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Mechanical vibration — Ground-borne noise and vibration arising from rail systems —

Part 32:
Measurement of dynamic properties of the ground

Vibrations mécaniques — Vibrations et bruits initiés au sol dus à des lignes ferroviaires —

Partie 32: Mesurage des propriétés dynamiques du sol

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Foreword

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The committee responsible for this document is ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

ISO 14837 consists of the following parts, under the general title *Mechanical vibration — Ground-borne noise and vibration arising from rail systems*:

- — *Part 1: General guidance*
- — *Part 32: Measurement of dynamic properties of the ground*

The following parts are under preparation:

- — *Part 31: Measurement for the evaluation of complaints at residential buildings*

Introduction

In order to resolve received vibration and noise from rail systems where there is soil or rock in part of the transmission path between the source at the track and the receiver location in the building, it is necessary to know the noise and vibration transmission function of the ground. To know this necessitates knowledge of the properties of the materials in the ground and their stratification which influence the transmission. In general there is a need to measure or in other ways to estimate these properties. To this aim, this part of ISO 14837 defines methods for measurement and estimation of the relevant dynamic ground parameters.

After a brief survey about ground-borne noise and vibration in Clause 4, the key content of this part of ISO 14837 is outlined in two clauses. Clause 5 defines the relevant dynamic ground parameters, describes how they are interrelated and how they are related to basic physics of wave propagation. Clause 6 deals with methods to determine these parameters: 6.3 presents simple estimation methods based on empirical correlations with conventional geotechnical and engineering geological index parameters; 6.4 presents methods for indirect determination from geotechnical in-situ penetration test data, while 6.5 and 6.6 present more precise methods for direct measurement of the parameters in-situ and in the laboratory.

Mechanical vibration — Ground-borne noise and vibration arising from rail systems —

Part 32:
Measurement of dynamic properties of the ground

1 Scope

This part of ISO 14837 provides guidance and defines methods for the measurement of dynamic properties of the ground through which ground-borne noise and vibration is transmitted, from the operation of rail systems and into foundations of neighbouring buildings. The purpose is to determine the parameters of the ground system which are necessary to reliably predict the noise and vibration transmission, to design railroads and foundations to meet noise and vibration requirements, to design countermeasures and to validate design methods.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 14837-1:2005, *Mechanical vibration — Ground-borne noise and vibration arising from rail systems — Part 1: General guidance*

3 Symbols

The following symbols are used in this part of ISO 14837.

NOTE Abbreviations are summarized in Annex A.

B	dimensionless constant in equation for G_{max}
D	loss-related distance attenuation factor
d	distance travelled by wave
E_{max}	Young's modulus, low-strain dynamic value
e	void ratio, $e = \varphi/(1 - \varphi)$
f	frequency
G^*	complex shear modulus
G_{max}	shear modulus, low-strain dynamic value
G_{sec}	secant shear modulus, dynamic value
I_p	plasticity index
K_{max}	bulk modulus, low-strain dynamic value
k^*	complex wave number

M^*	complex constrained modulus
M_{max}	constrained modulus, low-strain dynamic value
N_{60}	corrected blow count from standard penetration test (SPT)
n	stress exponent in equation for G_{max}
P	vibration power flux
p_{a}	reference stress (pressure), $p_{\mathrm{a}} = 100$ kPa
Q	material quality factor
Q_{c}	rock quality factor
q_{t}	tip resistance from cone penetration test (CPT)
R	radial distance, slanted or along surface
R_0	reference radial distance, slanted or along surface
S_{PP}	power spectrum of wave power flux
S_{r}	degree of saturation
S_{vv}	power spectrum of vibration particle velocity
s_{u}	undrained shear strength
t	time
V	wave speed independent of wave type
$\bar{V}$	average wave speed
V_{p}	compression wave speed
V_{s}	shear wave speed
V_{water}	sound (wave) speed in water
v	particle velocity of vibration
v_0	particle velocity of vibration at reference distance
v_{RMS}	root-mean-square value of vibration particle velocity
W	potential energy in a hysteresis loop
Z_{p}	specific impedance for plane compression waves
Z_{s}	specific impedance for plane shear waves
z	depth coordinate, depth below ground surface
α	distance attenuation exponent
γ_{cy}	cyclic (dynamic) shear strain
Δt	time interval, time difference
ΔW	energy loss in one hysteresis loop

