INTERNATIONAL STANDARD

ISO 14963

First edition
2003-12-01

Mechanical vibration and shock — Guidelines for dynamic tests and investigations on bridges and viaducts

Vibrations et chocs mécaniques — Lignes directrices pour essais et études dynamiques sur ponts et viaducs

Reference number
ISO 14963:2003(E)

PDF disclaimer

This PDF file may contain embedded typefaces. In accordance with Adobe's licensing policy, this file may be printed or viewed but shall not be edited unless the typefaces which are embedded are licensed to and installed on the computer performing the editing. In downloading this file, parties accept therein the responsibility of not infringing Adobe's licensing policy. The ISO Central Secretariat accepts no liability in this area.

Adobe is a trademark of Adobe Systems Incorporated.

Details of the software products used to create this PDF file can be found in the General Info relative to the file; the PDF-creation parameters were optimized for printing. Every care has been taken to ensure that the file is suitable for use by ISO member bodies. In the unlikely event that a problem relating to it is found, please inform the Central Secretariat at the address given below.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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.

ISO 14963 was prepared by Technical Committee ISO/TC 108, *Mechanical vibration and shock*, Subcommittee SC 2, *Measurement and evaluation of mechanical vibration and shock as applied to machines, vehicles and structures*.

Introduction

Dynamic investigations can contribute to the control of structures through the measurement, interpretation and reporting of their response to dynamic excitation. The design of the tests should correspond to the specific purposes of the investigation and the type of structure. The measurements usually lead to a characterization of the dynamic behaviour of the whole bridge, including foundations, or local structural elements in the frequency and/or time domain.

This International Standard is for use with permanent design, temporary works, construction and maintenance of bridges and viaducts as defined. Dynamic tests may be undertaken with the objective of

— evaluating the safety of bridge structures under construction,

— confirming after construction the values used in design,

— evaluating dynamic characteristics to be used in wind and earthquake analysis and for live loading,

— monitoring of real bridges in-service and detecting any damage,

— confirming reinforcement effects on bridges,

— bridge diagnosis under an emergency, and

— diagnostic testing as a basis for condition monitoring.

Dynamic investigation may be used as part of the design process (design by testing) for new construction or for maintenance and rehabilitation management.

Mechanical vibration and shock — Guidelines for dynamic tests and investigations on bridges and viaducts

1 Scope

This International Standard provides guidelines for dynamic tests and investigations on bridges and viaducts. It

— classifies the testing as a function of construction and usage,

— indicates the types of investigation and control for individual structural parts and whole structures,

— lists the equipment required for excitation and measurement, and

— classifies the techniques of investigation with reference to suitable methods for signal processing, data presentation and reporting.

This International Standard provides general criteria for dynamic tests. These can supply information on the dynamic behaviour of a structure that can serve as a basis for condition monitoring or system identification. The dynamic tests detailed in this International Standard do not replace static tests.

The tests may seek to define all of the dynamic characteristics of each mode of vibration examined (i.e. frequency, stiffness, mode shape and damping) and their non-linear variation with amplitude of motion.

This International Standard is applicable to road, rail and pedestrian bridges and viaducts (both during construction and operation) and also to other works (or types of works), provided that their particular structure justifies its application.

The application of this International Standard to special structures (stayed or suspension bridges) requires specific tests which take into account the particular characteristics of the work.

NOTE Hereinafter in this International Standard, the term “bridges” means “bridges and viaducts”.

2 Normative references

The following referenced documents are indispensable for the application 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 2041, *Vibration and shock — Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 2041 apply.

4 Classification

4.1 General

The dynamic behaviour of bridges is highly influenced by the type of superstructure, static design and construction method, deck cross-section, support conditions, foundation type and elevation substructures (piers and abutments). Since these characteristics need to be considered in dynamic tests, a classification of bridges is given in 4.2 to 4.4. This classification aids the proper reporting of measurements.

4.2 Type of superstructure

The main categories of bridge deck with respect to the superstructure material are the following:

a) reinforced concrete bridge decks (either *in situ* or precast);

b) prestressed concrete bridge decks (either *in situ* or precast); pretensioned or post-tensioned, or combined pre- and post-tensioned units are generally used;

c) steel bridge decks (with orthotropic plate or longitudinal stiffeners);

d) composite steel beam and concrete slab bridge decks;

e) masonry bridges;

f) new materials (e.g. fibre reinforced concrete, fibre reinforced plastic).

4.3 Static design, methods of construction and substructure

4.3.1 Static design

The static design and the support conditions influence the dynamic behaviour of the structure and they should be taken into account in programming the tests.

With respect to static design, bridges can be classified as follows:

a) single-span bridges or bridges with simply supported independent spans;

b) viaducts with spans resting with their extremities supported and suitably constrained, yet independent in every span;

c) multi-span continuous bridges, generally with significant variations in the longitudinal flexural rigidity along the span;

d) a statically determinant Gerber-type continuous span; the longitudinal profile can be of constant or variable cross section;

e) framed bridges;

f) arch bridges;

g) truss bridges;

h) prefabricated modular bridges;

i) tubular steel arch bridges.

