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Mechanical vibration — Measurement of vibration generated internally in railway tunnels by the passage of trains

Vibrations mécaniques — Mesurage des vibrations produites à l'intérieur des tunnels ferroviaires par le passage des trains

Reference number
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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

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*.

This second edition cancels and replaces the first edition (ISO 10815:1996), of which it constitutes a minor revision with the following changes:

— normative references have been updated;

— subclause numbering has been updated;

— bibliography has been updated.

Introduction

Railway tunnels are regularly exposed to vibration originating from internal sources (trains and service carriages. maintenance work, etc.).

In this document, only vibration resulting from the passage of trains is considered.

Vibration is measured in tunnels for different purposes, which are summarized as follows.

When a tunnel is reported to be exposed to vibration which might cause concern regarding its integrity, suitable measurements (see 9.2) should be taken to assess whether the levels are acceptable.

Measurements of vibration might be carried out in the following cases:

— when the maximum allowable vibration level has been established and a regular check is required (see 9.3);

— when the dynamic performance of a newly built tunnel has been predicted and performance has to be checked against design data (see 9.2);

— a special situation may arise when the tunnel has been exposed to abnormal external action (e.g. due to fires, earthquakes, blasting, pile drivers or demolition of nearby buildings) and the integrity of the structure has to be checked (see 9.2);

— when any modification to the track and/or internal vibration sources (e.g. load on vehicle axles) has been made.

Mechanical vibration — Measurement of vibration generated internally in railway tunnels by the passage of trains

1 Scope

This document establishes the basic principles for measuring, processing and evaluating vibration generated internally in railway tunnels by the passage of trains.

By establishing a standard procedure, comparative data may be obtained on response of the tunnel elements from time to time, provided that the excitation source is the same. Data obtained in different tunnels may also be compared.

The measurements considered in this document concern the response of the structure and secondary elements mounted in the tunnel. They do not concern the response of persons in the tunnel or in its vicinity, or of passengers on trains running through the tunnel.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 1683, *Acoustics — Preferred reference values for acoustical and vibratory levels*

ISO 5348, *Mechanical vibration and shock — Mechanical mounting of accelerometers*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
tunnel
underground structure in which passenger trains, freight trains or service trains travel

3.2
background noise
sum of all the signals except the one under investigation

4 Factors affecting vibration

4.1 Tunnel-related factors

4.1.1 General

The dynamic characteristics of a tunnel depend largely on its geometry, secondary elements, depth of the tunnel and soil properties.

A lined tunnel is usually a system of discrete elements (concrete, ventilation channels, etc.) each coupled with the soil. They may have different response characteristics and coupling with the surrounding soil and/or rock.

4.1.2 Tunnel types and conditions

There are many kinds of tunnels, all of which respond to vibration in a different way. Examples are given in Annex B.

4.1.3 Natural frequencies and damping ratios

For this document, the frequencies of interest are likely to relate to the response of the tunnel elements and not to a fundamental frequency of the tunnel cavity in the surrounding medium. The natural frequencies of these elements can be determined as follows:

— measurement of the response of the tunnel elements when they are affected by a large, transient external influence such as, for instance, pile driving or blasting;

— the use of a shaker as a mono-frequency source together with measurement of the response amplitude;

— measurement of the response using ambient excitation and spectrum analysis.

Accurate determination of damping is a difficult task, especially for tunnels containing both lightly damped elements, such as beams, and elements which are in firm contact with the tunnel surfaces and therefore are highly damped due to wave radiation.

4.1.4 Soil

The soil surrounding the tunnel has an important effect on the stiffness of the tunnel and on the tunnel response to vibration, and as such is therefore of main concern when making predictions about response. Its characteristics depend on soil particle size, compaction, saturation, underground water level and bedding, and upon amplitude, frequency and duration of the excitation.

4.2 Source-related factors

The vibration produced by the passage of trains may be classified according to the signal type, the duration and the frequency range (see ISO 4866).

The signal depends on the mechanical properties of the train, the track, the wheel-rail contact and on the loading and speed of the train.

The frequency range to be analysed depends on the spectral distribution of the excitation forces and the transfer function from the source to the tunnel walls or linings.

The frequency range from 1 Hz to 100 Hz covers the responses of different elements of the tunnel. On the rail, the frequency range of interest is usually up to 2 kHz, although higher frequencies are often present.

5 Quantities to be measured

In the frequency range of interest for tunnel vibration, usually a kinematic value such as velocity or acceleration is measured.