ε_{cy}	cyclic (dynamic) normal strain
ζ	degree of critical damping (damping ratio) of SDOF
η	material loss factor
η_{p}	material loss factor for compression waves
η_{s}	material loss factor for shear waves
η_{max}	material loss factor at very small strains, in linear range
λ	wavelength
λ_{max}	1st Lamé constant, low-strain dynamic value
μ_{max}	2nd Lamé constant, low-strain dynamic value
ν_0	Poisson’s ratio, low-strain value
ξ	damping ratio, $\xi = \eta/2$
ρ	bulk mass density
ρ_{mineral}	mass density of mineral grains
ρ_{water}	mass density of water
σ_{cy}	cyclic (dynamic) normal stress
σ'_{mean}	mean effective stress
σ'_{v}	effective vertical normal stress
τ_{cy}	cyclic (dynamic) shear stress
φ	porosity

4 Transmission of ground-borne noise and vibration

4.1 General

Ground-borne noise and vibration from rail systems are transmitted through the subsurface as mechanical waves. The wave propagation is influenced both by geometrical parameters like shape, extent and stratification of the various bodies of the ground, as well as by the dynamic properties of the individual ground materials.

To determine the influence of the geometrical parameters, it is necessary to understand wave types, wave speeds and impedances which are again dependent on properties of the soils and rocks involved. The distance attenuation of ground-borne noise and vibration is largely controlled by the geometrical effects in addition to the effect of loss mechanisms in the various ground materials.

For ground-borne noise and vibration from rail systems, the typically appearing dynamic strains in the ground are predominantly low and mostly within the range where the materials behave linearly. Elastic wave propagation can therefore be assumed. However, even at these small strains, ground materials do expose some internal energy loss, materializing as a contribution to the distance attenuation. Slightly viscoelastic or hysteretic rather than purely elastic behaviour do therefore better describe ground materials for this purpose.

In an unbounded, homogeneous elastic medium only two fundamental wave types can exist; dilatational waves (p-waves) and shear waves (s-waves). Dilatational waves have their particle motion back and forth along the direction of wave propagation while in shear waves particles move perpendicular to the direction of propagation. Shear waves can therefore be polarized in various planes while p-waves are un-polarized. A real ground is far from unbounded and homogeneous. It has free surfaces and interfaces between various layers and bodies of ground materials with different properties. The dilatational and shear waves in these layers and bodies of the ground are transmitted, reflected and refracted and in other ways interact to form different kinds of inferred waves like surface waves and guided waves along the surfaces and interfaces in the ground. These waves can often carry most of the vibration energy and thus control the distance attenuation. These types of waves are usually dispersive, meaning that vibration propagation properties can vary largely with frequency and wave length.

Since this whole complex of wave types that make up the vibration transmission path through a real ground all originate from the two fundamental waves, the information needed to resolve the transmission wave field is limited to the ground material properties that govern these fundamental waves, in addition to how these properties are distributed throughout the ground. From these properties and the geometry of their distribution in layers and bodies of the ground throughout the transmission path, the whole wave field can be solved, at least theoretically. In practice, however, major simplifications are usually necessary to be able to come up with reasonable solutions for real cases.

Complementary information on these issues are found in Reference [105].

4.2 Ground-borne noise versus vibration — Effect of frequency

What is termed ground-borne vibration and ground-borne noise are both transmitted through the ground and into buildings as mechanical vibration waves. The same physical wave mechanisms and fundamental waves do therefore apply to both noise and vibration. The only distinction is the frequency and thus the wave length. According to ISO 14837-1, the relevant frequency range of ground-borne vibration from rail systems is defined to be the range of whole-body vibration perception, which goes from 1 Hz to 80 Hz (see ISO 8041). The relevant frequency range of ground-borne noise from rail systems is in the audible range and is in ISO 14837-1 considered from about 16 Hz to 250 Hz. Ground-borne noise is reradiated as sound from vibrating building surfaces, while ground-borne vibration is transmitted to the whole body primarily from vibrating floors. In addition to affecting people, ground-borne vibration may also have an effect on sensitive installations and even on building structures.

Even though the basic wave propagation physics is the same, geometrical effects, secondary waves and loss mechanisms usually dominate the ground transmission of mechanical vibration, and introduce frequency-dependent transmission properties. The transmission of ground-borne noise at a given site can therefore be drastically different from the transmission of low-frequency vibration.

5 Parameters for wave propagation in the ground

5.1 General

Clause 5 gives an overview of the most important material parameters for transmission of ground-borne noise and vibration and how they are theoretically composed and interrelated. Clause 6 presents methods to quantify these parameters through empirical estimation and measurement.

