Measurement and estimation of vibration of old buildings

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Abstract

Vibrations on buildings caused by earthquakes by traffic or by special construction methods as surface compaction or driving in sheet piles with a vibratory hammer or by blasting can lead to damage if the strength of the structure oversteps empirical developed limits. A numerical determination of the problem is often not possible because in many cases the dynamic behaviour of the structure and the surrounding soil is unknown. It is therefore necessary to carry out measurements to get real information whereby the measured velocity of vibration in most standards is a measure for vibrations of the building.

Introduction

It was found that two types of waves were possible in an elastic infinite medium – waves of dilatation and waves of distortion (space waves). In an elastic half space, however, it is possible to find another solution for the equations of motion, known as a Rayleigh wave, which corresponds to a wave whose motion is confined to a zone near the boundary of the half space. The influence of the Rayleigh wave decreases rapidly with depth. Therefore nearly the whole energy is stored in a one wave length thick layer of the boundary. Another type of wave was found by Love in the layered half space. The Love wave is a horizontally polarised shear wave trapped in a superficial layer and propagated by multiple total reflections [1].

The decrease of the wave amplitude in dependence of the distance depends on the viscose characteristics of the soil (material damping) and on the dominating wave type (space waves, surface waves). The decrease of the amplitude of space waves which spread out on spherical surfaces is proportional to $\frac{1}{r}$ (geometrical damping), and by surface waves (Rayleigh waves) which spread out on cylinder surfaces the decrease of the amplitude is proportional to $\frac{1}{\sqrt{r}}$. By the assumption of an exponential decrease of vibration caused by damping, where α is a damping factor which depends on the kind of soil and the frequency, the velocity of vibration in dependence of the distance from the exciting point is given for space waves by the equation

$$v(r) = v(r_1)\frac{r_1}{r}e^{-\alpha(r-r_1)} \tag{1}$$

and for surface waves

$$v(r) = v(r_1)\sqrt{\frac{r_1}{r}}e^{-\alpha_R(r-r_1)} \tag{2}$$

$v(r_1)$	measured amplitude of velocity of vibration
$v(r)$	unknown amplitude of velocity of vibration
r, r_1	distances
α	damping coefficient

For vertically oscillating Miller and Pursey [2] determined the distribution of total input energy among the three elastic waves to be 67 percent Rayleigh wave, 26 percent shear wave, and 7 percent compression wave. The facts that two-thirds of the total input energy is transmitted away from a vertically oscillating footing by the Rayleigh wave and that the Rayleigh wave decays much more slowly with distance than the body waves indicate that the Rayleigh wave is of primary concern for foundations on or near the surface of the earth.

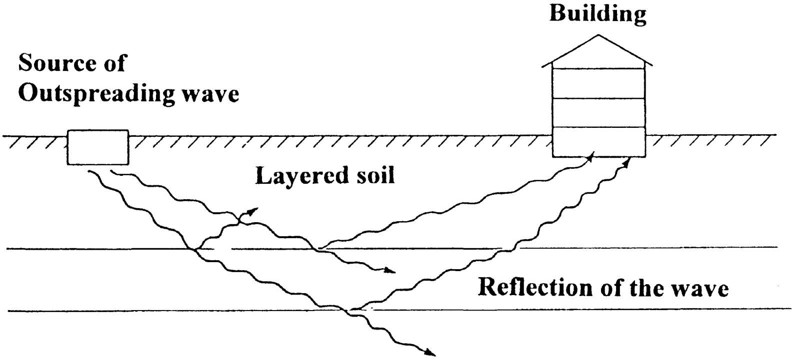

Figure 1: Transmission of vibration from soil to the foundation of a building.

Fig.1 shows transmission of vibration from the exciting point (blasting for example) to the foundation of a building. A numerical determination of the problem is often not possible because in many cases the situation of soil layers the law of material the material constants the damping factors of different kinds of soil and the transmission coefficient soil – building are not known exactly and often unknown. The only way getting real information is to carry out measurements.

