Attenuation of Ground Vibration Induced by Dynamical Machinery

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SYNOPSIS. Attenuation of ground vibration induced by dynamic machinery is investigated with fundamental theory established for both Rayleigh and body waves. Therefore, for determining such attenuation is established, in which the effects of both of them and a coefficient of attenuation of soil that makes the practical calculation easier are involved. A lot of data in relation to the surface vibration measured at some production shops and construction sites has proved that the developed formula more satisfactory than Bornitz's.

INTRODUCTION

The problem of attenuation of ground vibration caused by machinery traffic or pile driving has been studied by several reasearchers (1,2,3,4). Traditionally, such a problem is solved with Bornitz's (1931) formula i.e. (5).

$$A_r == A_1 \frac{r_1}{r} \exp -\alpha(r-r_1) \qquad \text{(I)}$$

where A_1 amplitude of vertical component of the R-waves at distande r_1 from the source

A_r- amplitude of the vertical component of the R-waves at distance "r" from the source.

r_1 - distance from the source to the point of known amplitude.

r - distance from the source to a point of unknown amplitude.

α - coefficient of attenuation, having a dimension of 1 distance.

It may be seen that formula (I) is a precipitous exponential curve, therefore, the amplitude measured near the source is smaller and that measured far from the source is greater than predicted by Bornitz's formula. This is especially true for ground vibrations caused by powerful source. Obviously, in this problem the rapidly attenuated body waves near the cource should be considered, and it is well-known that the frequency and area of the source have important effects on the amplitude attenuation of ground vibration.

In this paper a practical attenuation formula is developed and coefficients of attenuation of soil for practical applications area presented.

ATTENUATION OF GROUND VIBRATION INDUCED BY DYNAMICAL AREAL SOURCE

Due to the complexity of the mechanics of energy dissipation of dynamic areal source in soil, theoretical computation of ground vibration induced by it is extremely tedious and may not be practical for engineering applications. With source approximate relationships the attenuation of ground vibration is presented as a function of distance from the source "r", effect coefficient of the source area and body wave ξ, coefficient of attenuation of soil α, it may be a practical method for solving this problem.

1. THE SURFACE WAVES ARE PROPAGATED AS PLANE WAVES

Let us consider another characteristic of the attenuation of surface wave would be spreaded as a ring and the soil is not perfectly elastic. In real earth materials part of energy is consumed due to material damping. The energy of surface wave on the edge of the source r_o is presented as:

$$U_{r_0 R} = \frac{U_{oR}}{2\pi r_0} \exp\left[-2f_o \alpha_o r_o\right]$$

$$= \frac{I_R}{r_0} \exp -2f_0\alpha_0 r_0 \qquad (2)$$

where U_{r_0R} - energy on the edge of the source

$$I_R = \frac{U_{0R}}{2\pi}$$

U_{0R} - total energy of source

f_0 - excitation frequency of source

α_0 - coefficient of attenuation of soil

r_0 - radius of source

If the average energy on soil surface at all point in a distance r_0 from source centre is equal, the amplitued of soil surface are:

$$A_0 = \sqrt{\frac{I_R}{I}} \frac{T_0}{\sqrt{r_0^2\zeta}} \exp\left[-\alpha_0 f_0 r_0\right] \qquad (3)$$

where $I = 2\pi^2\zeta$

ζ - coefficient related to the condition of source

ρ - mass density of soil

T_0 - period of source

In similar manner, of the energy on soil surface at all point in the distance r from source centre is also equal, the amplitude of vibration on surface are:

$$A_{rR} = \sqrt{\frac{I_R}{I}} \frac{T_r}{\sqrt{r}} \exp\left[-\alpha_0 f_0 r\right] \qquad (4)$$

where T_r - period of ground surface in r.