4.3.2 Methods of construction

Bridges are generally erected using different construction methods that may effect both global dynamic behaviour and the theoretical modelling of the structure. As an example, some common construction methods are the following:

— *in-situ* construction with precast concrete or steel beams and concrete (*in-situ* or precast) slab;

— precast segmental or staging construction.

Furthermore, strengthening or retrofit effects need to be considered in the test design.

4.3.3 Type of deck cross-section

The main categories of bridge deck cross-section are as follows:

— slab on girder cross-sections with steel or concrete girder (usually connected by means of transverse beams);

— single-cell or multi-cell box girder;

— solid or hollow slab cross-sections.

4.3.4 Type of foundation

The main categories of foundations are the following:

— strip, slab or mass concrete foundations on competent soils or directly on rock;

— pile or sheet-pile foundations;

— caisson foundations.

The behaviour of such foundations on the ground may influence the degree of constraint of the structures (piers and abutments) and it is suggested that, whenever possible, investigation of their behaviour is undertaken during construction.

4.3.5 Piers, abutments and parapets

4.3.5.1 Piers

Most pier systems consist of the following:

— wall-type piers;

— single-column (hollow or solid, straight or tapered) piers;

— multiple-column (hollow or solid, straight or tapered) bents;

— framed piers.

Other types of pier may be classified as a combination of the above main categories.

4.3.5.2 Abutments

Abutment systems generally consist of the following:

— reinforced concrete cast-in-place abutments (solid or with counterforts);

— hollow reinforced concrete cast-in-place abutments;

— precast reinforced concrete abutments;

— mechanical stabilized earth abutments, e.g. soil reinforcements.

4.3.5.3 Parapets

Parapet constructions are generally made of the following:

— concrete;

— masonry.

4.3.6 Special bridges

Special bridges such as the following require special attention:

— skew bridges (with angle of skew > 15°);

— curved bridges ($R/L < 10$);

— inclined bridges (with slope angle > 5 %);

— cable-stayed bridges;

— suspended bridges;

— mobile bridges (e.g. swing and lifting bridges);

— floating bridges.

4.4 Function classification

With respect to function, bridges may be classified as

a) road bridges,

b) railway bridges,

c) pedestrian bridges,

d) product and services bridges, or

e) a combination of the above.

5 General criteria for testing

5.1 General

It is advisable for investigations to be preceded by theoretical models and/or by numerical analysis to obtain the order of magnitude of values to be measured. If similar works have already been investigated, it is reasonable to anticipate a similar order of values. This could concern a whole bridge, or elements, or structural parts. This initial analysis should supply the likely values of displacements, deformations, natural frequencies, mode shapes and damping as guidelines in the choice of the following:

— investigation technique;

— excitation method (type, duration of excitation, spectral distribution);

— choice of measuring instruments;

— location of transducers and/or exciters.

5.2 Choice of test techniques

The choice of the test techniques depends on many factors such as the frequency range, damping and level of excitation necessary for a correct evaluation of the response having regard to the accuracy of the transducers and the environmental noise.

If the signal-to-noise ratio is less than 3, measurements should be processed with particular care and the test report should indicate the corrections adopted and the estimated errors.

5.3 Choice of excitation methods

5.3.1 General

In choosing the excitation methods, two types of structural motion should be considered: free and forced motion. In both cases investigations may be performed in the time, or in the frequency, or in the time-frequency domains.

The free motion may be excited by sudden application of a static load or of imposed displacement, or as tail-response to transient excitation (including the effect of running or braking vehicles). The excitation may be “environmental forced” or “artificial forced”. The first is due to the wind, road traffic, micro-earthquake, and has a random-characteristic wide spectrum. The second is through controlled excitation and may be particularly suitable for concentrating forcing energy around different natural frequencies. It requires the use of one or more exciters which can apply a controlled load of known amplitude and frequency. This type of excitation may be used to evaluate the dynamic characteristics and possible non-linearities of the system.

For pedestrian bridges, consideration should be given to footfall excitation and stochastic interactions.

5.3.2 Equipment type

For the choice of equipment for use with artificial vibration, see 6.1. To select the type of excitation, it is necessary to evaluate both the frequency range and required vibration levels.

5.3.3 Sites of excitation

The number and location of the excitation points should be chosen in relation to vibration modes to be investigated. These sites, zones of maximum modal amplitude, should be selected taking account of the progress of the construction phase and the stiffness of the resistant section. It might be necessary to verify that the structure can bear the anticipated dynamic load.

5.4 Choice of response measuring system

5.4.1 General

The method of monitoring the response should be scheduled in advance in relation to the specific information to be obtained from the tests. Such information may come from the measurement of acceleration, velocity, displacement, inclination, strain or deformation. Particular care should be taken in the detection of the physical parameters that concern fatigue in order to find the deformation and stress ranges for specific points of the structure. This information is of particular importance for evaluating possible local and overall damage.

