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SYNOPSIS; Based on the model, field test and theory research, this paper puts forward the design method of ground vibration isolated by silo and pilo barriers, the practical engineering calculation and the remained problems in this respect. It is pointed out that although the diameter of pile is much smaller than that 1/6 shielded wave length (Woods 1978), the ground wave motion can be effectively shielded so long asthe proper pile distance is to be selected. This makes it possible that the silo and pile (as well as the pile of other form and material) barriers can be used in practical engineering. A successful example of silo and pile barrier engineering is firstly reported. The paper also establisheds some design specifications as "Transmission effect" —efficiency of vibration isolation; "Diffraction effect" —range of vibration isolation; and "Coincident effect" —result of vibration isolation. The auther's view on the relationship between the wave length and the depth and length of near fieled barrier (active vibration isolation) and far field barrier (passive vibration isolation) is also presented.

INTRODUCTION

As the rapid development of science and technology and industry production, the vibration of induatry invironment is getting more aggravated. On the other hand, the high precision equipment and automatic contro lsystem are commonly used which are very sensitive to vibration. Also, as the going up of people's living standard, their demand for life and production invironment is raised. In China there are a lot of ancient buildings and cultural relics and historic sites. All above makes it necessary to speed up the research and development of anti-vibration measures for industry environment. The vibration isolation of silo and pile researched by this paper is an effective and practical measure for isolation of ground vibration according to the test result and engineering practice. It will be beneficial to study and develop at this respect.

The elastic wave propagated on ground will generate reflection, scattering and diffration when encountering the barriers. This is the theory foundation of vibration isolation by ground barriers. The barriers are usually composed of empty ditch, solid body and fluid body or hole raws in the soil, among which the empty ditch has the best shield efficiency prakash(1988). The reson is that the elastic wave can not pass through the empty ditch in any form. But the available depth of empty ditch is limited, so it will be failure to function in the condition of longer wave length. By using the silo and pile barriers, the limitation of depth of empty ditch has been overcome. Although its efficiency of transmission shield is lower than that of empty ditch, the efficiency of diffraction shield will be increased as its depth is increased, so that the effect of vibration isolation is improved. The efficiency of transmission shield of silo rows is higher than that of pile rows because the material of pile rows also has the transmission effect which will lower its shield efficiency. On the other hand, the pile itself has the stiffness and might produce "coincidence" with the wave. This makes the effect of vibration isolation even lower. The so-called "coincident effectof wave" is the new concept of barrier theory which is firsyly put forward by the auther and has been initially tested and verified. The coincidence is different from resonance, but it is a wave motion question which is as siginificant as resonance in the dynamic reaction. This paper will show that by using the scattering disturbance phenomena of the wave, the diameter and distance of piles can be reduced (the diameter of pile is much smaller than 1/6 λ [λ—shield wave length]). The beneficial result of vibration isolation with practical engineering value is also gained.

TRANSMISSION EFFECT OF SILO AND PILE BARRIERS

Wave scattering caused by round holes in elastomer. One of the simplest case of wave scattering is that the SH wave acts on round holes of which the polarization plane is parallel to the longitudinal axis. In this case, the SH wave will not change at the free surface of the holes. But a scattering wave which radiates circumferentially along the hole direction will be added. So its displacement field can be expressed by a single equation. The already known acoustic answer is (K,F, Graff 1975)

$$Us(r\theta t)=Uo\sqrt{2/\pi\gamma r}\,\exp[i(\omega t-\gamma r)]\,\psi s(\theta) \qquad (1)$$

In Witch $\psi s(\theta)=-i\mathrm{Sin}\gamma_o\ \exp[-i(\gamma_o-\pi/4)]+2\sum_{n=1}^{\infty}(-i)^{n+1}\ \mathrm{Sin}\gamma_n\ \exp[-i(\gamma_n-(2n+1)\pi/4)]\cos n\theta$

Where r—abscissa axis of polar coordinates; θ—incident angle of wave; t—time; v—wave number; ω—circular frequency.

