Where i=1, 2, 3, ......

$\psi$——space effect coefficient both elastic foundation soil and the plate.

Then plate amplitude is

$$y_i(o)_{max}=\frac{P\beta_i}{\psi C_zF+M\omega^2_i} \qquad (3)$$

in which $\beta_i$——amplification factor for P in three modes of vibration, respectively (Warburton, G. B. 1984)

M——the plate mass

$F=2a\times2b=(16.2\times14.2)m^2$——the plate size.

In Eq. (3), both terms $M\omega^2_iy_i(o)$ and $C_zFy_i(o)$ are mass inertia force. The out of phase higher than second mode of vibration is neglected because the plate stiffness is large enough. The flexible plate effect component is included in dynamical amplification coefficient.

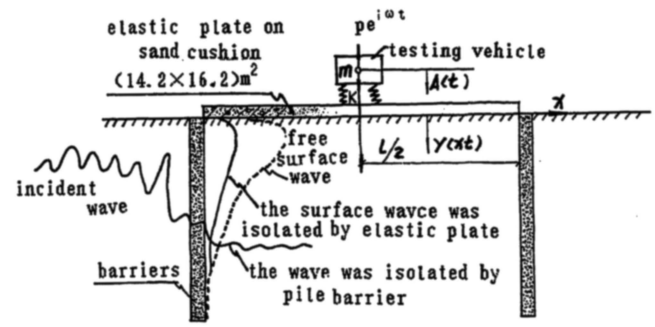



Fig.3, a).Calculation of Combined Isolation

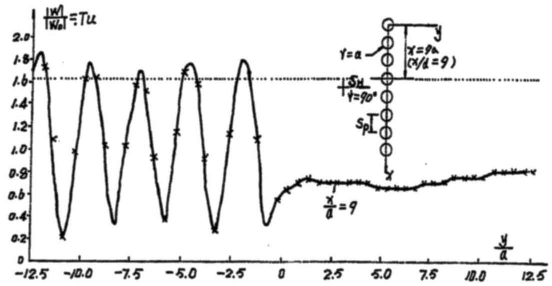



Fig.3, b).Normalized Amplitude Caused by Incident SH Wave ($x/a=9$, $d/\lambda_R=0.4$, $S_P=1.5d$, $\rho_S/\rho_P=0.75$)

The plate amplitude in case of disturbing frequency $\omega_1$.

By selecting $\psi=1.5$ in Eq .(3), $f_1=18.38H_z$. Then the disturbing force approximates to P=4000N, making the half-space a plane problem to get Cz value and simplifing two-way plate to one-dimensional plate, $\psi C_zF=1.5\times14.2\times16.2\times32000=11.042\times10^6$(kN/m), $M\omega^2_1=14.2\times16.2\times0.8\times25/9.81(2\pi\times18.38)^2=6.26\times10^6$(kN/m). In Fig.3, the coefficient 0.01 indicates the spring K, the plate and soil viscous damping are considered, thus $\beta_1=80$. From Eq.(3), we get $y_1(o)_{max}=18.5\mu m<20\mu m$ .

The amplitude in case of disturbing frequency $\omega_2$.

If $f_2=24.43H_z$, then P=10,000N is the corresponding disturbing force. $\beta_2=20$, the $y_2(o)_{max}=9.054\mu m<20\mu m$.

The amplitude in case of disturbing frequency $\omega_3$.

If $f_3=59.85H_z$, then P=22,000N is the corresponding disturbing force. $\beta=34$, and then $y_3(o)_{max}=11.279\mu m<20\mu m$.

## MODEL TESTING

The experiments were conducted in a sand box (brick wall) with the dimensions of 3.5×4.0 meters in plan and a depth of 1.0 meter, which was located in the lab. of the Fourth Design and Research Institute of the Ministry of Machinery and Electron . In order to prevent the disturbance by wave reflection, the PVC foamed plastics with 50mm thick was filled on the pond bottom and four sides of the wall. The soil was a dense mediun sand , its property in the foregoing discribed in sand cushion .

The measurements were performed on a model plate with dimension of 1.0×0.875m and a thickness of 0.04m, modeling the prototype plate with size of $16.2\times14.2\times0.8m^3$. From geometric similarity, the action force on the model plate, P=1N, corresponding to P=16N on the prototype plate. According to dynamic response similarity, the model plate natural frequency was approximately four times that of the prototype plate .

The exciting force were generated in the half-space model with an electromagnetic vibrator on the model plate. The vertical vibrating componant of the test block was measured by a vibration transducer, amplifier and recorder etc. were ordinary dynamical testing equipments .