5.2 Fundamental wave propagation parameters

In an elastic, isotropic, homogeneous solid, two fundamental plane body wave types can exist: the dilatational wave (p-wave, compression wave) and the shear wave (s-wave). The propagation speed V of these waves is related to the stiffness moduli and bulk (effective) mass density of the soil and rock through which they propagate, according to the following:

a) propagation speed, V_p, of dilatational wave

$$V_p = \sqrt{\frac{M_{max}}{\rho}} \quad (1)$$

b) propagation speed, V_s, of shear wave:

$$V_s = \sqrt{\frac{G_{max}}{\rho}} \quad (2)$$

where

M_{max} is the elastic constrained modulus;

G_{max} is the elastic shear modulus of the medium;

ρ is the bulk (effective) mass density.

By using Pa as unit for the moduli and kg/m^3 for the mass density, the wave speeds from these formulae appear with m/s as the unit.

The subscript max comes from the terminology of soil and rock dynamics. It denotes the maximum, stable plateau value reached for the respective moduli when the dynamic strains are sufficiently low to make the ground materials behave linearly elastic. At higher dynamic strains, non-linearity leads to a reduced secant modulus compared to this maximum value. It is vital to distinguish these dynamic moduli from moduli provided for use in conventional static or quasi-static soil and rock mechanics. Those moduli are determined for much higher stresses (strains) and for more long-term (permanent) loads where non-linearity and creep play an important role. This usually leads to drastically lower moduli than their linear dynamic counterparts. Applying static moduli in rock and soil dynamic calculations can lead to severely incorrect results.

The deformation properties of an isotropic, elastic medium are in general uniquely defined by two independent elastic parameters. These may be M_{max} and G_{max}. By instead introducing Poisson's ratio, ν_0, as the second parameter, the constrained modulus, M_{max}, can be expressed from the shear modulus, G_{max}, through Formula (3):

$$M_{max} = \frac{2(1-\nu_0)}{1-2\nu_0} G_{max} \quad (3)$$

The Poisson's ratio used here with subscript 0 is the one that applies to low dynamic strains in the linear elastic regime and can be largely different from the quasistatic counterpart used in soil and rock mechanics.

The dilatational wave speed, V_p, can further be expressed from the shear wave speed, V_s, and Poisson's ratio, ν_0, as Formula (4):

$$V_p = \sqrt{\frac{2(1-\nu_0)}{1-2\nu_0}} V_s \quad (4)$$

It appears from Formula (4) that V_p is always larger than V_s, i.e. $V_p > V_s$, and that V_p/V_s increases drastically if ν_0 approaches 0,5.

Poisson’s ratio ν_0 can be determined from the speeds of the two fundamental body waves, V_p and V_s, by Formula (5):

$$\nu_0 = \frac{V_p^{\,2} - 2V_s^{\,2}}{2\left(V_p^{\,2} - V_s^{\,2}\right)} \tag{5}$$

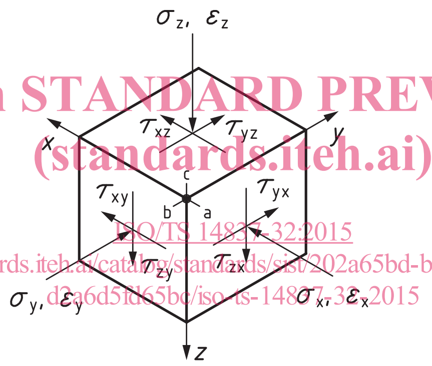
If the Young’s modulus E_{max} is instead introduced as the second elastic parameter it is related to the shear modulus G_{max} and Poisson’s ratio ν_0 through Formula (6):

$$E_{max} = 2\left(1 + \nu_0\right)G_{max} \tag{6}$$

Alternatively, the bulk modulus K_{max} can be introduced as one of the two elastic parameters. Its interrelation to the others reads:

$$K_{max} = M_{max} - \frac{4}{3}G_{max} \tag{7}$$

Figure 1 specifies the stress and deformation quantities as well as the coordinate axes in the ground. Compression is positive, i.e. $\sigma > 0$. The first subscript of the shear quantity τ is the direction and the second is the plane.