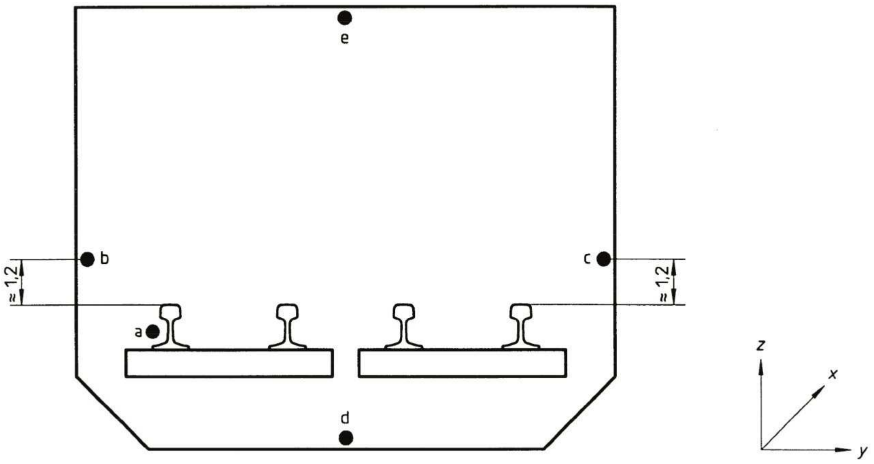
In the lower frequency range, velocity measurement is preferred although in the higher frequency range, instrumental factors dictate that acceleration be measured.

6 Measurement methods

6.1 Positioning the transducers with respect to passage of trains

Ideally, a straight stretch of the tunnel, at least 200 m long, should be available for the readings. The transducers should be placed away from any visible singular features (major cracks, water seepages, switch points and crossings), unless the effect of such a feature is to be investigated. To investigate the tunnel response, the transducers should preferably be oriented in line with the three principal axes of the tunnel (one vertical, two horizontal; see Figure 1).

Dimensions in metres



Type of test	Measurement points
Full (see 9.2)	a, b, c, d, e
Limited (see 9.3)	b, d, e

Figure 1 — Measurement points at a cross-section, depending on the type of test

In the following assignment of measurement points, it is assumed that the train is running over the left track (see Figure 1).

For full and limited tests (see 9.2 and 9.3), the transducers should be arranged as follows:

— on the invert at the cross-section vertical centre line (point d of Figure 1), between two sleepers in the case of tracks laid on ballast, or between two successive fasteners or rail spikes for other types of track;

— on the vault (point e of Figure 1), directly above point d;

— on the tunnel wall close to the track where the train will run, 1,20 m above the level of the rails (point b of Figure 1).

In order to investigate the relationship between trains as excitation sources and vibration transmitted to the tunnel, measurements should be made on the foot of the rail perpendicular to the plane of the rails (point a of Figure 1).

Position a is prone to local effects and its typicality and stability should be established before its selection as a control point for a limited test.

Allowance should be made for the slope shaping the foot of the rail (see Figure 2).

If the invert is not accessible, the transducer should be placed at the nearest suitable point and any element between the transducer and the invert should be indicated.

For full tests (see 9.2), readings shall also be taken at other two sections away from the middle section (typically 20 m) in order to minimize local influences. However, when the signal issuing from two corresponding points on two sections placed 20 m away from each other are equal, measurements may be taken at one section only.

If, however, such readings differ systematically by more than 25 % (2 dB), they should be discarded and a third section considered.

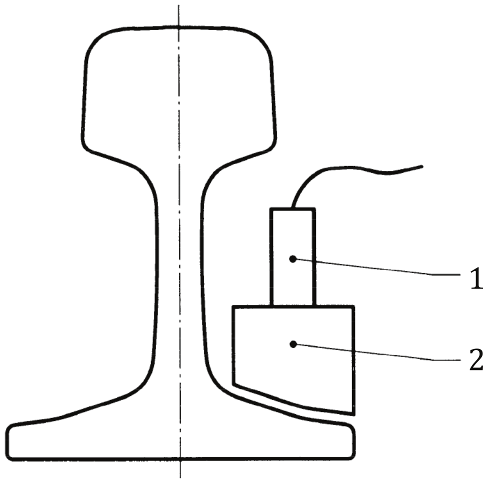
When the readings taken at all three sections are in disagreement, the local conditions should be examined and another measurement section selected.

6.2 Fastening the transducers

For mounting the transducers, the principles laid down in ISO 5348 shall be followed, so as to reproduce the motion of the vibrating elements, minimizing the response due to the mounting system.

The mounting, therefore shall be rigid and as light as possible.

When fixing transducers to the foot of a rail, a shaped steel plate should be rigidly fixed between the transducer and the rail (e.g. welded to the rail); otherwise, the transducers cannot be mounted perpendicular to the foot of the rail (see Figure 2).



Key

1 transducer

2 shaped steel plate

Figure 2 — Measurement point at the foot of a rail

It is very important that the system of transducers, mounting support and bolt has a mounting resonance frequency much higher than the upper frequency of the range of interest (see ISO 5348).

It may be noted that accelerometers can be very sensitive to air-coupled response during the passage of a train. It is, therefore, necessary to protect them from airborne sound.

6.3 Signal-to-noise ratio

It is advisable to measure the background noise (see 3.2), whenever possible, deactivating the sources of vibration to be measured. For instance, when the vibration caused by a passing train is recorded, the signal present in the absence of the train should be recorded and processed in the same way. The results of both are then compared; their ratio is the signal-to-noise ratio S/N.

