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THE EFFECT OF VIBRATION ON BUILDINGS AND THE OCCUPANTS

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INTRODUCTION

The trend towards light weight and continuous construction with fewer expansion joints makes for a much easier transmission of vibration than hitherto. The introduction of prestressed concrete beams and of welded joints in steel framed structures can reduce considerably the energy dissipation so that once a disturbance has entered the structure it can be transmitted to every part unabated. Should a certain section of the structure, albeit far removed from the source of the disturbance, have a natural frequency in sympathy with a prominent frequency transmitted vibration, then a state of resonance can be built up and the effects of the disturbance will be much more severe in that area than closer to the source. Another trend in development is that the only vacant sites in the larger cities are the undesirable ones, i.e., alongside or over a railway or a road. The disturbance is often tolerated when the passing vehicles can be seen, but when they are underground, a sudden rumble can be very irritating and can give a certain degree of startle. The awareness of a disturbance from an underground train is often by the noise, but the transmission path for the ground-borne vibrations is solely through the structure

STRUCTURAL RESONANCE

Where vibrations cause damage or are a nuisance it is often because a state of resonance has been built-up by the excitation. Structural resonance can occur when a predominant frequency of the excitation coincides with a natural frequency of a part of the building or of the entire structure. As a complex structure possesses many natural frequencies (in the limit an infinite number) the chance of exciting a state of resonance is quite high. The amplitude of the response at resonance is controlled solely by the energy dissipation in the structure. In modern buildings there is less damping than in brick construction with timber floors, although a continuous construction without expansion joints can be beneficial in that vibrational energy from a localized source will be dispersed throughout the structure. The magnification at resonance can be qualified by the Q-factor. Typical values for a concrete structure cast in-situ fall between 15-60 but can be higher with pre-stressed concrete. Values of the Q-factor for steel structures can be greater than 100, especially with welded construction.

Floor resonance. An estimate of the lowest natural frequency of a slab can be based on the static deflection at mid-span, although a correction has to be applied for an r.c. slab because the dynamic modulus of elasticity for concrete is higher than the static value used by structural designers. For a simply supported slab the lowest natural frequency is approximately:

$$\frac{1}{2\pi}\sqrt{\frac{4g}{\pi\delta}} \text{ Hz}$$

when

δ = mid-span deflection
g = gravitational acceleration
= 9.81 m/s^2

The ease whereby large span floors can be made to vibrate has been described by Fahy and Westcott(1) who carried out tests in several buildings of different construction and some of their results have been reproduced in Figure 1. The mobility for a resonant mode of vibration has been recorded at that frequency. Only a small force is required to set up a state of resonance, e.g. a maintained exciting force of 200 N at about 20 Hz on a slab of 5 tonne would induce a velocity of vibration of about 1 mn/s. The effect of floor vibration on the occupants has been studied recently by Ohlson(2).

Foundation response. A foundation block set into or on top of an elastic half space will have 6 resonant frequencies, 3 in translation and 3 in rotation. The dynamic stress distribution in the soil at the interface with the foundation varies over the area of contact and is different from the static stress. The dynamic response to steady state harmonic vibration can now be predicted with confidence for blocks with a circular, square and rectangular base area(3,4,5). The response at resonance is dependent largely upon the ratio of the mass or of the inertia of the foundation block to that of the bowl of soil immediately underneath the base. As an example, taken from ref. 5, the non-dimensional response for vertical motion is shown in Figure 2 for a base with a square area. The family of curves is for different values of the mass ratio, b, and have been plotted as a function of a frequency factor = $p\ d/c_2$, where p = excitation frequency (rad/s), d = half of one side and c_2 = velocity of shear waves in the soil.

A strong response at resonance can occur with a high soil loading whereas there is hardly any response for a low mass foundation with a wide base and low stresses in the soil (b<20). This is because with a low mass ratio all the vibrational energy is radiated away into the half space whereas with a concentrated mass some interchange between strain energy in the soil and kinetic energy of the mass can take place to build up a state of resonance. The curves in Figure 2 show clearly the effect of radiation damping.

Time to build up a resonance. It is said sometimes there is no need to worry about structural resonances when the excitation is of short duration or intermittent. Such an attitude can be misleading. For example, the structural response from ground vibration caused by pile driving is always at the natural frequencies. The time taken for a train to pass a building is generally longer than 10 seconds and the build-up time to establish resonance is usually only about 1 sec. as can be seen in Figure 3. The build-up time for resonance has been plotted to a base of the undamped natural frequency for different values of the Q-factor. Typically, the build-up time for a floor with a resonant frequency of 25 Hz and a Q of 15 would be about 1 sec.