To estimate the vibrations of a building it must be distinguished if the building have to be protected against damage, if people have to be protected against molestation or if the guarantee of correct function of industrial machinery equipment is necessary. This leads to the question which measured quantity, the amplitude of vibration, the velocity of vibration or the acceleration characterises in the best way the influence of vibrations.

To judge vibrations of buildings the velocity of vibration is taken as a measure in standards (ÖNORM S 9020, DIN 4150, part 3, SN 640312), because the kinetic energy introduced into soil by vibratory hammers, traffic or blasting for instance is proportional to the velocity squared. An other reason to take the velocity of vibration as a measure of damage is given by Gasch and Klippel [3]. Gasch and Klippel found for in resonance vibrating beams and plates a direct connection between the dynamic stress $\sigma(x,t)$ and the measured velocity of vibration $v(x,t)$ by

$$\sigma(x,t) = C\,k_i \frac{\omega_i}{\Omega} v(x,t) \quad , \quad C = \sqrt{\frac{E\rho A z^2}{I}\left(1 - \frac{\mu_p}{\mu_g}\right)} \tag{3}$$

E	modulus of elasticity	μ_p	total mass
ρ	density of material	μ_g	dead mass
A	cross section area	ω_i	natural frequency
z	distance from the neutral axis	k	mark of the mode
I	moment of inertia	Ω	exciting frequency

Standards which estimate the degree of molestation caused by vibrations are given in ÖNORM S 9010 and in VDI-standard 2057.

Effect of earthquakes

It is difficult to assess if, and to which extent the forces caused by earthquakes have been the cause of cracks if there is no historical evidence. Some strong earthquakes in the last century caused heavy damage on old masonry buildings (churches, castles, towers). This experience corresponds with the fact that the range of the first natural frequency of many old buildings especially towers is near the range of the peaks in the smoothed averaged earthquake response spectra as shown in Fig.2.

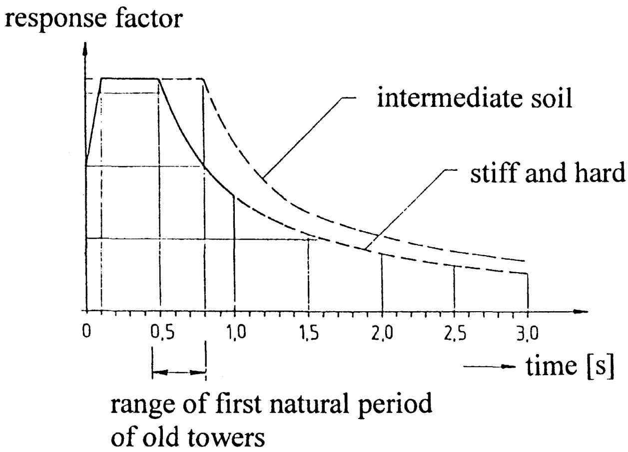

Figure 2: Smoothed averaged earthquake response spectra for intermediate and stiff soil

Waves caused by earthquakes contain low frequencies. For such waves the acceleration which is proportional f^2 is used as a measure for damage. Statistic evaluation of dates of the past allows a determination of a connection between maximal acceleration of soil a and the intensity I of the MSK-scale of Medvedev, Sponheuer and Karnik. The connection is given by equation (3).

$$I = b \lg a + c \quad \text{with} \quad b = 2 - 3{,}5 \text{ and } c = 1{,}5 - 2{,}7 \tag{4}$$

Not only the acceleration and the displacement of soil caused by earthquakes have an adverse effect on buildings but also the duration of such events are important because it needs some time t to set buildings vibrating stationary. Assuming linear elastic behaviour of a building and harmonic exciting the time t depends on the natural frequency f of the building and the damping rate ς and is given by

$$t = \frac{1}{2\varsigma f} \tag{5}$$

Buildings or parts of buildings which contain natural frequencies between $f = 1 - 5Hz$ and a damping rate of 3 percent for instance need $t = 3{,}3 - 16{,}7$ seconds until they fall in stationary oscillation. The period of time of strong

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earthquakes continuous about 0,5 till 7,5 seconds which means that the time of influence is too short to produce damage. Equation (4) is also applicable to shock like excitations caused by traffic and blasting.