Figure Ia-c show, for different γ_o value, the distribution of SH wavescattering with θ. It is consistent with eguation(1)It can be seen from the figure, when $\gamma a=1$ (a—diameter of round hole) most amount of energy of scattering wave is to be opposite to the incident wave, and only less energy scatters to the back of the hole. When $\gamma_a=5$, large amount scattering will be generated at the front of the hole. In thiscase, the wave motion field and disturbance wave form a "shadow" area at the back side of the hole. So if the γ a value become bigger the "shadow" area can be expected to increase a lot. Figure Id is the reflection wave front along the hole circumference when the compression wave is radiated. As to the effect of substrate wall inside the hole on scattering wave, when the hole wall is very thin, wave scattering in medium is similar to that in the round hole without substrate wall. For commonly used in R.C. substrate thickness, when $\gamma=0.3$ the dynamic concentration factor only exceeds 10%—15% compared with that of static stress. When the thickness of substrate wall is further increased, the dynamic stress in substrate wall will follow to increase. On the other hand, the dynamic stress around the medium will reduce. When the inner diameter of substrate wall is zero, i. e the solid elastomer (pile), the above scattering field will change to be the scattering of elastic pile colume in the medium.

Transmission and reflection of wave caused by silo row. In plane question, wave scattering caused by hole rows (hole becomes silo when depened) will disturb each other. There is a much difference between the reflection to wave front and to single round hole. This difference depends on the diameter of holes and the distance between the holes. For example, after the incident plane wave is reflected by two round holeson plane, the wave transmitted to the back of the holes has been reduced a lot. So if the wave length, the diameterof holes, the distance between holes and the soil character of ground are designed properly, better efficiency of vibration isolation will be obtained.

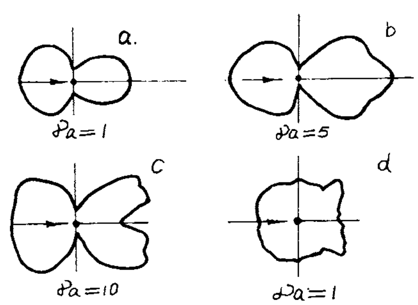


Fig.1 The Round Hole's Radius at a and Wave Nambet at γ.
a. b. and c —— Scatter by SH Wave (A.A.Skan)
d —— Reflected by P Wave (X.J.Yang)

Practical calculation for tranmissivity in vibration isolation by soil and pile barriers. When the elastic wave propagating in a medium encounters another medium which has different wave velocity and mass density from the propagation medium, the progressing wave will generate reflection, scattering and diffraction, and then the energy has been partly shield. So the barriers can be assumed to be a heterobody in the medium, as shown in figure 2. Suppose that for incident wave, $U_i=U_o\sin r(vt-x)$, V_1—longitudinal wa velocity of medium I; ϵ—Poisson's ratio; E_1—elastic modul of medium I; ρ_1—mass density of medium I; the transmissivity wi be (Ejima, 1988)

$$T_u=4\alpha/\sqrt{(1+\alpha)^4+(1-\alpha)^4-2(1-\alpha^2)^2\cos\omega d/V_2} \quad (2)$$

Where $\alpha=(\rho_2V_2)/(\rho_1V_1)$. The dependence curve for equation (2) is shown in figure 3. It can be seen from the figure, when $\alpha=1$, no hetero barrier exists in the medium, and $T_u=1$ (i.e. al incident wave passed through). $\alpha<1$ is accordance with medium I: $\rho_2V_2<\rho_1V_1$ (silo barrier), and $\alpha>1$ with $\rho_2V_2>\rho_1V_1$ (pile barrier or stiff barrier). In both of above case, Tu is chang with α and $\omega d/V_2$. So the Tu can beobtained only by evaluatir the wave velocity of barrier.

(1) For single row silo barrier

$$V_2=V_1(1-T_h) \quad (3)$$

Where $T_h=[(S_p/S)/(\lambda_R/d)]^{1/n}$, n=6 for common soil (from the actural test information available), λ_R—plane wave length, Sp—distance between holes, S—net distance between holes. It c be seen, that the wave velocity of medium II is reduced after th hole is dug, and then the wave barrier is formed. The degree wave vetocity reduction is increased with the reduction of λ_R o incident wave. When S=0, it becomes the empty ditch. That is say that to get better effect of shield by silo and pile barrie the S should be minimized.