The global response is the direct detection of the vibration modes of a pier or abutment or of the structure in one or more spans. Often it might be sufficient to detect selected vibration modes, either vertical, horizontal, torsional or combined. The measurement of the global response requires the deployment of measuring instruments along the whole structure or of its elements, with different configurations for each test. This should be programmed after preliminary investigations. If this approach is adopted, it may be necessary to maintain some test positions in order to check the repeatability of the measurements and to correlate the various results. At lower frequencies, consideration may be given to sub-centimetre global positioning systems (GPS).

Local response requires specific programming on the position of measuring instruments, following theoretical analysis of parts of the structure during the construction stage (foundation piles, foundations as a whole, etc.) or structural elements in operation (cross sections, overhangs, etc.).

5.4.2 Placement of transducers

For the measurement of global response, measuring instruments should not be placed on elements sensitive to local vibration. The overall measurement chain (transducers, signal conditioners, recording) should be calibrated according to specifications of the manufacturer or applicable standards (for vibration transducers, see, for example, the ISO 5347 or ISO 16063 series). In the test report, the measurement and data collection chain should be described and the frequency range of the system should be specified.

The initial positioning of transducers depends on the objectives of the investigation and is affected by the type of bridge, its condition and the mode of vibration of concern. Subsequent locations may be required depending upon the results of previous measurements.

5.4.3 Installation techniques

The technique of mounting transducers should allow the reproduction of the vibration of the element to which they are fixed, over the frequency range of interest. The mounting system should be as rigid as possible to avoid resonance phenomena due to the mounting. The mounting of transducers should be in accordance with the specifications of the manufacturer or to applicable standards (for accelerometers, see, for example, ISO 5348). These mountings should be described in the test report.

5.4.4 Data transmission

Data should be transferred without corruption.

6 Testing equipment

6.1 Excitation equipment

Excitation equipment should be suitable for the purpose. Annex A provides details of vibration generators and impulsive systems and their specification.

6.2 Measurement equipment

The measurement equipment should be suitable for the purpose. Guidance on measurement equipment and its specification is given in Annex B.

6.3 Control, acquisition and analysis systems

A control function, which is the set of operations to control all actions to be applied to the structure during the tests, should be installed. Depending on the type of exciter, force transducers may be required between the ground and the structure under investigation.

The data should be recorded and made available for processing and analysis.

An analysis, which is the set of operations that examine the recorded data and allow the identification of the dynamic characteristics, should be performed.

7 Techniques of investigation

7.1 General considerations

7.1.1 Grouping

The techniques of dynamic investigation on structures can be grouped according to the nature of the vibration (i.e. forced or free) and the techniques adopted for data processing.

7.1.2 Forced vibration

Forced vibration can arise artificially or environmentally, i.e. it can be induced either from artificial or environmental causes.

Artificial excitation can generate applied loads with specified characteristics. Depending on the excitation system used, the dynamic load can be sinusoidal, stationary random, non-stationary random or transient. The excitation can be measured in some situations, but may be difficult in others.

Forced environmental vibration can be produced by wind, traffic (road or rail), micro-earthquake, industry, road works, etc. The dynamic excitations can be stationary random, non-stationary random or transient.

7.1.3 Free vibration

Free vibration is that which persists after the cause which produced it has ceased. It is characterized by the combination of damped sinusoids. Free vibration depends on the modal characteristics of the work. It can be artificially induced or due to environmental causes.

In the first eventuality, it is due to transitory actions, for instance the use of the technique of pull and quick release or by using devices generating pulse loads.

In the second eventuality, it can be induced on the structure by the stopping of environmental transitory actions such as, for instance, the run-by of vehicles, or cessation of the wind.

7.1.4 Data processing

Data processing may be in the frequency domain, or in the time domain, or in the time-frequency domain. The procedures of structural identification which may be used should be reasonably supported by practice or literature. The test report should describe the procedure used and the specific references.

7.2 Tests using artificial excitation

Testing with artificial excitation is one of the most widely used techniques of investigation. It requires the installation of one or more exciters and the mounting of a network of measurement transducers whose number and position depend on the structural typology of the bridge to be examined and on the objective of the investigation. The types of excitation are as follows.

a) Sinusoidal excitation

This is the application of forces which vary with time according to a strictly harmonic law. During the test the frequency can vary in such a way that the fundamental modes of the structure can be examined. The frequency variation can be slow or quick. The advantage of these tests is to concentrate the energy of excitation in one mode at a time and to produce a response of relatively high amplitude.

b) Random excitation

This consists of the application of dynamic actions which vary with time with a stationary random law, and excite various modes of the structure.

c) Impulsive excitation

This consists of the application of dynamic actions (pull and quick release, impact of loads, use of hydraulic vibration generators, explosions near the work, etc.). This kind of technique is used for the analysis of induced free vibration.

7.3 Ambient natural actions

7.3.1 Wind

The excitation produced by the wind may be considered as “quasi-random”. The dynamic load actually produced by the wind activity is difficult, and often impossible, to measure, due to the distribution of the load on all exposed surfaces.