When the signal is more than three times higher than the noise (S/N > 10 dB), the readings can be accepted without correction. When the signal is between two and three times higher than the noise (6 dB ≤ S/N ≤ 10 dB), the readings should be corrected and this should be mentioned in the test report.

When the signal is less than twice as high as the noise (S/N < 6 dB), the readings are unreliable and merely have an indicative value.

7 Measuring instruments

The choice of transducers is important for correct evaluation of vibratory motion (see ISO 4866). It should be made with regard to the quantity to be measured, taking into account its frequency (see 4.2) and amplitude ranges and the environment in which it needs to function.

Particularly important is the resonance and the phase response of transducers, and the complex transfer function of integrators, which can lead to different results for the same mechanical input.

In most measurements on a rail, an accelerometer is used; on the other points it is suggested that geophones be used with a natural frequency lower than the minimum investigated frequency.

The measuring chain should be calibrated before and after the sequence of measurements and at least every two years the components of the measuring chain should be calibrated by an accredited laboratory, which issues the relevant certification.

It is recommended that, except on a rail, a velocity transducer be used and values expressed in millimetres per second. Each measured velocity component should be reported with its frequency of oscillation. If a decibel scale is used, the reference quantity is 10^{-6} mm/s in accordance with ISO 1683 (see Note).

If there is a need to compare the results of an accelerometer with the velocity outputs of other transducers, an integration (preferably digital) should be performed with the original acceleration time history and Fourier spectrum reported. Electronic integration, such as via a low-pass filter, may produce different results, depending on the amplitude and phase components of the original signal and complex function of the integrators.

For the decibel scale, the reference acceleration is 10^{-6} m/s^2 in accordance with ISO 1683.

NOTE The decibel scale widely used in acoustics can give rise to some confusion when adopted for structural vibration if the kinematic quantity upon which it is based, i.e. velocity (mm/s) or acceleration (m/s^2), is not stated along with the appropriate reference value (see ISO 1683). This is especially the case where vibration is to be compared.

8 Measurement for internal sources

8.1 Conditions of the track

For the tests according to 9.2 and 9.3, the track should be in good condition, free from visible flaws and corrugation.

8.2 Conditions of the train

For the tests according to 9.2 and 9.3, the vehicle should be in a well-maintained condition. Specifically, wheels should be free of flats and other visible flaws. The vehicle should travel empty, a driver and signal and inspection crew being alone on board. The train composition should be as for normal operation. Passenger vehicle speeds should be as follows:

— 11 m/s (40 km/h) for tramcars;

— 17 m/s (60 km/h) for metropolitan railway trains;

— 22 m/s (80 km/h) for rapid transit vehicles;

— the maximum speed allowed at the measurement section.

During vibration recording, the vehicle should be coasting, except for the last condition (maximum speed).

9 Types of test

9.1 General

The tests can be of two types: full tests and limited tests.

In any test, for recording of levels with analogue instruments, an integration time of 1 s should be used.

9.2 Full tests

These tests are designed to establish that the tunnel system is performing within the required specifications. They are also carried out to check the effect of any significant structural modification. These tests should provide information for full dynamic analysis.

In this case:

— there are three measuring sections 20 m apart, as specified in 6.1;

— three single transducers, one for each orthogonal cartesian axis, or a triaxial unit should be placed at each measurement point (see 6.1);

— a minimum of three passages of the train through the measurement section, in one direction of travel only, should be recorded;

— with analogue instruments, the highest r.m.s. value of the time history should be read (integration time 1 s);

— the three values that do not differ by more than 11 % (1 dB) in overall value and 40 % (3 dB) in each frequency band should be taken as true values; the arithmetic means should then be calculated to obtain the values of each of the velocity components v_x, v_y, v_z;

— the S/N ratio (see 6.3) should be higher than 10 dB as overall values and at least 6 dB in each frequency band; three orthogonal components should be recorded.

9.3 Limited tests

Limited tests are intended to monitor specific characteristics and are routinely performed at regular time intervals.

In this case:

— one measurement section only is needed;

— at each point one transducer only is needed, perpendicular to the relevant plane (see 6.1);

— examination of the time history is likely to be sufficient;

— it is sufficient when S/N ≥ 6 dB (see 6.3);

— a minimum of three passages should be recorded; the three values that do not differ by more than 3 dB shall be taken as true and the arithmetic mean calculated and rounded off to the nearest whole decibel.

This test may be affected by train performance. Although it is specified that the train should be in a good state of repair (see 8.2), a “control” measuring section, with little traffic, should be available.

For experimental tracks, the time interval normally should not exceed one year in the first five years and two years in the following six years.

Such a control section should be used to check the vibration velocity obtained one year or two years earlier with the above mentioned train, so as to determine any difference ascribed to the train rather than to the conditions of the tunnel and permanent way.