EFFECTS OF VIBRATION

On people. Recommended levels in rms acceleration for various classes of building have been set by ISO (6). An awareness of the low levels of vibration such as from trains is often confused with noise. The spl produced by structural vibration can be predicted even for intermittent disturbance [7].

Structural damage. There is no international agreement on the levels to cause damage, although some recommendations have been prepared by ISO[8]. The permissable levels are much higher in America than in Europe, in particular from blasting. This is because of differences in construction and of the need to protect the historic buildings in Europe (see the German DIN 4150-1975). The damage criteria are expressed in terms of the vector sum of the peak particle velocities in three directions and they are independent of frequency in the range normally associated with ground vibration. Some guide values are given in Table 1 of velocities at the foundations.

Table 1 - VIBRATION DAMAGE LEVELS

Type of building	Peak particle velocity below which damage would not be expected, mm/s.
-ancient buildings with architectural finishes in a poor state of repair	2
-generally sound buildings	
- architectural damage	8
- light structural damage	12
- severe damage	30

These levels are much greater than the sensivitivity threshold for a person standing, which is about 0.13 mm/s at 10 Hz. Complaints are often ill-founded because the people can feel the vibration and are therefore afraid that damage is being caused to their home. Ground vibrations can cause secondary effects such as liquefaction and the settlement of foundations with a subsequent cracking of walls.

Isolation from internal disturbances can be provided by floating floors on resilient pads[9]. Entire buildings can be isolated from ground borne vibration by supporting the structure on resilient bearings[10]. There are a number of buildings where trains run in between the piles or even through a tunnel in the basement without the occupants being aware of it.

(1) F.J.Fahy & M.E.Westcott,"Measurement of floor mob. at low freq.in some buildings with long floor spans",1978,J.Sound.Vib.57(1),101.

(2) S.Ohlson, "Floor vibrations and human discomfort", Doctoral Thesis Chalmers Univ. of Engineering, Gotteborg, Sweden, 1981

(3) A.O.Awojobi, & P.Grootenhuis, "Vibration of rigid bodies on semi-infinite elastic media", Proc.Roy.Soc. A 287, 27-63, 1965.

(4) P.Grootenhuis, "The dynamics of foundation blocks", Proc.Int.Conf. "Dynamics and waves", Inst.Civ.Eng. Swansea, 95-105, 1970.

(5) H.R.Hamidzadeh-Eraghi & P.Grootenhuis, "The dynamics of a rigid foundation on the surface of an elastic half-space", Earthquake Eng. & Struc. Dyn 9, 501-515, 1981.

(6) ISO 2631 (1978), "Guide to the evaluation of human response to vibration and shock in buildings".

(7) P.Grootenhuis & P.H.Allaway,"Noise & vib. nuisance within bldgs", Symp."Env. aspects of pollution", Soc. Env.Eng.Lond.,1971.

(8) ISO (ref.ISO/TC 108/SC 2/WG3 N.35), "Methods of measurement and evaluation of the effects of vibration on buildings".

(9) P.H.Allaway, "Floating Floors", J.Soc.Env.Eng., 16 (2) 1977.

(10) P.Grootenhuis, "Resilient mounting of large structures", Chap.13, Elastomers: Criteria for engineering design.Appl.Sci.Pub.1979

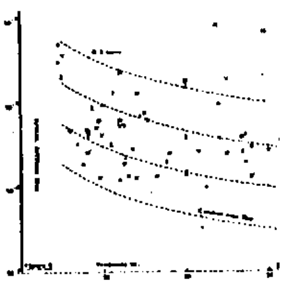
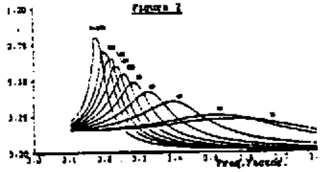


Figure 2



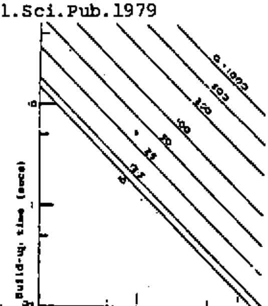


Figure 3 Undamped Natural Freq