7.3.2 Earthquake

The excitation produced by an earthquake is a transient variable which may last for tens of seconds. The effective dynamic load produced by an earthquake is from movements on the ground, therefore the measurement of the excitation should be performed by placing accelerometers or seismometers on or in the ground at the expected positions of seismic input. If possible, soil/structure interaction should be evaluated and measurements made in the free field.

Because an earthquake is usually a rare event, its use as a source for testing is limited and could be recorded only with monitoring systems.

7.3.3 Micro-tremors

Micro-tremors (M_L less than 2,0) generate very low-amplitude motion and major bridge sites are often monitored using suitable seismometers. The excitation produced by micro-tremors may be regarded as a sequence of transients of short duration.

Many sites exhibit a near continuous succession of small transients (surface waves) which can be attributed to “man-made noise”. In addition, there is longer period of ambient vibration which is generated by meteorological sources, such as classical long period micro-seisms linked to low pressure centres and littoral wave action.

7.3.4 Measurement of traffic-induced vibration

The dynamic response produced by this type of excitation can easily be detected in structures which are being used. If a cycle of dynamic tests on several similar structures is to be conducted, it is suggested that similar investigations are also performed on a test structure excited artificially. The traffic may be controlled (for instance, only vehicles with known characteristics) or normal traffic may be used. In the latter event, the actual measurement of the dynamic excitation is not widely used. Normal traffic may be monitored to obtain information on the presence and intensity of the traffic itself. For railway traffic, with some sensors the position of train axles, the axle load and the train speed can be detected.

Human traffic may also be mobilized to excite lightweight bridges, including pedestrian bridges. People walking at constant frequency provide a load at that frequency and at whole number multiples of it. Therefore the pacing frequency can be selected to excite the fundamental mode. Cessation of walking, or a single jump, may be used to initiate free vibration of the bridge. Crowded pedestrian bridges can undergo complex interactive stochastic loading.

7.3.5 Other dynamic actions

There are other dynamic actions which may produce measureable motion in bridges, e.g. interaction with water, either waves or currents.

8 Testing and inspection

8.1 General

The principles to be adopted in regard to the specific circumstances of testing are given in this clause, together with matters which require special attention for each application. Usually the excitation is provided by mechanical or servo-hydraulic means, although impact with or without force measurement may be used. The methods of attaching the exciter to the structure or structural element should not induce unwanted movements in other than the desired direction. Where the mass of the exciter and any attachment is significant, its effects on dynamic response need to be assessed.

8.2 Testing during construction (interim inspection)

8.2.1 General

Dynamic tests may be carried out on bridges or on their structural elements during construction in order to confirm assumptions made on design, modelling and analysis. The range of tests which may be used during or after construction is described. The number and type of tests depend on the characteristics and importance of the structure.

8.2.2 Surface and shallow foundations

Dynamic tests are not often used on surface or shallow foundations, which are usually restricted to softer soils and would not generally be used for substantial bridges. They can be used to check assumptions in the geotechnical design. Because the testing in these circumstances is unusual, a preliminary study using a numerical model based on plausible geotechnical data is useful and can help in the selection of appropriate soil dynamic parameters and the form of testing, e.g. Dynamic Plate Testing. Procedures for such testing can be found in soil dynamics text books.

8.2.3 Piled and diaphragm wall foundations

In addition to verification of design, testing of piled foundations can reveal variations in the properties of the supporting soils and foundation characteristics. Knowledge of such variations is particularly useful in the analysis of laterally extended structures under seismic loading.

Diaphragm walls require special consideration in that they may be installed in panels of concrete *in situ* or in prefabricated elements. The extent of the participation in response when testing at different construction stages needs to be considered.

8.2.4 Dynamic vertical behaviour

8.2.4.1 Dynamic tests on a single pile

Vertical tests on a sample pile should determine the modal frequency and damping in the vertical direction. Care should be taken to ensure that the vertical forces only are applied to the pile, especially if part of the pile is free standing above ground level.

Tests may need to be carried out on one or more piles depending on the dimensions and importance of the work and homogeneity of the soil. Where powerful and heavy exciters are used, the effects of the added mass may need to be taken into account. At low frequencies it may be difficult to achieve sufficient dynamic displacement to yield realistic damping values. At higher frequencies the damping terms may be frequency-dependent.

Dynamic pile testing may be used for quality control purposes using a much lower power source (for example, reflected sonic testing in the time domain and mechanical admittance in the frequency domain).

8.2.4.2 Dynamic tests on a pile group

Dynamic testing of pile groups should be related to the tests carried out on a single pile, in order to assess the model used to calculate the vertical dynamic behaviour of the foundation block supported by the pile group. The foundation block design should permit the mounting of the exciter so as to minimize rocking motion, having regard to the geometry of the foundation and the disposition of the piles.

8.2.5 Dynamic horizontal behaviour

8.2.5.1 General

Dynamic horizontal tests are especially important for the verification of the geotechnical model used in the calculation of seismic response. The sequence of testing on a single working pile should take into account the potential for affecting the working function of that pile. Consideration should be given to the displacements which need be induced in the tests if non-linearities and strain-related damping are to be invoked in design.