Results of measurements, Fig.4 shows the first mode shape resonance frequenay of the model plate is 80Hz, which matches that of the prototype plate, 20Hz, approximating the same value of calculated frequenmcy, $f_1=18.38H_z$. In the center of the model plate (at testing point 2), in case of P=137.3N , the measured resonance max. amplitude was 2.5μm, the computing amptitude at this point was 2.925μm. The average damping ratio was $D_z\approx0.234$, but at the testing point, the measured damping ratio was rather large, $D_z=0.40$. The results showed that the measured and calculated amplitude coincided very well and confirmed that the calculated data by the simplified model might be used to this projeot designing.

## VIBRATION ISOLATION BY PILE BARRIERS

A vibrating source results in transmission of energy through the surrounding soil in the form of waves. A certain distance beyond the source, a major part of the eneryy is carried by Rayleigh waves, which travel near the ground surface and harmfully effect nearby structures, precision equipments and residents . One of the possible ways to prevent the effect is to use wave barriers. When the wavelength is long, it has been found as an effective method to use piles as isolation barriers in the ground environmental vibration. Compared with common open trenches, the pile barries can be installed to large sized depth and may have fairly good efficiency of vibration isolation. The isolation of vibrations by using piles is based on the scattering disturbance of the wave energy carried by the incoming wave fields. Fig. 3 provides theoretical numerical solution for scattering problem of a row piles as barriers with circular section (Guang Yun Gao, 1991). The calculated results show one row of piles can be effective in

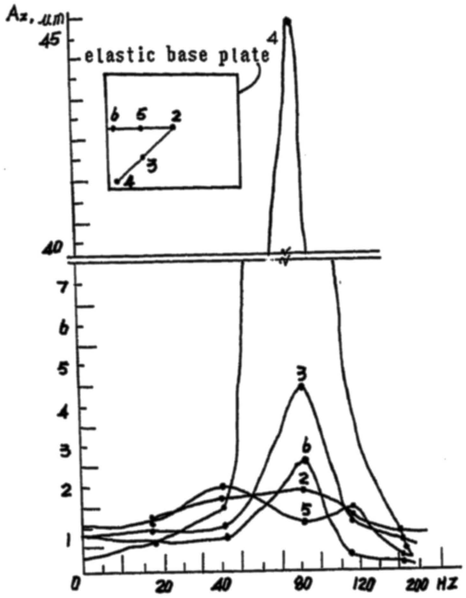



Fig. 4, Curve of Dynamical Response of Elastic Base Plate (model testing).

isolating ground vibratian as long as some conditions are met, which are that the diameter of the pile, the spacing between the piles, and the depth and length of the pile barrier system should be appropriate to the incident wavelength in designing. Further theorical analysis and test research can be seen in the references of X.J.Yang (1991) and G.Y. Gao (1991). This engineering made use of the foundation piles as passive isolating barriers, which originally were just used to bear the building of the semi—anechoic chamber. The pile diam. and the space between piles were set in the light of the demands of vibration isolation. The double row piles were employed to get more isolating effect. The barriers equivalent wave velocity of the multi—row piles was given by (X.J.Yang, 1991)

$$V_B = VS_D[(D/\lambda_R)/\Sigma\,\delta(1+T_p)]^{-1} \qquad (4)$$

in which V——shear wave velocity (near—field active isolation) or surface wave velocity (far—field passive isolation) of the soil

$D=(210\Sigma I)^{1/4}$——equivalent thickness per unit width of the multi—row piles

I——single-pile moment of inertia

$S_D=(S_p/S)+(D/\lambda_R)$

$S_p$——centrepoint space between two consecutive piles

S——net space between two consecutive piles unit

$\delta=1$ (no groundwater)