Divide Eq. (4) by (3) and assume $T_r \approx T_0$. we get:

$$A_{rR} = A_0 \sqrt{\frac{r_0^2\zeta}{r}} \exp\left[-\alpha_0 f_0 \quad (r - r_0)\right] \qquad (5)$$

2. THE BODY WAVES ARE PROPAGATED AS A HEMISPHERICAL SURFACE

Assume the body waves propagated radially outward from the source along a hemispherical wave front and the soil is not perfectly elastic and part of the energy is lost due to material damping, then we get:

$$A_{rps} = A_0 \sqrt{\frac{r_0^2\xi}{r^2}} \exp\left[-\alpha_0 \; f_0 \quad (r - r_0)\right] \qquad (6)$$

3. ATTENUATION OF GROUND VIBRATION INDUCED BY DYNAMIC AREAL SOURCE

The energy of a dynamic areal source is transmitted through the ground by a combination of body (p,s) and surface (R) waves. By superposing both of them, the amplitude on free surface of soil at a distance r from source centre is:

$$A_r = \sqrt{(Ar_R)^2 + (Arps)^2} \qquad (7)$$

Substitute the Eq. (5) and (6) into Eq. (7) and neglect the phase difference between the body and R waves, then we obtain:

$$A_r = A_0 \sqrt{\frac{r_0}{r}\left[1 - \xi_0 (1 - \frac{r_0}{r})\right]} \exp\left[-\alpha_0 f_0 \quad (r - r_0)\right] \qquad (8)$$

where A_r - amplitude on free surface of soil of a distance r from dynamic areal source centre.

A_0 - amplitude in source

ξ_0-dimensionless coefficient in relation to an area source, as given in Table I.

r_0 - radius of source, for a rectangular or square area, the equivalent radius is:

$$r_0 = \mu \sqrt{\frac{F}{\pi}}$$

F- source area

μ_1 - coefficient for dynamic effects
for $F \leq 10\ M^2$, $\mu_1 = 1.0$
$F = 15\ M^2$, $\mu_1 = 0.9$
$F > 20\ M^2$, $\mu_1 = 0.8$

α_0 - coefficient of energy attenuation of soil, as given in Table 2.

TABLE 1 Coefficient ξ_0

r_0 m	< 0.5	1	2	3	4	5	6	≥ 7
ξ_0	0.99 ∿0.85	0.70	0.60	0.55	0.45	0.40	0.35	0.25 ∿0.15

NOTE: 1. For intermediate values of r is calculated by means of the method insertion.

2. For horizontal source, ξ_0 should be multiplied by a reducing coefficient 0.3∿ 0.4.

TABLE 2. Coefficient of Attenuation of Soil α_0

Soil Group	α_0 s/m
Intensely weathered hard rock	$(0.375 \sim 0.625) \times 10^{-3}$
Hard plastic clay, broken stones of medium density	$(0.875 \sim 1.150) \times 10^{-3}$
Plastic clays, coarse sands and gravels of medium density	$(1.000 \sim 1.250) \times 10^{-3}$
Soft plastic clays, slightly dense, medium or coarse sands	$(1.150 \sim 1.450) \times 10^{-3}$
Silty clay and saturated fine sand	$(1.500 \sim 1.750) \times 10^{-3}$
Recently deposited clay and unsaturated loose sand	$(1.850 \sim 2.150) \times 10^{-3}$

NOTE: For horizontal amplitude attenuation, such multiplied by reducing coefficient 0.7 ∿0.8.

From this solution it is clear that in formula (8), the radical expressions indicate the energy density for waves decrease as the distance from the source is increased i.e. geometrical damping, and the part other than it indicates consumption of energy by soil material damping. For $\xi_0 = 0$ and $f_0 = 1$, Eg. (6) becomes identical with the Bornitz's formula.

EXAMPLE INFIELD MONITORING

1. By machinery and pile driving source, Fig. 1 shows amplitude-decay curves obtained in the field at four sites described in Table 3.

TABLE 3. Site Condition and Source of Excitation for Field Data Presented in Fig. 1.