8.2.5.2 Dynamic tests on a single pile

Horizontal dynamic tests should determine the modal frequencies and damping. The pile selected for testing (which may become in due course a working pile) while construction is underway should be representative of the completed structural element. Where a pile is tested with free length above ground level, account should be taken of any backfilling to be undertaken before completion of construction. Where the pile is to have pile cap, its effects should be taken into account.

In order to explore response at low frequencies, a reaction block or reaction piles may have to be provided and any proximity effects need to be examined. Where large displacements are required at more than a few hertz, a servo-hydraulic actuator capable of handling large flows of hydraulic fluid is likely to be needed.

Large-diameter single piles, such as caisson piles and completed diaphragm wall foundations, are difficult to excite. It is not usually possible to mobilize sufficient displacement to reproduce the full response which would be expected in extreme service condition, and any extrapolation would have to make use of theoretical geotechnical arguments.

8.2.5.3 Dynamic tests on a pile group

Horizontal tests on a foundation block supported by a group of piles or by a diaphragm wall may be planned using the same criteria for the corresponding vertical tests with the determination of modal frequencies and damping.

The test equipment should be capable of exciting measurable horizontal motion of the concrete block-piles/soil system. For large pile caps and large foundation elements, it may not be practicable to explore displacements and strains which approach even serviceability limit states of performance, and inferences on strain-related behaviour have to be extrapolated from single-pile tests. The measurement equipment should record displacements and rotations of the concrete block, because the global motion can also be influenced by the vertical behaviour of the piles. If the block can deform, the distribution of transducers and the directions in which they respond should be designed to define the principal distortions.

The results of investigations on the foundation block may be compared with the single-pile investigation, with the aim of establishing the group behaviour usually at small displacements. It should be noted that some numerical modelling of dynamic group effects is based upon a wave field and interactions which are not simulated by excitation of the block itself. “Stand-off” explosive sources may be used to study these aspects. If excessive settlement beyond the static design limit has occurred during the test on the single pile, due precautions should be taken when developing the tests on the pile group.

8.2.6 Support structures (piers and abutments)

8.2.6.1 General

Vibration tests on support structures are important, especially for structures in seismic areas and for piers in which buckling is to be considered.

8.2.6.2 Piers

The vibration tests should yield modal frequencies, damping values, stiffness and the shapes of the natural modes on slender piers.

Interaction between the foundations of the supporting soil can influence modal frequencies and the shapes of the natural modes. The transducers should be located so as to define the most important natural mode shapes. Some preliminary numerical analysis may be required before selecting the excitation system required to excite the natural frequencies of such structures.

For slender piers, natural excitations (e.g. wind) or shock excitation may be useful. For stiffer structures, it is generally useful to use imposed horizontal vibration produced by mechanical shakers. Where impact is used, the pulse shape can be modified by a compliant coupler to enhance the response in the fundamental mode.

8.2.6.3 Abutments

Dynamic tests on abutments are particularly relevant for important structures in seismic areas. Testing needs to be carried out when the abutment is complete since many incorporate backfilling which has an important effect on static and dynamic behaviour.

8.3 Testing the completed construction

8.3.1 General

When construction is complete, dynamic tests can complement traditional checks, verify the assumptions and procedures in dynamic analysis and provide a benchmark for future periodical checks as part of process of condition monitoring.

8.3.2 Global behaviour of the structure

8.3.2.1 General

Dynamic testing of the bridge deck requires that it be excited at appropriate locations if artificial means are to be used (see 8.3.2.2). A grid of transducers is necessary, sufficient in number to identify principal bending and torsional modes and to describe their mode shapes. In order to identify both bending and torsional modes, at least two transducers need to be located in the same section located on the shoulder responding to vertical motion. The number of transverse sections instrumented depends on the complexity of the bending and torsional modes which are to be studied. A reduction in the number may be possible using symmetry.

If modes which include transverse deformation of sections are monitored, several transducers across the section may be required. In considering global behaviour of the structure in the horizontal plane, it is necessary to monitor the dynamic effects due to the exciter(s) in that plane and here significant components of such motions may occur at low frequencies.

8.3.2.2 Forced artificial excitation

Forced-vibration tests are the most useful tool for finding the overall dynamic behaviour of the structure and for evaluating the transfer functions of the fundamental modal parameters (natural frequencies, damping, stiffness and mode shapes).

The excitation position(s) should be chosen bearing in mind both the need to excite the various modes of interest and the operational aspects of the location. One location might be sufficient, depending on the complexity of the work and on the kind of modes to be investigated. The excitation equipment should be rigidly connected to the structure in such a way as to impose motion only in the desired direction. Tie beams passing through the slabs, avoiding places where the transversal bending is noticeable, may be used. In such cases, locations can be chosen with beams or transversal diaphragms, or positions corresponding to main beams (for open sections) or walls (for closed sections).

8.3.2.3 Environmental vibration

Environmental vibration generated by wind is useful for examining exposed flexible slim structures having low natural frequencies. Also micro-earthquakes (micro-tremors) are always present; they supply a low-energy excitation and can be used for the linear dynamic identification. Vibration due to traffic induces a response at similar or higher levels to the pulse tests or artificial non-sinusoidal excitation. The technique of analysis for traffic-induced vibration may be used (see 7.3.4).