$$T_p=[S_d(1+\alpha_n)/(\lambda_R/d)]^{1/n} \qquad (5)$$

$S_d=S_p/S$

$$\alpha_n=(\rho_p V_P)/(\rho_S V_S) \qquad (6)$$

$\alpha_n$——impedanc ratio

$\rho_p$——mass density of pile material

$V_p$——longitudinal wave velocity in the pile material

$V_S$——shear wave velocity of soil medium

$\rho_S$——mass densiy of soil medium

$\lambda_R$——Rayleigh wavelength

n=1——for concrte or reinforced concrete pile

d——diameter of a pile

According to Eq.(4), getting the results, $S_p-S=0.8$m (average value), $\lambda_R=3.85$m (measured value), $V_p=4800$m/s, $\alpha_n=41.56$, $\Sigma I=0.074+2\times 0.021=0.1160(m^4)$, $D=(210\Sigma I)^{1/4}=2.1$(m), $V_B=18.05V=2780$(m/s), in which case $\alpha=(\rho_B V_B)/(\rho_S V_S)=21.066$, $(\omega B)/V_B=0.197$, where $\rho_B$— mass density of the equivalent barrier system of the pile and soil, ω——circular frequency of the environmental vibration, B=D+d=3.2m. Then from the reference of X.J.Yang, the transmission ratio of this system was $T_u=0.320$. This ratio is a measure of the effectiveness of an isolation barrier. A transmission ratio equal to zero indicates the incoming wave is completely reflected, or this value equal to 1 indicates the barrier is transparent to the wave energy. In the condition of Rayleigh wavelength $\lambda_R=3.85$m, the measured transmission ratio Tu was 0.250(<0.320). The other measurements on different $\lambda_R$ values were given by

| $\lambda_R$ | $H/\lambda_R$ | $T_u$* |
|---|---|---|
| 15.40 | 0.68 | 0.524 |
| 7.70 | 1.36 | 0.276 |
| 5.13 | 2.05 | 0.270 |
| 3.85 | 2.73 | 0.250 |

in which H——depth of the barrier, H=10.5 (as show in Fig.2).

*The measurments were conducted before sand cushion and elastic plate had not been constructed. The transmission ratioes, as provided herein, were merely the effectiveness of using piles as isolation barriers.

The above data show that, for ordinary low-frequency, in case of $\lambda_R=15.4$m, the vertical vibration reductive effect of the barrier is of the order of 50%. When the wavelength shorter than 10m, 70% to 75% of the vertical amplitude values are reduced by the barriers. The results are very ideal and beneficial to practical use.

## RESULTS OF COMBINED ISOLATION

Finally, the combined isolation system of elastic plate on sand cushion and pile barrier in soil was used in this project. After the large semi-anechoic chamber was built up, the effectiveness of this isolation system had been tested by the Acoustics Research

Institute of the China Academy of Science and soon later retested by the Luoyang Tractor Research Institute of the Ministry and Electronics Industry(P.R. China), the measured results being shown in Tab.1. The effectivenenss of the combined isolation has been confirmed by the practical measurments . For example , as the wavelength was about 7m~15m, with a large tractor passing through the room door of measurement of power, outside the barrier as shown in Fig. 5 , the measured acceleration value at this point was $5.25\times10^{-3} m/s^2$, the same value measured at the indoor floor plate was $1.20\times10^{-3} m/s^2$. The vibration transmission ratio was $T_u$=0.229. If there was no sand cushion and but merely pile barriers, the actucal measured value at the ground surface was $T_u$=0. 400. On condition that the reinforced concrete floor plate was constructed, the Tu value was reduced about 43% less than the former Tu. Another vibration isolating effect came from existence of the sand cushion damping and especially relativly good rigidity of the floor plate.

If a part of the incoming energy was transmitted through the soil with a lower wave velocity to the elastic plate with higer wave velocity ,a certain amount of the wave energy could be reflected and then travelled . This amount of reflection and transmission was partly absorbed by the sand cushion, its damping ratio was higher than the soil. The decreased vibrating energy was about 40% of the original, coincided with the measurements. Meanwhile, the above Tu values were measured in case of the floor plate surface ( thickness of 50mm) connected with the barrier ( demand is no connection of them in designs). After one side of the floor surface was sawed off, the values of Tu was further decreased about 6% . If all sides of the surface were totally sawed off , the still more better results would be obtained .

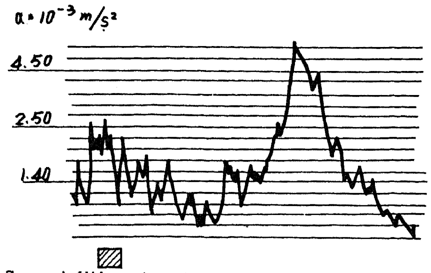
Without external exciting sources, in this engineering project, the background vibrating acceleration was $(1.0\sim1.1)\times10^{-3} m/s^2$. Under the background frequency of $15H_z$, the amplitude of vibration was 0.113~0.124 μm .It would be smaller than that of 0.30~0. 35 μm in case of the larg size trucks passing through the main road in daytime and the disturbing of the strong vibrating equipments working in manufacturing district . If there was not any external disturbing , the background noise level was 16dBA. This value is the best up till the present in the domestic large scale noise chambers. If the floor plate surface were completely separated from the isolation barrier according to the demands of the design, the background vibration and noise would be further reduced .

This anechoic chamber has been put into use for a few years. On the testing vehicle driven at full speed, and at different disturbing frequencies, the amplitude of the anechoic chamber floor has not exceeded allowable value. As a result, this new successful vibration isolation system has been achieved.