Curve identification	soil condition			source of excitation			
	soil description	Vs m/s	α_0 s/m	condition	r_0 m	f_0 Hz	A_0
L2 vertical	Loessialsand clay in a plastic state	131∿ ∿153	1.25×10^{-3}	rotation mass vibrator	0.8	16.7	100
M24 horizontal Tajimi	Lam clay	82∿ ∿145	1.05×10^{-3}	large scale shaking table	17.5	3.0	100
M22 vertical	Soft plastic clays and rock	186	1.50×10^{-3}	forging hammer	1.82	15	100
L25	Lossial sandy clay in a plastic state	131∿ ∿153	1.25×10^{-3}	pile driving	2d 0.9		100

2. By traffic source, Fig. 2 shows acceleration-decay curve in the field at the traffic site described in Table 4. The acceleration attenuation of ground surface is designated by:

$$a_r \quad a_0\sqrt{\frac{r_0}{r}\;1-\xi_0\left(1-\frac{r_0}{r}\right)} \quad \exp\left[-f_0\alpha_0\,(r-r_0)\right] \qquad (9)$$

where a - acceleration in source.

TABLE 4. Site Condition and Source of Excitation for Field Data Presented in Fig. 2

soil condition			source of excitation			
soil description	Vs m/s	α_0 s/m	condition	r_0 m	f_0 Hz	a_0 gal.
cobble and clay with sand	110 280	0.875×10^{-3}	large truck	2.5	2.0	8.5