10 Evaluation of measurements

The simplest procedure is to note the maximum value of the kinematic quantity being measured or the highest r.m.s. value with an integration time of 1 s (see 9.2).

In particular circumstances, it is possible to calculate a kinematic value by integrating or differentiating the measured one. These operations, however, performed either using analogue or digital methods, can be affected by intrinsic errors which in some cases are difficult to quantify.

One solution is to perform at least at one measurement point, a simultaneous recording of two kinematic values to be able to evaluate the quality of the integration (or of the differentiation).

It should be noted that for complex waveforms, low-frequency integration requires care and knowledge of the amplitude and phase response of the transducers and measurement chain. Procedures and limits of the signal processing should be described and assessed in detail.

The time history, over an appropriate duration, should be measured in the three orthogonal directions unless it has been experimentally shown that fewer than three components are sufficient for the problem being considered.

The frequency range of the vibration in a tunnel (1 Hz to 100 Hz, see 4.2) normally requires measurement of the vibration velocity; therefore, velocity values are commonly found in the literature and in some national standards covering the vibration of structures (see, for instance, Reference [4]).

In full tests, one-third-octave band analysis may be performed and, in special circumstances, narrow-band analysis (bandwidth <1 Hz) may be undertaken to yield Fourier spectra.

11 Test report

The test report should contain the following:

— the place, date and name of supervising engineer and operator;

— a description of the tunnel and track structure;

— a dimensioned drawing of a cross-section of the tunnel showing the position of measurement points and of the track;

— geotechnical data for the ground surrounding the tunnel;

— the position and details of attachment of the transducers;

— the type and purpose of the test;

— the type of instruments, date of last calibration and date of manufacture;

— the background noise level and signal-to-noise ratio;

— a description of the excitation source (e.g. speed of train, its composition and axle load);

— the overall levels and one-third-octave band levels (depending on the type of test), preferably in graphic form, with one-third octave corresponding to 5 mm and 10 dB corresponding to 20 mm;

- the highest value of the velocity should be expressed in millimetres per second and of the acceleration expressed in metres per second squared;
- the acceleration data, if any integration is performed;
- the integration time;
- indication of the standards adopted and of the vibration specifications, if any.

Annex A
(informative)

Tunnel vibration resulting from the passage of trains

Typically, the rail excitation is non-stationary and random, lasting about 10 s for urban railways.

As a guideline to the vibration values which can occur in tunnels, it may be noted that on tunnel walls, the following values have been measured:

— 0,01 mm/s to 0,08 mm/s in Milan depending on the kind of track; values up to 1 mm/s have been found under conditions of bad maintenance;

— 0,01 mm/s to 0,03 mm/s in Paris (see Reference [6]).

Indicatively, the attenuations are as follows:

a) rail/invert: 20 dB to 40 dB depending on the track;

b) invert/wall: 10 dB to 20 dB depending on the kind of tunnel.

Annex B
(informative)

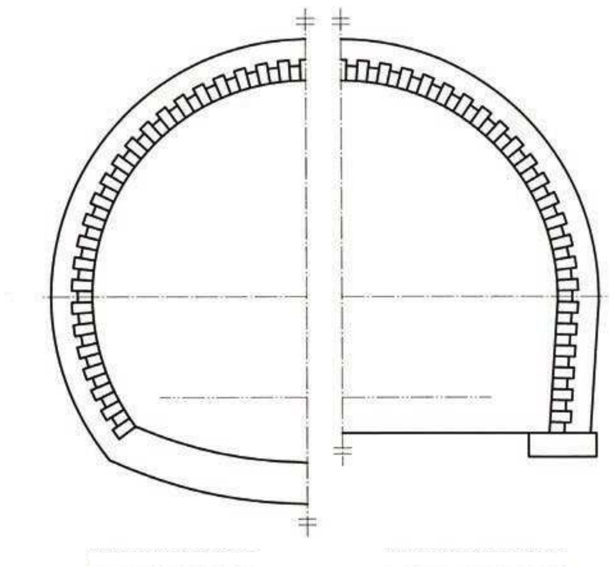
Examples of railway tunnels

B.1 Ancient works (constructed before 1960)

B.1.1 Underground tunnels

B.1.1.1 Masonry tunnels

These may be of rock (in courses or not in courses), with or without invert structural closure (see Figure B.1). They may also be of concrete (see Figure B.2) or of mixed masonry (see Figure B.3).