Vibrations caused by traffic

To find out the influence of vibration on buildings caused by traffic accelerometers were fitted on the foundation, on ceilings and on the masonry in different levels of the building. The measurements have confirmed that vibrations caused by cars are generally negligible, while lorries produce shock like vibrations if the road surface is in bad condition (pot-holes). Pot-holes were simulated by a 0,05m thick board which the lorry passed with different velocities. Fig.4 shows the measured velocities of vibration in dependence of time of an old tower caused by a passing lorry (weight of the lorry, 35 tons; velocity of the lorry, 40km/h). The graphs A3, A5 and A6 represent the measured velocities in three orthogonal directions in one point of the foundation (the accelerometer A3 was directed vertical and the accelerometers A5 and A6 were directed parallel and radial to the passing road) and A1 and A2 the response of the tower at a point 20m above ground level. Fig.3 shows the accelerometers A3, A5 and A6 mounted on the foundation of the tower. Graph A1 shows distinctly the natural oscillation of the tower (1,66Hz), stimulated by the lorry.

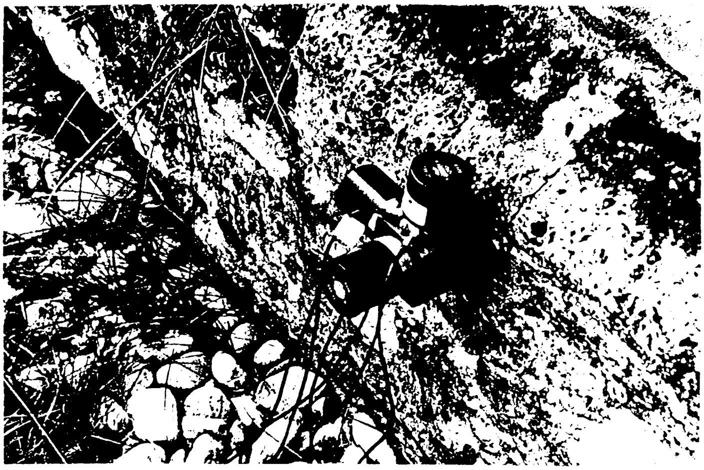

Figure 3: Piezoelectric accelerometers mounted on the foundation of the tower in three directions, in vertical direction and in horizontal direction parallel and radial.

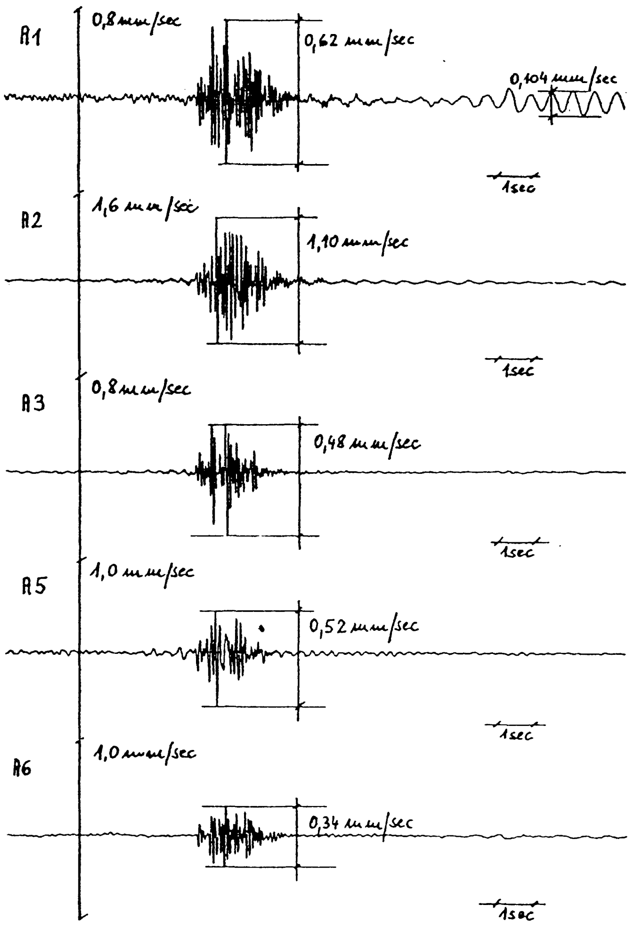

Figure 4: Velocity of vibrations of the tower caused by a passing lorry in some measuring points. Distance lorry-tower, velocity of the lorry 40 km/h.