8.3.3 Local behaviour

In parallel with the investigations concerning global dynamic characterization, dynamic tests or observations of the dynamic response of local structural elements and non-loading bearing parts or service attachments may be required, especially if their failure has safety implications. Examples of such local elements are overhangs, slabs, etc. or of other structural parts such as constraints, some supporting structures such as piles or piers, etc.

This kind of investigation needs to be applied if the structure shows cracks whose structural meaning cannot be evaluated easily; in these circumstances strain-gauge measurements allow an evaluation of the continuity of the section examined. The type of instruments and its location shall be studied in every situation considering the kind of information required and the structural behaviour to be investigated.

8.4 Investigation and controls during operation

During the operation of the bridge, periodic investigation involving dynamic testing may be scheduled as part of a programme of condition monitoring to supply data on the durability of the work and for scheduling maintenance work related to degradation during the life of the bridge.

For evaluation of the dynamic behaviour during operation, see the general considerations in 7.1. Such investigations should have a minimum impact on the operation of the work, but maintain technical efficiency.

8.5 Monitoring

8.5.1 General

A monitoring system with continuous or near continuous operation, such as can be provided by a fixed installation, is the preferred option and for complex frames is the most effective tool to control the work during its operation. Sufficient data over an appropriate time period are needed to provide proper dynamic information on the behaviour of the structure under ambient environmental and operating conditions.

An essential part of a monitoring system is a management plan and pre-formulated behavioural features which lead to defined actions (alarm algorithms). In addition to monitoring, periodic forced-vibration tests provide information which may be compared with benchmark behaviour. In general, the monitoring systems also supply information on environmental conditions which may have an effect on structural parameters (air and works temperatures, rain, sun, wind, etc.).

8.5.2 Traffic monitoring

Monitoring of traffic vibration (as in 7.3.4) is the most suitable tool for continuous control because the traffic excitation is always present during operation.

8.5.3 Seismic monitoring

Strong-motion seismographs may be installed close to the bridge, such as in the abutments, and suitable transducers may be mounted on important structural elements. A “free-field” instrument on ground similar to that on which the structure is founded yet set far enough to be clear of interaction effects is needed to provide reference to the design seismic action. This monitoring is relevant in areas having a record of seismic activity.

Seismic monitoring does not allow a continuous diagnosis of the state of the bridge. The information supplied does enable the status of the work to be evaluated. This aspect is important during the emergency (civil protection) for work belonging to a strategically important infrastructure (railway or road).

8.5.4 Wind monitoring

Monitoring wind response may be used when the dynamic excitation due to the wind represents an important aspect for the work (suspension and cable-stayed bridges and bridges or viaducts at high levels), and in areas where the wind activity is significant.

8.5.5 Multi-functional monitoring

Consideration may be given to optimization in the use of measuring instruments by combined monitoring of several functions. For instance, with the same network of transducers it is now possible to monitor vibration due to traffic and to earthquakes.

In this situation, a system operating with two measuring ranges may be required. Moreover the possibility for static and geotechnical monitoring, alongside dynamic monitoring, should not be overlooked. Multi-functional systems may extend to monitoring meteorology and to the detection of the number, kind and speed of vehicles.

8.5.6 Threshold criteria

In a monitoring set-up, threshold limits need to be established for defining the operation ranges relevant for the particular subject under examination (response to normal operation, to exceptional stresses, to unusual or dangerous facts, etc.). The definition of such levels relates to the monitoring design and to the objective of the tests.

In setting threshold criteria, care should be taken in the development of alert/alarm algorithms to understand ambient noise and uncertainties in order not to generate spurious alarm states.

9 Final report

9.1 General

The tests should be conducted following a procedure, or design, defined by the administration managing the structure (see, for instance, ISO 14964). Such a design should describe the following:

— the work or structure to be examined;

— the aim of the investigation;

— the methods to be used in the investigation, considering the type of test, the data processing and methods and algorithms to be used for structural identification;

— the location of the test equipment.

The tests may be undertaken by the administration, providing it has the relevant test equipment and experience, or by an expert from an external laboratory. The test report should include all of the main aspects of the investigation, in particular the following:

— a description of the instruments used, including calibration;

— a description of the measurement procedure and instrument location;

— a description of the data analysis procedures;

— an assessment of the quality of the data;

— the relevant results.

Finally, the test report should specify the following:

— the customer;

— the manager of the work;

— the engineer(s) undertaking the tests and data processing;

— the date of investigations;

— envionmental conditions at the time of testing;

— references to tests and investigations already undertaken on the same work.

9.2 Test design

9.2.1 Description of the work

The following data about the work should be specified:

— classification and normal usage;

— the age and state of preservation;

— the presence of possible structural damages.

The description of the work should include construction details that can influence dynamic behaviour (joints, bearings and/or particular constraints, kind of floor, etc.) and an assessment of their condition.