a) With invert structural closure b) Without invert structural closure

Figure B.1 — Tunnel with rock masonry in courses

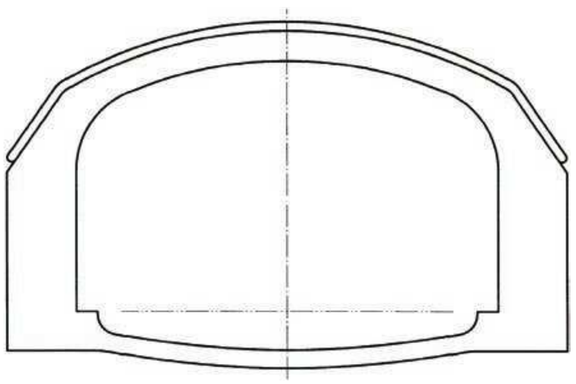
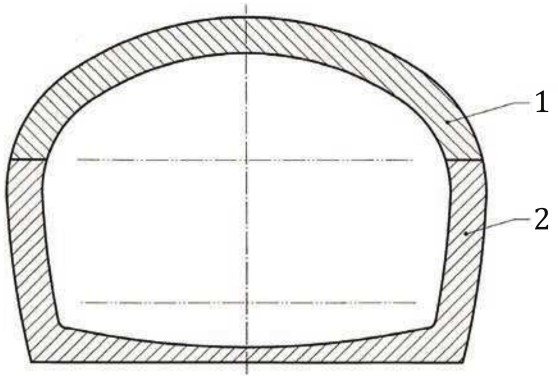


Figure B.2 — Underground tunnel made of concrete



Key

1 rock masonry

2 concrete

Figure B.3 — Tunnel with mixed masonry

B.1.1.2 Tunnels made up with metallic elements

These may be cast segments (apparent in intrados or embedded in concrete) with or without invert structure (see Figure B.4 and Figure B.5).

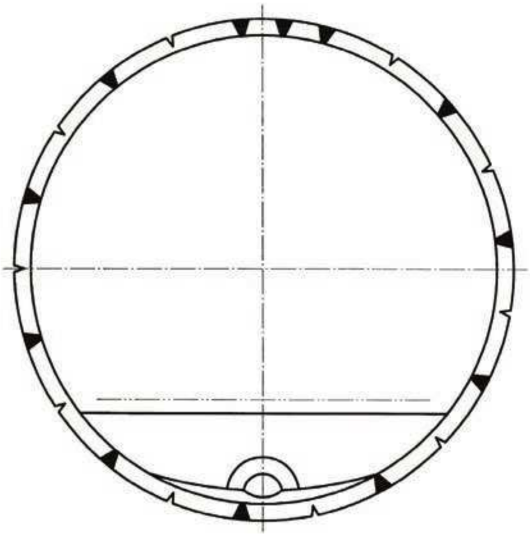
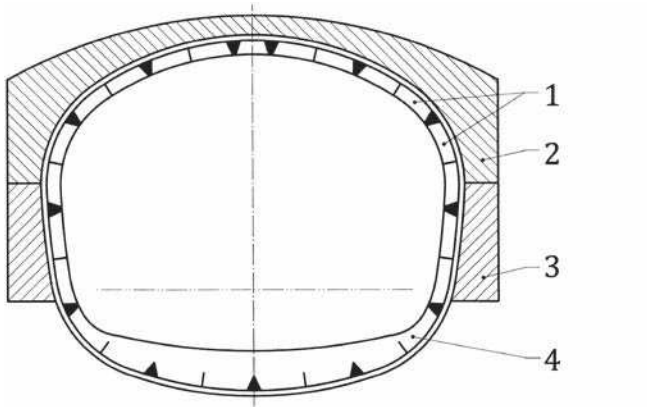


Figure B.4 — Tunnel made up of cast segments apparent in intrados



Key

1 cast arch segments

2 rock masonry

3 concrete

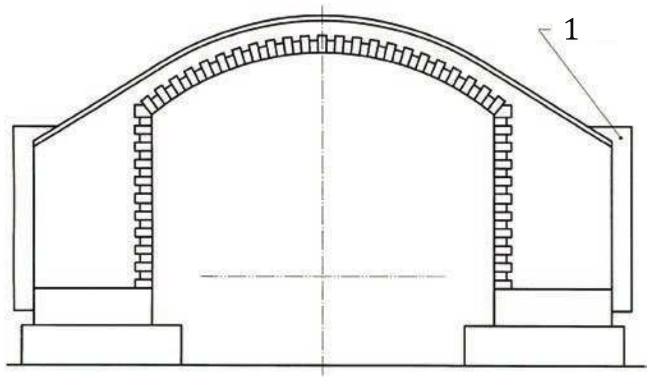
4 reinforced concrete

Figure B.5 — Tunnel made up of cast segments

B.1.2 Works executed above the surface

B.1.2.1 Vaulted works

These may be of rock (in courses or not in courses) or of concrete, with or without invert structural closure (see Figure B.6).