Vibrations and shocks due to construction work

In the course of building conduit-type sewers by weak soil conditions and high groundwater level bulkheads were build to secure the working people. The sheet piles were driven in by a vibratory hammer. The planned bulkhead passes in a minimal distance an old five store building which is in bad condition of construction. For safety the vibrations of the building were steadily watched by measurements. On the base of running measurements it should be recognised if the building could be damaged and when an other construction method for the bulkhead should have been used.

If the underground is loaded by pile driving the produced vibrations spread out in form of waves. At the beginning of the driving works the waves were produced on the surface (Rayleigh waves), later on by increasing advance of the pile point space waves were produced in the lower zone of the subsoil (compression waves, shear waves).

In the concrete case the soil was noncohesive. By vibrations the granular friction is reduced and the soil is set into a pseudoliquid state. Because of the reduced granular friction the pile penetrates easier. The vibration frequency of the hammer must be nearby the resonant frequency of the system pile-soil, because then a maximum of pile action is obtained. In Tab.1 the range of natural frequencies of different soils can be seen. Fig.5 shows the velocity of vibration in dependence of time measured at the foundation of the building in the surrounding in three directions, in vertical direction and in horizontal direction radial and parallel to the building.

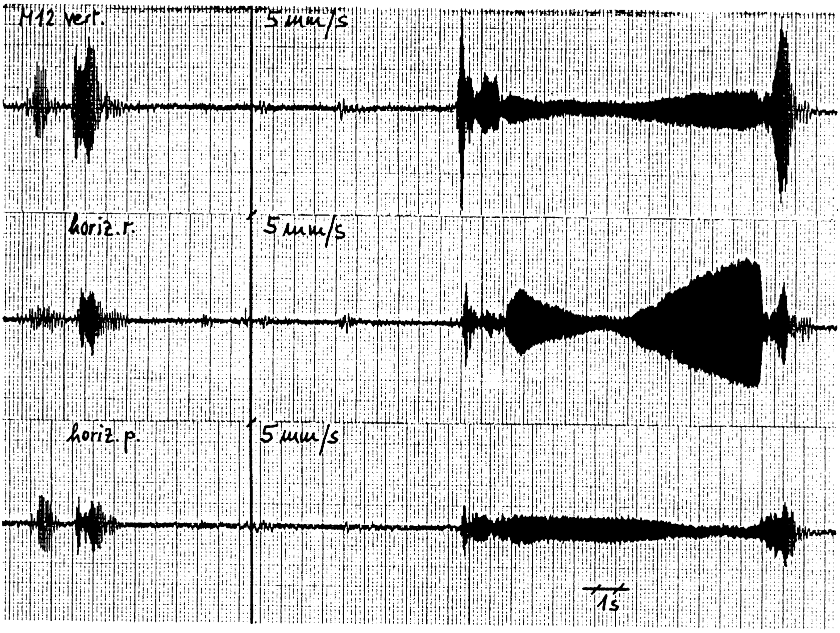

Figure 5: Velocity of vibration of the foundation measured in three directions during ramming the pile (distance pile-foundation ca. 7m)

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Tab.1: Natural frequencies of different kinds of soil

Kind of soil	Natural frequency [Hz]
Marsh	10 – 13
Loamy sand	21 – 23
Loam	ca. 22
Clay	30 – 34
Gravel +sand	ca. 30
Crushed rock	ca. 63

Because the values of these frequencies are often very near by the values of natural frequencies of ceilings of buildings, it is recommendable to vibrate in the neighbourhood of delapidated buildings with a detuned soil resonance frequency. This affects a reduction of ram action but also a reduction of the vibrations of the building. After starting or turning off the vibrator often larger displacements of the building occur if a resonance frequency is passed (Fig. 5).

To watch over the vibrations caused by ramming and extracting the piles the velocities of vibration were measured on the foundation, in the first and fourth floor and on ceilings of the building in three directions.