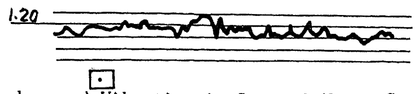
TABLE 1. Measured results of the plate vibration and noise in semi— anechoic chamber *

| No. | Exciting Sources | Exciting Position | Floor Plate Condition | Measured Position | Acceleration ($m/s^2$) | Amplitude of Vibration ( μm) | Indoor Noise Level (dBA) | Remarks |
|---|---|---|---|---|---|---|---|---|
| 1 | Four large tractors | At the four corners of the lab. | The plate surface connected with the ground isolation barrier | Indoor floor plate near to the door | $1.26\times10^{-3}$ | 0.142 | 20.5 | |
| 2 | A large tractor | Passing through the room door of measurment of power | Do | Outside of isolation barrier, near to the exciting source | $5.25\times10^{-3}$ | | | |
| 3 | Ditto | Do | Do | At the indoor floor plate | $1.20\times10^{-3}$ | 0.135 | | |
| 4 | No disturbing source | | Do | Do | $1.10\times10^{-3}$ | 0.124 | 17~18 | Background vibration and noise |
| 5 | Ditto | | The plate surface no connected with the isolation barrier in one side only | Do | $1.00\times10^{-3}$ | 0.113** | 16*** | **Conversion value<br>***Measured value |

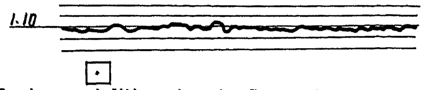
* Note, These listed results were provided by the Acoustics Resarch Institute of China Academy of Science and the Luoyang Tractor Research Institue of M. E. I. (P.R.China.).



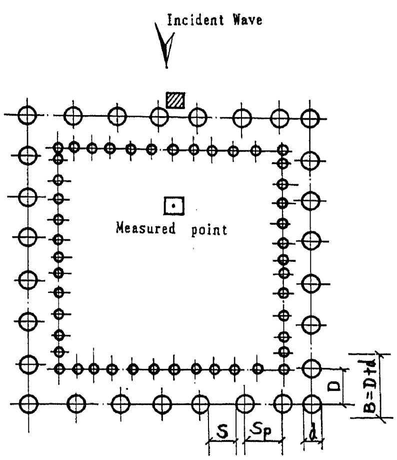

b). Ground Vibration in Case of No.2 (See Tab.1.)




c). Background Vibration in Case of No.3 (See Tab.1.)




d). Background Vibration in Case of No.4 (See Tab.1)




a). Barrier Arranged Plane

Fig.5, Pile Barriers Arranged Plane and Elastic Plate on Sand Cushion

## CONCLUSIONS

This engineering isolation designing was a new concept, which laid stress on designing scheme and the simplification of the calculation as simple as possible, and adopted the idea of concept designing. Through the practice of the model tests and the modelling tests in-situ, plus the judgement by the experience of the designer, the results of the simplified calculating is partly corrected. The simplified calculation is proved reaching a high accuracy for a project as shown in the practice of the prototype project.

This project is the largest and most successful case history of putting the noncontinuous pile barriers into practice.

The theory of both the dynamic response of the flexibale plate on elastic foundation and the vibration isolation of the noncontinuous pile barriers are the complicated problems, which include the subjects of structural dynamics, elastic dynamics and soil dynamics and so on. There are little results to use in the practical designs. This research simplified the method of calculation. Under the same conditions, compared the simplified calculated with the complicated computed results, the former was more approached to the actual measured results. ( Guang Yun Gao, Xian Jan Yang, 1991).

Both theoretical and measuremental researches show that there is no such a phenomenon that the wave energy is concentrated and amplified in front of noncontinuous barries simultaneously. In front of a general open trench, the incoming wave can be amplified two times in theory. The measured value is actually amplified three times in horizontal excitation. But in front of noncontinuous barrier, this amplitude may be reduced to more than 30% in theory, the actual measuremented value may be between 20% to 30% (Guang Yun Gao and Xiana Jing Yang, 1991). This effect is extremely beneficial to control the floor vibration on the action of dynamic load of testing vehicle. It is because of the screening of incoming wave in between the noncontinuous barrier units ( e.g. reinforced concrete pile and silo etc.), so in front of the barriers, part of the vibrating wave (the measurements is 20% to 30%) is absorbed and converted into heat eneryy in soil, being continuously dissipated. In this case, differring from the wave energy concentration in front of the open trenches, the floor vibrating amplitude can not be concentrated and amplified in front of the noncontiouous barriers. Thus, the floor vibration is further decreased. This is another notable advantage of the design plan.

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