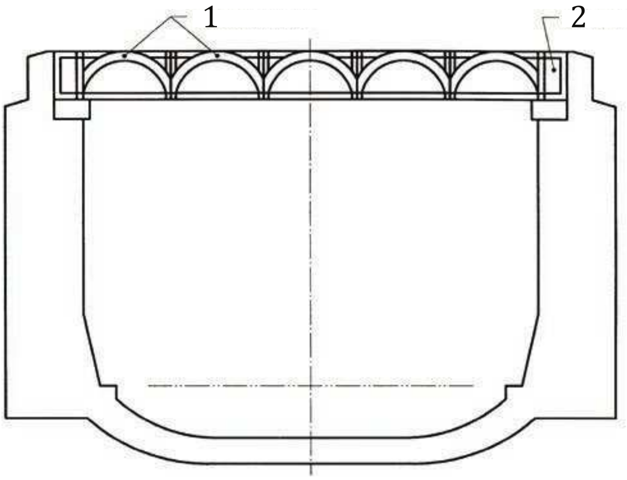
Key

1 dry-rock wall

Figure B.6 — Above-surface tunnel made of masonry

B.1.2.2 Plate-covered works

These may have a metallic covering, without crown structural closure (see Figure B.7) or may be of reinforced concrete with crown structural closure (see Figure B.8).



Key

1 small masonry vault

2 metallic shelf

Figure B.7 — Metallic covered tunnel

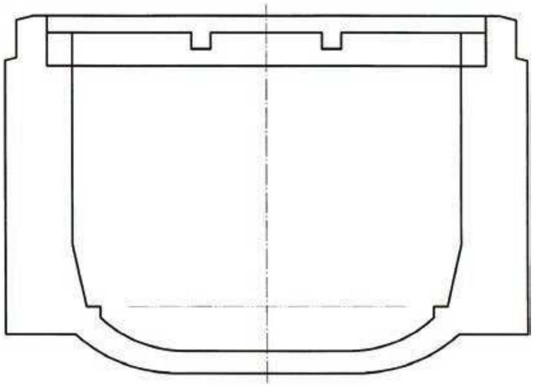
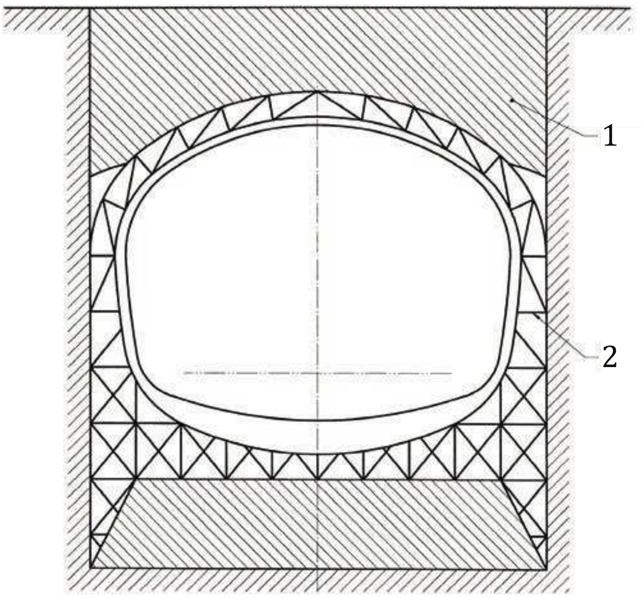


Figure B.8 — Tunnel with reinforced concrete cover

B.1.3 Cut-and-cover construction

These may have a metallic covering (see Figure B.9) or may be of reinforced concrete.



Key

1 backfill

2 metallic covering

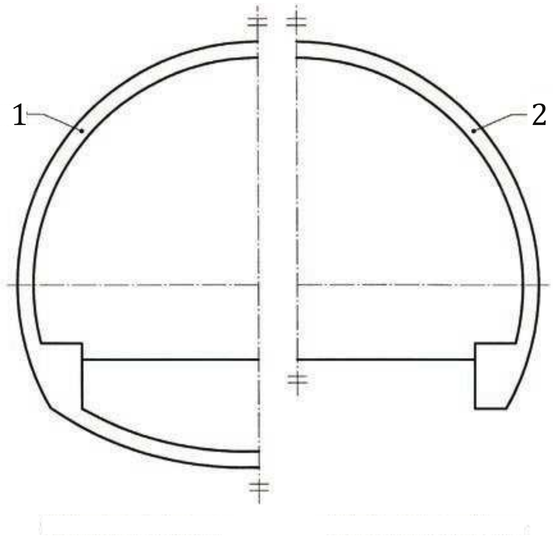
Figure B.9 — Tunnel with metallic covering

B.2 Recent works (constructed after 1960)

B.2.1 Underground tunnels

B.2.1.1 Tunnels with concrete cast *in situ*

These may be not reinforced (see Figure B.10) or may be reinforced (with abandoned supporting arch or with reinforcement), with or without invert structural closure (see Figure B.11).