(2) For multi row silo barrier. Use the principle of serie connection and take the scattering effect of wave in consideratic V2 can be as follows.

$$V_2=V_1S_0[(\Sigma\beta S_d+D/\lambda_R)/(1-T_h)]^{-1} \quad (4)$$

Where $S_0=S_p/S+D/\lambda_R$, D--total thickness of multirow holes, generally, $D\geq S_p<4d$, d—hole diameter. It is clear that when D i fixed, the more rows of holes there are between D, the smaller th V2 is, till it tends to be zero. When D between holes in two row is increased, V2 is not accordingly reduced. $\beta=0.7\sim0.8$ (n underground water).

(3) Single row (solid) pile barrier

$$V_2=V_1(1+T_p) \quad (5)$$

Where $T_p=[S_d(1+\alpha n)/(\lambda_R/d)]^{1/n}$, $\alpha n=(\rho_pv_p)/(\rho_1v_1)$, ρ_p—unit lengthmass density of pile material, v_p—longitudinal wav velocity of pile, $S_d=S_p/S$, n=1 for singleS row concrete pile .

(4) Multi-row (solid) pile barrier

$$V_2=V_1S_0'[(D'/\lambda_R)/\Sigma\delta(1+T_p)]^{-1} \quad (6)$$

here $D'=(210\Sigma I)$, I—moment of inertia of pile,
$_{D'}=Sp/S+D'/\lambda_R$,
$=1$(underground water).

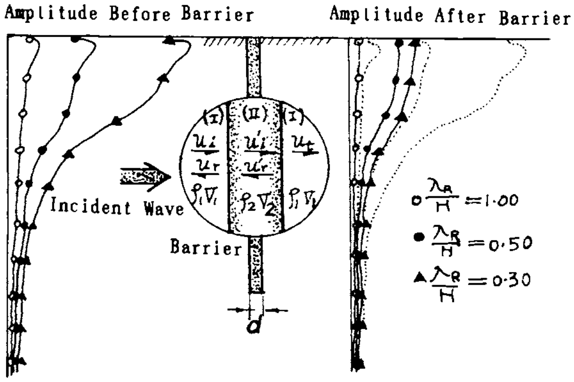


Fig.2 Wave Propagation When Encountered the Barrier

$H>(0.8\sim1.0)\lambda_R$. (2) Far-field (passive vibration isolation), when $r\geq2\lambda_R$, $H=(0.7\sim0.9)\lambda_R$.

2. The design length L of arrier. (1) Near-field (active vibration isolation), when $r\leq2\lambda_R$, $L\geq(2.5\sim3.125)\lambda_R$. (2) Far-field (passive cibration isolation), when $r\geq2\lambda_R$, $L\geq(6\sim7.5)\lambda_R$.

The barrier depthes proposed by this paper are different from those proposed by Richart (1970) in which the $H=0.6\lambda R$ for near-field and $H\approx1.33\lambda R$ for far-field, the reason is that the near-field body wave can not be neglected. If the barrier is much too shallow, the body wave may diffuse toward outside through the bottom of barrier and then from the plane wave. At the same time, the body wave generated at the bottom of barrier by wave motion may be superimposed on the body wave of wave source to lower the shield efficiency. So the near-field barrier can be properly deepened. For the far-field, the shield plane wave plays the main role. When the barrier depth reaches $0.6\lambda_R$, it has very good shield efficiency for plane wave. Test and theory research have shown that when $H>1.0\lambda_R$, the diffraction effect (i.e. shield efficiency) will not increased any more.

DIFFRACTION EFFECT OF SILO AND PILE BARRIER

Diffraction principle of barrier in elastic medium. When incident wave energy is reflected and refracted wave energy and incident wave energy will act each other, the diffraction phenomenon is then formed. If the dimension of the hetero-medium (barrier) is much larger then the incident wave length, then a shield area in which the wave strength is much reduced can be formed at the back of barrier. On the contrary, the shield area will be very small or even no shield area. Figure 4 illustrates the diffraction principle. The shield principle of near-source barrier is that after body wave becomes tilting with some angle in the near field, it will not generate R wave at the near-source surface, and if the tilting body wave encounters the barrier, it will generate reflection. If the wave of transmission barrier is very less, some the reflection wave will reach the surface and form the R wave. These R wave sand the wave from the external ring diffusion of wave source will be partly dissipated by multiple reflection . As the result, the shield area is formed at the back of barrier. The shield principle of far-sourcebarrier is that the R wave reflecting free wave length founctions the shield. When the barrier has some degree of depth, the energy of R wave is changed into body wave type in the half space interior and is partly dissipated by forming the reflection at the half space surface.