Key

a x-plane

b y-plane

c z-plane

$\Delta\tau_{xy} = \Delta\tau_{yx}$

$\Delta\tau_{yz} = \Delta\tau_{zy}$

$\Delta\tau_{zx} = \Delta\tau_{xz}$

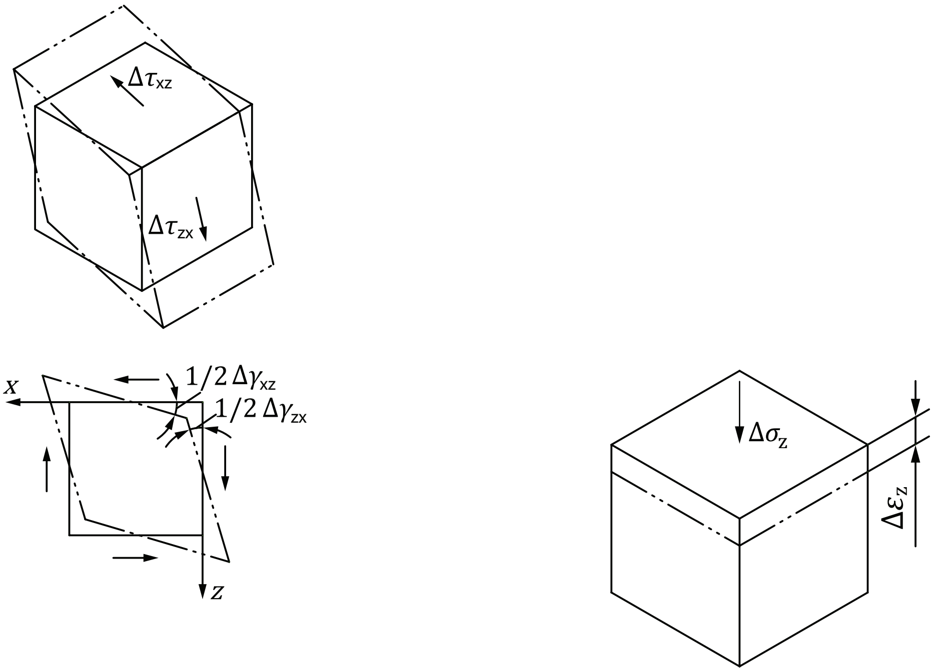
Figure 1 — Stress quantities and coordinate axes in the ground

Figure 2 illustrates the stress and deformation modes of change for which each of these moduli does apply. An alternative set of elastic parameters are the two Lamé constants.

NOTE 1 The two Lamé constants are an alternative set of elastic parameters. They are uniquely related to those already defined. When used for soil and rock materials, it is also convenient to denote the low-strain plateau values of these parameters by the subscript max, even if that is not so commonly used. The Lamé parameters relate to the other parameters through the formulae:

$\lambda_{max} = M_{max} - 2G_{max}$

$\mu_{max} = G_{max}$



a) Shear modulus $G = \Delta\tau/\Delta\gamma$ **b) Constrained modulus** $M = \Delta\sigma_z/\Delta\varepsilon_z$

c) Young's modulus $E = \Delta\sigma_z/\Delta\varepsilon_z$ **d) Bulk modulus** $K = \Delta p/\Delta\varepsilon_{vol}$

a) $\Delta\tau_{xz} = \Delta\tau_{zx} = \Delta\tau$, $\Delta\gamma_{xz} = \Delta\gamma_{zx} = \Delta\gamma$.

b) Sides restricted $\Delta\varepsilon_x = \Delta\varepsilon_y = 0$, no transverse strain.

c) $\Delta\varepsilon_x = \Delta\varepsilon_y = \Delta\varepsilon_T$, sides free $\Delta\sigma_x = \Delta\sigma_y = 0$, Poisson's ratio $\nu = \Delta\varepsilon_T/\Delta\varepsilon_z$.

d) $\Delta\sigma_x = \Delta\sigma_y = \Delta\sigma_z = \Delta p$, $\Delta\varepsilon_x + \Delta\varepsilon_y + \Delta\varepsilon_z = \Delta\varepsilon_{vol}$.

NOTE The illustrations are made for the *z*-direction being the active direction. The definitions equally apply as well for the *x*-direction or the *y*-direction being the active direction.

Figure 2 — Elastic constants and associated deformation modes for isotropic ground

Specific impedance of ground materials and impedance contrasts between materials are important parameters for evaluating the amount of wave energy transferred over interfaces from one ground material body into another and for the formation of interface waves along the boundaries between ground material bodies. It is, however, essential to be aware that for thin layers compared to the vibration wavelength, it is rather the thickness of the layers, and not the impedance contrasts that control the reflection and transmission of vibrations. This is particularly important when assessing the effect of typical vibration isolation screens.