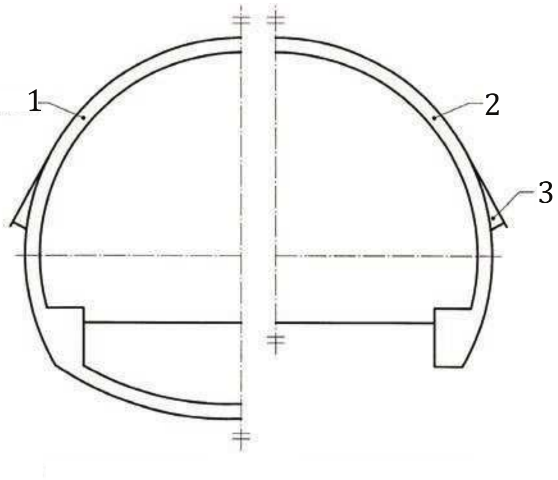
a) With invert structural closure b) Without invert structural closure

Key

1 cast concrete

2 concrete cast against shutters

Figure B.10 — Underground tunnel with concrete cast *in situ*



a) With invert structural closure b) Without invert structural closure

Key

1 cast concrete

2 concrete cast against shutters

3 embedding concrete

Figure B.11 — Underground tunnel with concrete cast *in situ* and reinforced with abandoned supporting arch

B.2.1.2 Tunnels made up with prefabricated elements

These may be entirely prefabricated, with metallic arch segments or reinforced concrete segments (see Figure B.12) or may have only the vault prefabricated (with arch segments or reinforced concrete arch), with or without invert structural closure (see Figure B.13).

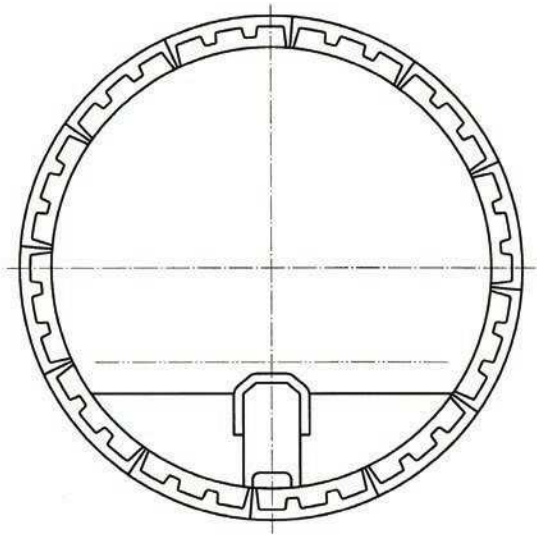


Figure B.12 — Reinforced concrete segmented arch tunnel

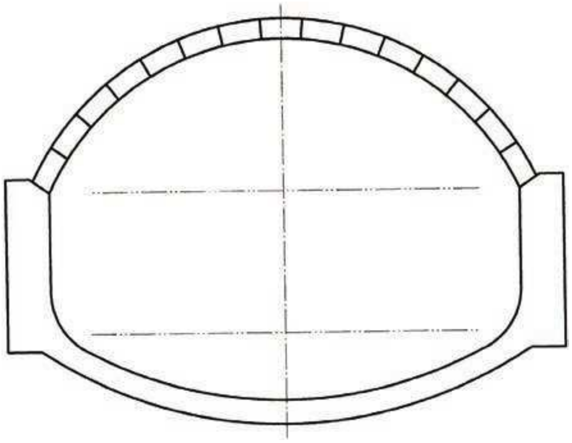
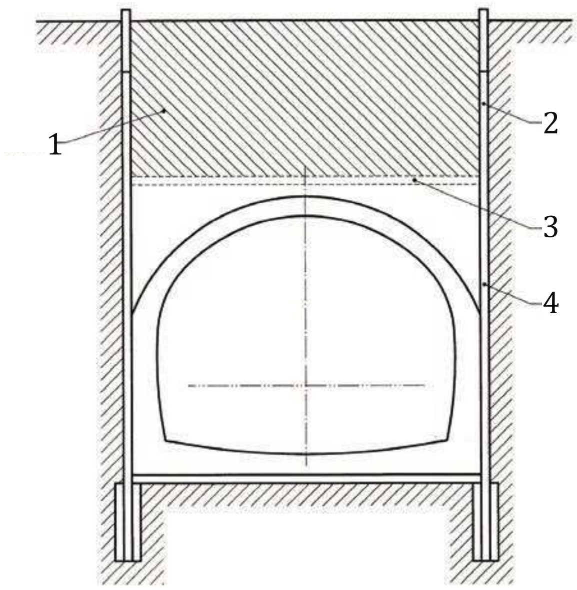


Figure B.13 — Concrete tunnel with reinforced concrete segmented arch

B.2.2 Works executed above the surface and set in excavation

B.2.2.1 Vaulted works

These may be in concrete or reinforced concrete, with or without structural closure (see Figure B.14).