Diffraction effect of barrier. After the transmissivity of silo row (or pile row) is determined, It is also necessary to determine the dimension of length and depth of barrier according to the incident wave length, the aboved mensioned diffraction principle is the basic theory of determing the barrier dimension.

1. The design depth H of barrier. (1) . Near- field (active vibration isolation), when the barrier position is at $r<2\lambda_R$, (r—the distance between the barrier and wave source) ,

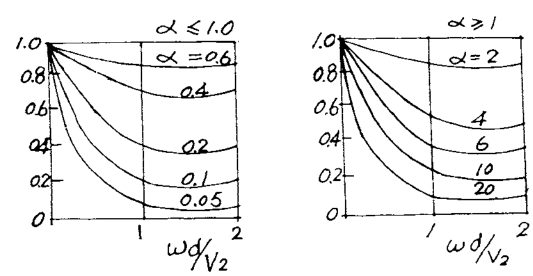


Fig.3 Wave Transmission Efficiency When Encountered the Barrier (Consulted Ejima)

COINCIDENT EFFECT OF WAVE IN SOIL AND PILE BARRIER.

The wave motion in elastic medium is propagated in the form of its energy. Now that the wave motion has energy, it can excit the barrier with certain stiffness to generate intensive vibration. In this case, the barrier does not isolate vibration, instead, it may form the second wave source to increase the ground vibretion. This phenomenon is defined by this paper as coinicident effect of wave according to acoustic theory. The phenomenon of this effect has been reported in the past model test and prototype engineering practice. For example, in a group of test reported by D.D. Barken in 1948 , it was just in the effective frequency range for vibration isolation, but the amplitude at the back of barrier was yet amplified. D.D.Barken noticed this phenomenon, but did not make any further explanation. At present, no meterial is available to analyze and discuss the reason for the amplified amplitude. This may be a important cause that some plate pile engineering which were meticulously designed in the efficiency of transmission and diffraction often fail.

1. Plane wave displacement when encountering the flexible barrier. When flexible barrier is acted by wave energy, it corresponds to the case that the acoustic wave is acted by barrier. From the acoustic definition on sound pressure we know, $Ps=V_s C\rho$, the dimension is kg/m^2. Here Vs—radial velocity of air (s), c—sound propagation velocity in air (m/s), ρ—air deusity (kg/m^3). The above equation can be compared with the following one, $P_d=kw$, the dimension is (kn/m^2). Here P_d—unit area kinamic pressure of barrier; K—stiffness factor of elastic medium (kn/m^3); w—elastic displacement of medium (m). Then the transverse displacement of barrier bending vibration can be derived from the known parameters,

$$W_b=\frac{z(kw)}{P_b dw^2}\ \frac{1}{[(Bw^2)/P_b dV^4_p]\sin^4\theta-1} \qquad (7)$$

2. The coincident frequency and bending wave velocity of barrier. The maximum possible bending vibration of barrier is that the denomination of equation (7) becomes zero. So, ($Bw^2+\sin^4\theta/\rho_b dVp^4=1$. If suppose that the bending stiffness of barrier B= 2/3E(0.5d3)(1-ε 2), here, ε—Poisson's ratio of barrier material, the coincident frequency (of possibly generated coincident effect) will be,

$$f_b=0.556V^2p/(C_P\sin^2\theta) \qquad (8)$$

In the equation, Cp—ngitudinal wave velocity of wave; Vp—longitudinal wave Velocity of elastic medium; d—barrier thickness; θ—incident angleof incident wave. When Sinθ=1, the critical coincident frequency is, $f_{bc}=0.556Vp^2/C\rho d$. In this case, the bending wave length is equal to incident wave length. If let the $C_B=Vp$, the bending wave velocity of barrier will be, $C_B=(1.8df_bC_b)^{1/2}$. It can be seen from equation (8) that the coincidence of wave in barrier exists and also is possible to take place. But if the wave length of incident wave is longer than that of bending wave of barrier, the coincident effect will not lake place. This is the substantial difference between the "coincidence" of elastic barrier in medium and the "resonance" in partical system, and yet the former has the same importance.