9.2.2 Scope of the investigation

It is important to have a clear understanding of the objective of the investigations and the reasons for choosing a specific type of dynamic investigation.

9.2.3 Methods of investigation and location of the measuring equipment

The nature and type of investigations to be performed should consider the guidance given in Clause 7. The selection, location and mode of application of the excitation should be described and justified; as should the choice and location of measuring points and the measured parameters. If the measurements are performed together with, or before, numerical computations, or if the aim of the investigation is the identification of a structural model, it will be necessary to supply information about any links between the modelling and the measurements, showing the limits of application and any problems in model validation.

9.3 Test report

9.3.1 General

The test report written by the investigators should include a description of the work, together with a clear and complete list of tests and records collected. Photographs of the parts monitored may be included, together with plan drawings and sections pertaining to the tests.

9.3.2 Description of the instruments and the measuring range

The measuring instruments used for the tests should be listed, in particular the following:

— the type of excitation and the specification of the excitation equipment;

— identification and specification of other test equipment;

— type(s) of transducer;

— identification, specification, performance range and calibration of the transducer(s);

— measurement chain and its performances;

— cables.

A list of excitation and measurement positions should be supplied, together with information concerning the set-up of the tests, such as the length of cables, any problems encountered, temperature of the work during the tests, short-period thermal variations, and meteorological conditions.

9.3.3 Quality of data and description of processing

The analysis procedures used in the tests should be described. An assessment of the quality of the data and the suitability of the measuring instruments should be expressed. The signal-to-noise ratio and the sensitivity of the instruments should be considered. Methods and numerical algorithms used in the data processing should be briefly described, quoting any relevant references.

9.3.4 Results

The main results of the investigations should be given in the test report with appropriate graphs, tables and notes, and details of possible anomalies.

9.4 Analysis of results and conclusions

Finally, after the experimental results have been obtained, an assessment of the behaviour of the work investigated should be made, with specific reference to the objective of the studies. Such an assessment should be made by the administration managing the work, or through an expert. Due care should be taken in the presentation of the final results, such as those related to the objectives of the investigation, as expressed in 9.2.2. Consideration should be given to the results of former investigations to enable checking of variations in the dynamic behaviour of the work.

Annex A
(informative)

Excitation systems and their specification

A.1 Excitation equipment

A.1.1 Vibration generators

Vibration generators are machines that use inertial masses to produce forces of various kinds on the structure. These can be either periodic, random or sine-sweep (sinusoidal with slowly varying frequency). They are used to determine structural characteristics such as natural frequencies, vibration modes and damping. Vibration generators may be grouped as follows.

a) Mechanical

These consist of contra-rotating masses which are eccentric with respect to the rotation axis. The periodic force is strictly sinusoidal and is a function of the eccentricity of the masses and their angular speed, therefore of the frequency. The frequency ranges from 0,5 Hz to 100 Hz with amplitudes up to 500 kN for the highest frequencies.

b) Electrodynamic

These consist of two bodies, a fixed magnet (or coil) and a mobile coil connected to an inertial mass. They are connected by a suspension system. The frequency ranges from 5 Hz to 1 000 Hz with amplitudes up to 50 kN for the highest frequencies.

c) Hydraulic

These consist of an actuator to whose stem an inertial mass is connected. The frequency ranges from 0 to 200 Hz with amplitudes up to 1 000 kN. They are controlled by servovalves, e.g. MOOG, and can require a large flow of hydraulic fluid to maintain large displacement. The actuators may also be placed between the structure to be tested and a reaction mass or a pile group and pile cap.

For the characteristics of vibration generators, see A.2, A.3 and A.4. The units are recommendations only. The choice of the vibration generator should be made at the design level of the dynamic investigation.

For tests on bridges, vibration generators should be employed which are able to supply forces of high amplitude and low frequency. Vibration generators for high frequencies and small forces may be used in the investigation of the integrity of structural parts.

A.1.2 Impulse systems

Impulsive force can excite the free motion of the structure through the application of a sudden load, for instance through a short-duration impact of a mass or the release of a load hanging from the structure, or through the run-by of a lorry on an obstacle or cat's-back, or via small explosions. The problem with this method is to supply sufficient energy to the structure without damaging it. The use of shock systems is particularly fitting if the natural frequencies of the structure are to be excited in a simple way.

The characteristics of the impulse systems are given in A.5.

EXAMPLE A mass of several hundred tonnes on piles can be excited to determine its fundamental frequencies by impact through pulse-shaping couplers and, if a dynamometer is placed in the system, its response can be further examined.