Key

1 backfill

2 retaining structure

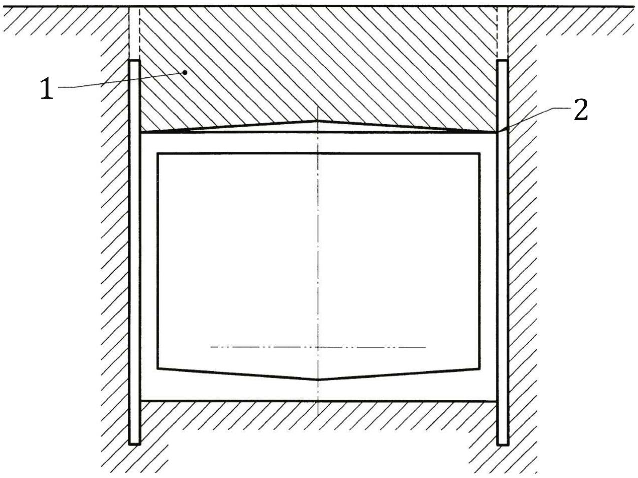
3 backfill support

4 Berlin-type shell

Figure B.14 — Reinforced concrete tunnel executed above the surface

B.2.2.2 Rectangular works (in reinforced concrete)

These may be opened (slabs not prestressed) or closed (slabs prestressed) (see Figure B.15, Figure B.16 and Figure B.17).

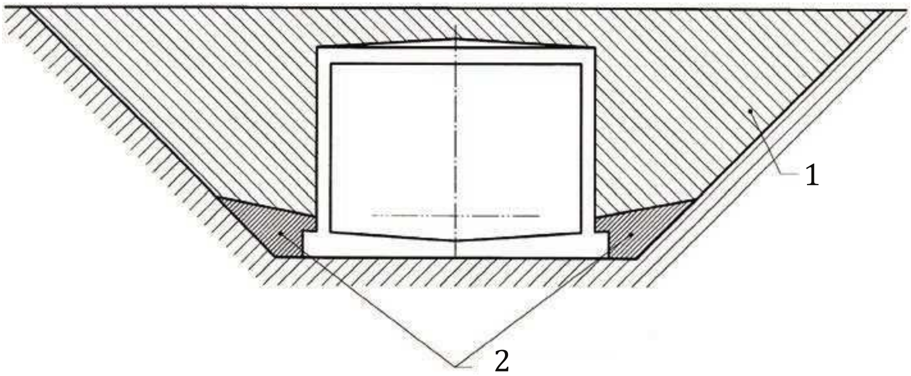


Key

1 backfill

2 abandoned section

Figure B.15 — Closed rectangular work with reinforced concrete

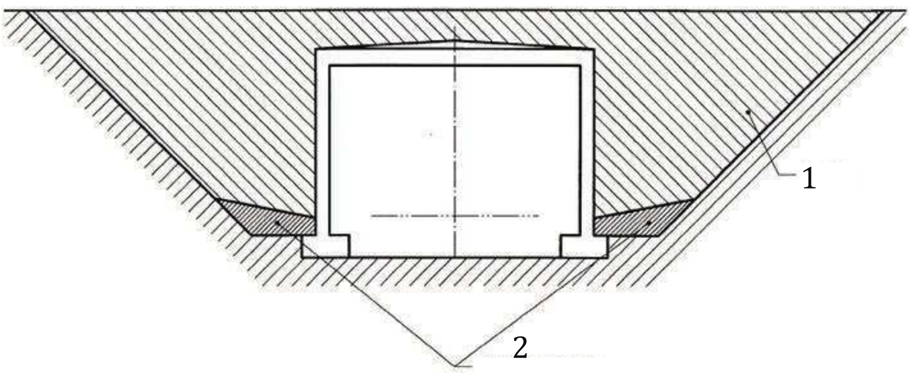


Key

1 backfill

2 reinforced concrete

Figure B.16 — Closed rectangular work set in reinforced concrete slab



Key

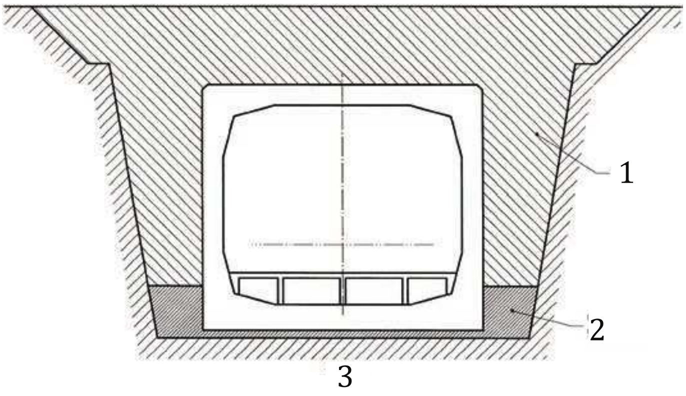
1 backfill

2 reinforced concrete

Figure B.17 — Open rectangular work with reinforced concrete slab

B.2.3 Finished work

See Figure B.18.



Key

1 backfill

2 concrete cast under water

3 clavage

Figure B.18 — Work completed in reinforced concrete

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[2] ISO 14837 (all parts), *Mechanical vibration — Ground-borne noise and vibration arising from rail systems*

[3] ISO 18431 (all parts), *Mechanical vibration and shock — Signal processing*

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