The specific impedances, Z, for plane waves in an elastic isotropic ground material body are defined as follows:

a) specific impedance, Z_p, for plane dilatational waves

$$Z_p = \rho V_p = \sqrt{\rho M_{max}} \tag{8}$$

b) specific impedance, Z_s, for plane shear waves

$$Z_s = \rho V_s = \sqrt{\rho G_{max}} \tag{9}$$

The inverse of the specific impedance is termed specific admittance and may be used alternatively.

The specific impedance has the unit Pa/(m/s) and relates dynamic stress (cyclic stress) in a propagating wave to the corresponding particle velocity. A plane shear wave with particle velocity v which propagates in one direction through a ground material with specific shear wave impedance, Z_s, imposes dynamic shear stress, τ_{cy}, in the plane of wave polarization equal to Formula (10):

$$\tau_{cy} = Z_s v \tag{10}$$

The corresponding shear strain, γ_{cy}, is:

$$\gamma_{cy} = \frac{v}{V_s} \tag{11}$$

Corresponding relations apply for normal stress, σ_{cy}, and normal strain, ε_{cy}, in the direction of propagation of a dilatational wave with particle velocity v:

$$\sigma_{cy} = Z_p v \tag{12}$$

$$\varepsilon_{cy} = \frac{v}{V_p} \tag{13}$$

Formulae (10) to (13) do only apply to one single fundamental wave component travelling in one direction. Where more wave components interact like in standing waves, surface and interface waves, superposition need to be considered and the above relations cannot be applied immediately.

The average mechanical power density flux, P, in W/m^2, transmitted in the direction of a propagating fundamental plane wave component at a single frequency is:

$$P = \frac{1}{2} Z \hat{v}^2 \tag{14}$$

where

Z is the specific impedance of the ground for the wave type in question;

$\hat{v}$ is the particle velocity amplitude of that single frequency component of the wave.

Correspondingly, for broad-band vibration propagation, the spectral density, S_{PP}, of the power flux is:

$$S_{\mathrm{PP}}(f) = \frac{1}{2} Z\, S_{\mathrm{vv}}(f) \tag{15}$$

where $S_{\mathrm{vv}}(f)$ is the power spectral density function of the particle velocity of the ground vibration propagated by the wave. By applying (m/s)^2/Hz as unit for $S_{\mathrm{vv}}(f)$, the resulting unit for $S_{\mathrm{PP}}(f)$ is (W/m^2)/Hz.

For a broad-band vibration with an r.m.s. value of particle velocity, v_{RMS}, the total power flux P_{tot} is:

$$P_{\mathrm{tot}} = \frac{1}{2} Z v_{\mathrm{RMS}}^2 \tag{16}$$

Vibration events from rail systems are transient and time varying. When it comes to representative values of particle velocities, strains, stresses and power, a form of running r.m.s. time domain amplitudes or running spectral values can be the most relevant as pointed out in ISO 14837-1:2005, 7.4. Further, from experience, a 1 s running time window analysis gives the most representative values for evaluation of the dynamic performance of soil and rock materials.

For resolving low frequencies around 1 Hz, a longer integration time is needed, typically 3 s to 5 s. However, this should be implemented with care, ensuring that the low-frequency content of the signal is sufficiently stationary over this period of time.

Strictly, the above formulae are valid for plane waves only. However, they can be used as good approximations for the real waves that appear in the handling of ground-borne noise and vibration related to rail systems. Only in particular situations like close to the vibration source, i.e. in the nearfield, spherical wave theory might need to be considered. Nearfield effects are further discussed in 5.5.

NOTE 2 For theory on spherical waves, see Reference [90].

5.3 Material loss and non-linearity

For ground-borne noise and vibration from rail systems, the dynamic strains in the ground are mostly within the range where the materials have a nearly linear behaviour. However, even at small strains, ground materials do expose some energy loss which materialize as a small amount of attenuation. Only close to the source of dynamic loads in the track structure, in close vicinity to the track, at sharp edges and discontinuities somewhat higher dynamic strain can appear. For critical train speed and train speeds exceeding the Rayleigh wave speed in the ground (trans-Rayleigh), excessive track and ground vibration can appear and the strains can be so high that non-linearity needs to be accounted for to simulate, understand and mitigate the condition.[102] For ground-borne noise and vibration, materials can conveniently and with sufficient accuracy be modelled as viscoelastic (Kelvin-Voigt model), with a material loss factor, η, defined as:

$$\eta = \frac{1}{2\pi} \cdot \frac{\Delta W}{W} \tag{17}$$

where

W is the potential energy in a hysteresis loop (load cycle);

ΔW is the energy loss in one load cycle.

The material loss factor quantifies the energy loss in each load cycle as a vibration wave passes by, as shown in Figure 3.