To get an idea of the size of introduced velocities of vibration for some precalculations measurements were carried out before the bulkhead was built in the neighbourhood of the endangered building. Using equation (1) the expected vertical velocity of vibration in the region of the foundation of the building was received to 1,48 mm/s by supposing a damping coefficient of 0,1, an usual value for coarse sandy soil. Calculating the transmission soil – foundation by a transmission factor of 0,8 [5] a velocity of 1,18 mm/s in the foundation of the building will be received. If the magnification factor of ceilings is chosen between 2 and 5, a value range which is realistic for old buildings, than vertical velocities of vibration of 2,96 mm/s to 5,9 mm/s on the ceilings were obtained.

The maximal vibrations of the building are measured during the ram work nearby the building. The resulting velocity of vibration caused by pile ramming, calculated by equation

$$v_R = \sqrt{v_x^2(t) + v_y^2(t) + v_z^2(t)} \tag{6}$$

was short by 5 mm/s. A value of 5 mm/s is not risky for such a building, but this value was much larger than the precalculated values and values measured before. The reason for this phenomenon may have been in a standing wave which arose between the old bank masonry and the foundation of the building. After clearing away the old bank masonry the high vibrations decreased by a half.

unfavourable case for estimation of vibration, namely taking the maximal values in three directions, the resulting velocity of vibration was obtained on average 3 mm/s. The components of the resulting velocity of vibration sometimes were greater than the precalculated values. The cause may be that sometimes the indriving of the piles was very difficult because parts of wood were bedded in the underground. If the measured values are compared with the Austrian Standard value for special classes of buildings (ÖNORM S 9020) – the concrete buildings belong to the class IV especially delapidated buildings with a limit value of 5 mm/s – the measured values are smaller, which means that the building is not endangered by the vibrations caused by ramming of sheet piles. A similar statement is given , if above mentioned facts are estimated by the German Standard (DIN 4150, part 3) in which the velocity of vibration of the foundation of a delapidated building indifferent in what direction must not exceed an amplitude of 5 mm/s and for the most upper floor 8 mm/s by an exciting frequency of about 30 Hz. The vibration frequency of the vibratory hammer was 27,3 Hz. For continuous vibrations only 60 percent of the above mentioned value is admissible. In the Standard of Switzerland (SN 640312) the lowest limit for the same type of building excited by a frequency of 30 Hz is 3 mm/s, a value which corresponds to the values measured in average.

Conclusion

If dynamic excited structures cannot analyzed by calculation, measurements on structures give the possibility to control the dynamic stress of the building during loading. So it is possible to estimate and to prevent the risk of damage. Tab.2 gives an overview of the dynamic behaviour of different kinds of buildings in dependence of the frequency range of excitation.

Tab.2: Dynamic behaviour of different kinds of buildings in dependence of the frequency range of excitation [4].

Frequency range of excitation [Hz]	0 – 5 [Hz]	5 – 10 [Hz]	10 – 60 [Hz]	>60 [Hz]
Building excited by	Machines			
	Earthquakes	traffic, vibratory hammers	vibratory hammers, blasting	Blasting
Natural frequency of	the whole building		walls, vertical vibrations of ceilings	walls and ceilings
	towers, high rise structures	low buildings		
Mode of vibration	Bending- and shear vibrations of the whole building	Combination of both	bending – and strain vibrations of walls and ceilings	
Dynamic stress	Inertia forces	Combination of both	stress caused by bending and strain	
Significant physical measure	Acceleration	Combination of both	velocity of vibration	

For several classes of buildings empirically founded limits exist in standards (ÖNORM S 9020, Din 4150, part 3, SN 640312). If they were overstepped damages are probable. To find realistic limits additional following points must be taken in account:

- knowledge of the mechanical system and the system parameters of the building (natural frequencies of the building and the ceilings, damping rates, modulus of elasticity, depth of foundation, ...)
- condition of the surrounding soil (natural frequency, damping rate, law of material, soil layers, groundwater level, ...)
- frequency range and time duration of excitation

It is the task of the engineer to decide the appropriate limit for a special problem.

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