A.2 Specification of mechanical shakers

A recommended specification of mechanical shakers is as follows.

a) Force

- constant force parameter C = ________ N/Hz^2
- maximum permissible force F_{max} = ______ kN

b) Frequency range

- maximum value f_{max} = _______ Hz
- minimum value f_{min} = _______ Hz

c) Permissible power

- at f_{max} P_{max} = ______ W
- at f_{min} P_{min} = ______ W

d) Operating conditions (delete as appropriate)

- horizontal YES NO
- vertical YES NO

e) Range of the adjustment angle

- maximum value α_{max} = ______ degrees
- minimum value α_{min} = ______ degrees
- adjustment step $\Delta\alpha$ = _______ degrees

f) System dimensions

- longitudinal A = ________ mm
- transversal B = ________ mm
- height H = ________ mm

g) Weight G = ________ N

or mass of the total shaker m = ________ kg

From these parameters the maximum sinusoidal forces for mechanical shakers are as follows:

— "low-frequency" range, where force relates to the unbalanced rotating mass

$$F_{max}(f) = C\, f^2 \cos\left(\frac{\alpha_{min}}{2}\right)$$

— "high-frequency" range, where the limit F_{max} is due to the maximum forces allowed in the design of the equipment (bearings, case, etc.)

$$F_{max}(f) = F_{max}$$

The cross-over frequency f_{ba} between the "low-frequency" and the "high-frequency" range is

$$f_{ba} = \sqrt{\frac{F_{max}}{C \cos\left(\frac{\alpha_{min}}{2}\right)}}$$

A.3 Specification of electrodynamic shakers

A recommended specification of electrodynamic shakers is as follows.

a) Peak-to-peak movement of the excitor δ = ________ mm

b) Mass of the mobile inertial deadweight M = ________ kg

c) Maximum permissible force F_{max} = ______ kN

d) Frequency range

— maximum value f_{max} = ______ Hz

— minimum value f_{min} = ______ Hz

e) Permissible power

— at f_{max} P_{max} = ______ W

— at f_{min} P_{min} = ______ W

f) Operating conditions (delete as appropriate)

— horizontal YES NO

— vertical YES NO

g) System dimensions

— longitudinal A = ________ mm

— transversal B = ________ mm

— height H = ________ mm

h) Weight G = ________ N

or mass of the total shaker m = ________ kg

From these parameters the maximum sinusoidal forces for electrodynamic shakers are as follows:

— “low-frequency” range where limits are due to the displacement amplitude of the exciter

$$F_{max}(f) = M\,(2\pi f)^2\,\frac{\delta}{2}$$

— “high-frequency” range where the limit F_{max} is due to the maximum force allowable by the exciter

$$F_{max}(f) = F_{max}$$

The cross-over frequency f_{ba} between the “low-frequency” and the “high-frequency” range is

$$f_{ba} = \frac{1}{2\pi}\sqrt{\frac{F_{max}}{M\,\frac{\delta}{2}}}$$

A.4 Specification of hydraulic shakers

A recommended specification of hydraulic shakers is as follows.

a) Peak-to-peak movement of the actuator δ = ______ mm

b) Mass of the mobile inertial deadweight M = ______ kg

c) Maximum permissible force F_{max} = _____ kN

d) Cross-section of the hydraulic actuator Ω = _______ mm^2

e) Maximum flow in dynamic regime for the hydraulic power supply Q = _____ m^3/s

f) Maximum dynamic pressure for the hydraulic power supply p = ______kPa

g) Frequency range

— maximum value f_{max} =________Hz

— minimum value f_{min} = ________Hz

— variation Δf = ________Hz

h) Permissible power

— at f_{max} P_{max} = _______ W

— at f_{min} P_{min} = _______ W

i) Operating conditions (delete as appropriate)

— horizontal YES NO

— vertical YES NO

j) System dimensions

— longitudinal A = ________ mm

— transversal B = ________ mm

— height H = ________ mm

k) Weight G = ________ N

or mass of the total shaker m = ________ kg

From these parameters, the maximum sinusoidal forces for hydraulic shakers are as follows:

— "low-frequency" range where the limit is due to the maximum displacement of the actuator

$$F_{\max}(f) = M(2\pi f)^2 \frac{\delta}{2}$$

— "medium-frequency" range where the limit is due to the maximum flow in the dynamic regime of the hydraulic power supply

$$F_{\max}(f) = M 2\pi f \frac{Q}{\Omega}$$

— "high-frequency" range where the limit $F_{\max}$ is due to the maximum pressure flow in the dynamic regime of the hydraulic power supply

$$F_{\max}(f) = \Omega p$$

The cross-over frequencies f_{bm} (between the "low-frequency" and the "medium-frequency" range) and f_{ma} (between the "medium-frequency" and the "high-frequency" range) are the following:

$$f_{bm} = \frac{Q}{\Omega \pi \delta}$$

$$f_{ma} = \frac{p\Omega^2}{2\pi Q}$$

A.5 Specification of impulse systems

A recommended specification of impulse systems consisting of a fall of deadweight is as follows.

a) Maximum displacement of the impact deadweight δ = _______ mm

b) Mass of the impact deadweight M = _______ kg

c) Elasticity of the elastomeric "pillow" K = _______ kN/mm

d) System dimensions

— longitudinal A = ________ mm

— transversal B = ________ mm

— height H = ________ mm

e) Weight G = ________ N

or mass of the total system m = ________ kg

For other pulse systems related to blasting, suitable operating characteristics should be defined (i.e. number of charges at the time, kind and quantity of explosive delays, in milliseconds, in priming of single charges, etc.).