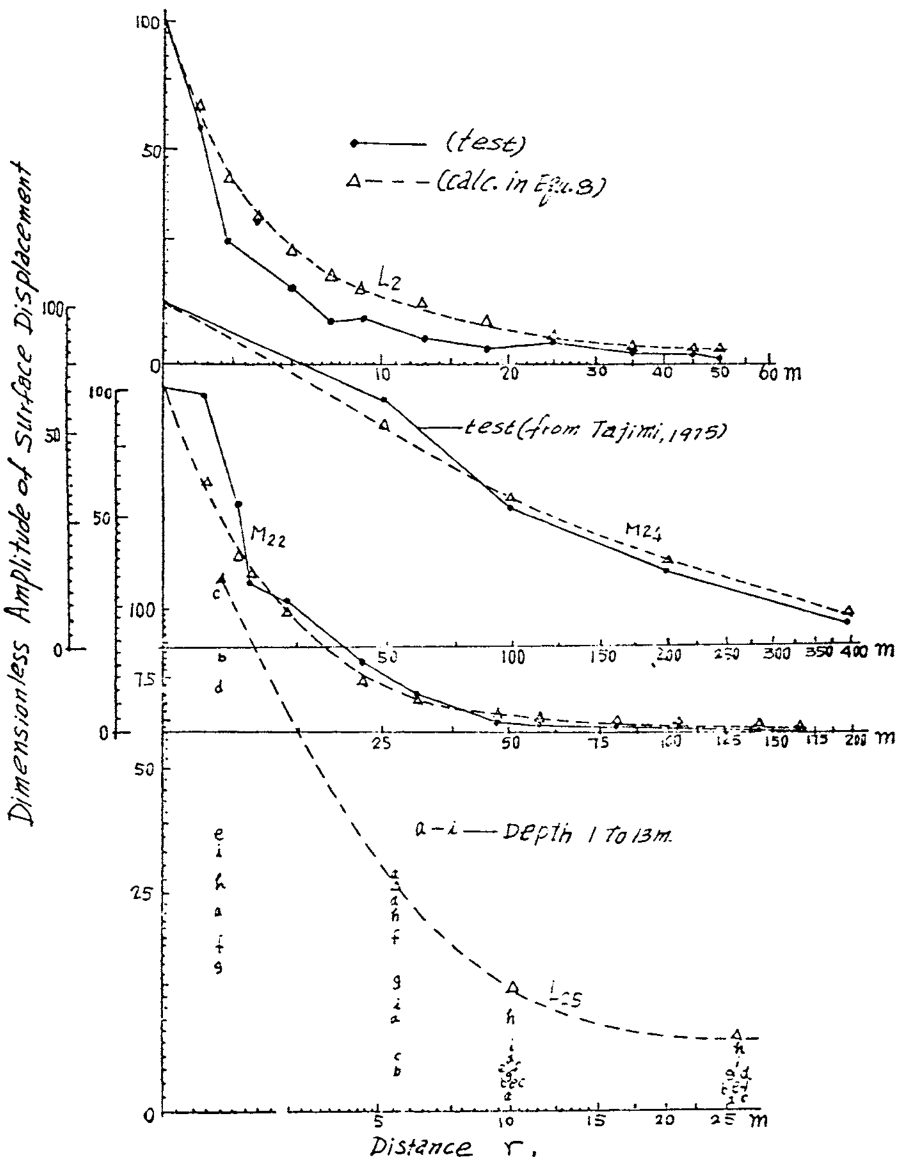

FIGURE 1.

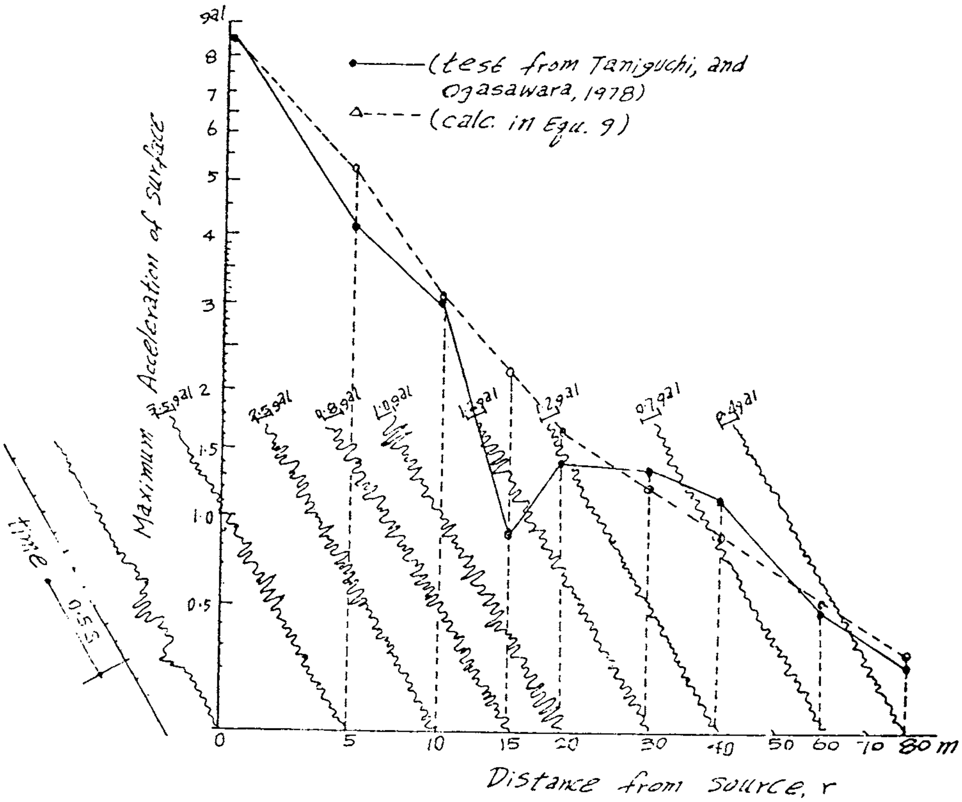

FIGURE 2.

CONCLUSIONS

By theoretical investigation to the attenuation of ground vibration induced by dynamical machinery, a fundamental concept is established that not only the Rayleigh waves, but also, body waves should be considered important fundamental parameters are obtained and a simple formula for calculating amplitude and acceleration attenuation of ground vibration caused by machinery, traffic or pile driving is developed, which would be satisfactory for engineering applications. In addition, we have yet another conclusion that the energy in an embedded foundation enduring vertical vibration, is released at the bottom and that in the nearby regions the source energy is transmitted not only in the form of Rayleigh waves, but also body waves.

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