EXAMPLE

1 Field test for silo and pile barrier. (1) foundation soil, the surface soil is 0.8～1.5m thick; the second layer is neo-Loess, -1. 5～-6. 5m [R]=60～80kpa; Underneath is the loessal mild clay, [R]=150～200kpa; V_R=154m/s. (2) Silo barrier, d=0.4m, Sp=0. 9m; hole depth H=8. 0m.(3) Test result is shown in figure 5. (4) Comparision between caculation and actural testng, $V_2=0.16\times V_1$ =24.64m/s, $\rho_2=1.1715T/m^3$(converted after the hole is dug).It is calculated, α=0.10413, $Wd/V_2>2$. From the figure 3, Tu=0. 25 is obtained. The shield area, when Tu=0.2 in figure 5 is not small, but is seperated into two areas because of the original building foundation.

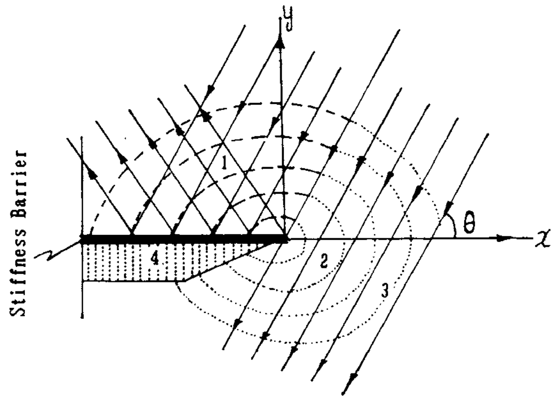


Fig.4 1.Incident Wave , Reflectionive and Diffractinat Wave
2.Incident and Reflectionive Wave
3.Diffractional Wave
4.Range of Barrier

2 Engineering example. A large precision test room,for which it required that ground floor vibration amplitude shoud not exceed μm within the frequency domain of 10～80HZ. In order to seper the ground vibration caused by outside traffic and dynamic mach the pile foundation surporting the building was used to be silo d pile barrier.The floor plan and the related dimensions are sh in figure 6.The geologic condition is the same as example 1.(ca lating approximately according to solid cement concret pile) th verage (Sp-s)=0.8m, λ_R=3.85m, Vp≈4800m/s, α_n=41.56, ΣI=0. 074 ×0.0201=0.1142 m^4, $D'=(210\Sigma I)^{1/4}$ =2.1m, $V_2=V_1\times18.05=154\times18.05$ 780m/s, α=21.066, $\omega d/V_2$=0.197 Tu=0.4.actual measurement, when λ =7.7m , Tu=0.276 The actual measurement result is higher t that of calculation.Coincidence condition, on the basis of D'=2 the bending wave length of half wave of barriier is 10m, which larger than the actual length of pile,H=8m.The wave coincide Will not take place (i.e. barrier is stiff body).According the al measurement made by author in room test,field test and engin eering prototype, no phenomenon of amplitud amplificat takes place at the front of silo and pile barrier . Yet t phenomenon is very common to take place at the front of em ditch and stiff wall.It can be furthermore seen figure 6 that the empty ditch of 10m deepis dug all around the floor, the fl is then surported by anisolated soil colume . And its vibrat stability is much worse than that of pile barrier. This is anot advantage of pile barrier.

3 Coincident effect of wood plate pile barrier on spot. The act measurement meterial of this example is from Barken (1948) θ≈45°, V_R=150～170m/s.The dynamic modulus of elasticity of common cis-lines wood $E_d=1.6\times106MPa$, $\rho=0.051TS^2/m^4$, $Cp=[160\times10^4/0.051(1-0.2^2)]^{1/2}$ =5680m/s.d≈0.3m. The coincide frequency can be derived from equation (8), f_b=16.5HZ. The resu

actual measurement, Within the frequency range of 13.5~22.5HZ, ne vibration amplitude was amplified after barriered by plate pile, specially at the frequency of 16.7HZ. This frequency range has come the region of coincident effect and is failure to isolate ibration.

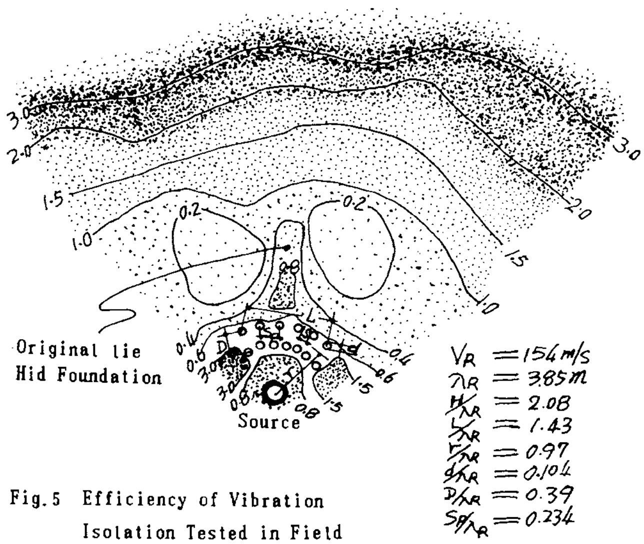
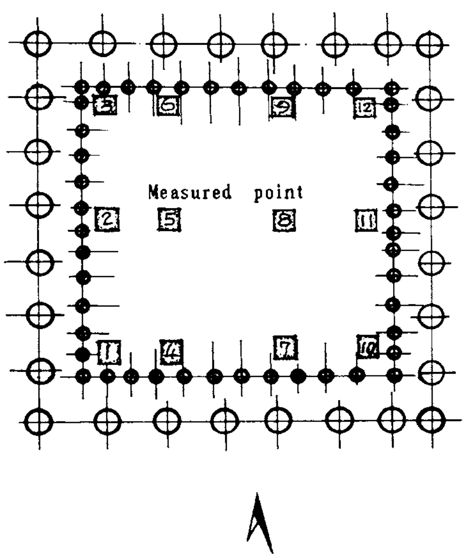


Fig.5 Efficiency of Vibration Isolation Tested in Field



Incident Wave

Fig.6 Silo and pie Barriers Arranged plane

Note: Measured Pionts are on the Natural Ground Surface

TABLE I. Parameter of Silo ana Pile Barries

NO	λ_R	H/λ_R	L/λ_R	r/λ_R	d/λ_R	D'/λ_R	Sp/λ_R
1	15.4	0.68	1.56	1.07	0.05	0.13	0.09
2	7.70	1.36	2.30	2.14	0.10	0.26	0.18
3	5.13	2.05	3.45	3.22	0.16	0.39	0.26
4	3.85	2.73	4.60	4.29	0.21	0.52	0.35

N0te: H=10.5m (depth); V_R=154m/s; d=0.8m(average diameter of piles). Date: 24.8. 1987.

TABLE II. Tu of Measurement Point in Barries

Point / No	1	2	3	4	5	6	7
1	0.54	0.27	0.42	0.50	0.50	0.94	0.31
2	0.48	0.005	0.08	0.23	0.17	0.62	0.35
3	0.53	0.16	0.22	0.09	0.11	0.06	0.22
4	0.17	0.28	0.09	0.18	0.26	0.16	0. 09

Point / No	8	9	10	11	12	average
1	0.57	0.64	0.11	0.70	0.80	0.524
2	—	0.54	0.05	0.16	0.35	0.276
3	0.41	—	0.10	—	0.80	0.270
4	0.48	0.40	0.30	0.26	0.34	0.250

Note: $Tu = \frac{\text{Ground Vibration after Barriers Establised}}{\text{Ground Vibration befor Barriers Establisbed}}$

CONCLUSION

1.By test research, engineering prototype measurement and theory analysis, it has been proved that the silo and pile barrier can be applied in practical engineering for vibration isolation. For the common frequency of vibration wave, the diameter of silo and pile can be smaller than the specification of $d > \lambda_R/6$, yet the better benifit of vibration isolation can also be gained.

2 The barrier design criterion raised by this paper, in which the vibration isolation efficiency of silo and pile barrier is

determined by Transmission effect, the shield aera of barrier is determined by diffraction effect, and the shield effect is determined by checking the coincident effect of etastic barrier, has made the barrier design theory and practical method more substantial and clear, and has been ratified by actual measurement and theory research.

3 For the non- supporting silo and pile, the cheap wall-protecting material such as brick thin wall, foamed plastics, foamed concrete and pulverized coal ash (Wu shi-ming etc.1988) can be used to obtain greater economicl benefit.For example, for the barriers of the same shield efficiency,if the double row brick substrate silo is used,the cost is less than one tenth of that of stiff wall of foamed plastics and concrete combination, which is commonly used abroad at present.

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