

Eurocode 8: Design provisions for earthquake resistance of structures —

Part 4: Silos, tanks and pipelines

ICS 11.120.25; 23.020.10; 23.040.01

National foreword

This part of DD ENV 1998 has been prepared by Subcommittee B/525/8, and is the English language version of ENV 1998-4:1998, published by the European Committee for Standardization (CEN).

ENV 1998-4:1998 results from a programme of work sponsored by the European Commission to make available a common set of rules for the structural and geotechnical design of buildings and civil engineering works. The full range of codes covers the basis of design and actions, the design of structures in concrete, steel composite construction, timber, masonry and aluminium alloy, and also geotechnical and seismic design.

This Draft for Development is not to be regarded as a British Standard.

An ENV or European Prestandard is made available for provisional application, but it does not have the status of a European Standard. The aim is to use the experience gained to modify the ENV so that it can be adopted as a European Standard (EN).

There is no existing British Standard equivalent to ENV 1998-4 and there is no requirement in the building regulations to consider seismic actions on buildings and civil engineering works in the UK.

ENV 1998-1-1 states that the provisions of Eurocode 8 may be simplified or not observed in regions of low seismicity. Within the UK, the application of Eurocode 8 should not be necessary, unless the client or user of the works assesses that the associated seismic risk is such that it needs to be addressed.

Users of this document are invited to comment on its technical content, ease of use and any ambiguities or anomalies, both with respect to use in the UK and also in other more actively seismic areas. These comments will be taken into account when preparing the UK national response to CEN on the question of whether the ENV can be converted into an EN.

Comments should be sent in writing to the Secretary to B/525/8 at BSI, 389 Chiswick High Road, London W4 4AL, quoting the document reference, the relevant clause and, if possible, a proposed revision.

A list of organizations represented on this subcommittee can be obtained on request to its secretary.

Cross-references

The British Standards which implement international or European publications referred to in this document may be found in the BSI Standards Catalogue under the section entitled “International Standards Correspondence Index”, or by using the “Find” facility of the BSI Standards Electronic Catalogue.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, the ENV title page, pages 2 to 65 and a back cover.

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English version

**Eurocode 8: Design provisions for earthquake resistance of
structures - Part 4: Silos, tanks and pipelines**

Eurocode 8: Conception et dimensionnement des
structures pour la résistance aux séismes - Partie 4: Silos,
réservoirs et canalisations

Eurocode 8: Auslegung von Bauwerken gegen Erdbeben -
Teil 4: Silos, Tankbauwerke und Rohrleitungen

This European Prestandard (ENV) was approved by CEN on 6 June 1997 as a prospective standard for provisional application.

The period of validity of this ENV is limited initially to three years. After two years the members of CEN will be requested to submit their comments, particularly on the question whether the ENV can be converted into a European Standard.

CEN members are required to announce the existence of this ENV in the same way as for an EN and to make the ENV available promptly at national level in an appropriate form. It is permissible to keep conflicting national standards in force (in parallel to the ENV) until the final decision about the possible conversion of the ENV into an EN is reached.

CEN members are the national standards bodies of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom.



EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

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Foreword

Objectives of the Eurocodes

- (1) The "Structural Eurocodes" comprise a group of standards for the structural and geotechnical design of buildings and civil engineering works.
- (2) They cover execution and control only to the extent that is necessary to indicate the quality of the construction products, and the standard of the workmanship, needed to comply with the assumptions of the design rules.
- (3) Until the necessary set of harmonized technical specifications for products and for methods of testing their performance is available, some of the Structural Eurocodes cover some of these aspects in informative annexes.

Background to the Eurocode Programme

- (4) The Commission of the European Communities (CEC) initiated the work of establishing a set of harmonized technical rules for the design of building and civil engineering works which would initially serve as an alternative to the different rules in force in the various Member States and would ultimately replace them. These technical rules became known as the Structural Eurocodes.
- (5) In 1990, after consulting their respective Member States, the CEC transferred the work of further development, issue and updates of the Structural Eurocodes to CEN, and the EFTA Secretariat agreed to support the CEN work.
- (6) CEN Technical Committee CEN/TC 250 is responsible for all Structural Eurocodes.

Eurocode Programme

- (7) Work is in hand on the following Structural Eurocodes, each generally consisting of a number of parts:

- EN 1991 Eurocode 1 - Basis of design and actions on structures
- EN 1992 Eurocode 2 - Design of concrete structures
- EN 1993 Eurocode 3 - Design of steel structures
- EN 1994 Eurocode 4 - Design of composite steel and concrete structures
- EN 1995 Eurocode 5 - Design of timber structures
- EN 1996 Eurocode 6 - Design of masonry structures
- EN 1997 Eurocode 7 - Geotechnical design
- EN 1998 Eurocode 8 - Design provisions for earthquake resistance of structures
- EN 1999 Eurocode 9 - Design of aluminium alloy structures

- (8) Separate subcommittees have been formed by CEN/TC 250 for the various Eurocodes listed above.
- (9) This Prestandard is being published as an European Prestandard (ENV) with an initial life of three years.

(10) This Prestandard is intended for experimental application and for the submission of comments.

(11) After approximately two years CEN members will be invited to submit formal comments to be taken into account in determining future actions.

(12) Meanwhile, feedback and comments on this Prestandard should be sent to the Secretariat of CEN/TC250/SC8 at the following address:

IPQ c/o LNEC
Avenida do Brasil 101
P1799 LISBOA Codex
PORTUGAL

or to your national Standard Organization.

National Application Documents

(13) In view of the responsibilities of authorities in member countries for the safety, health and other matters covered by the essential requirements of the Construction Products Directive (CPD), certain safety elements in this ENV have been assigned indicative values which are identified by ("boxed values"). The authorities in each member country are expected to assign definitive values to these safety elements.

(14) Some of the harmonized supporting standards may not be available by the time this Prestandard is issued. It is therefore anticipated that a National Application Document (NAD) giving definitive values for safety elements, referencing compatible supporting standards and providing guidance on the application of this Prestandard, will be issued by each member country or its Standards Organisation.

(15) It is intended that this Prestandard is used in conjunction with the NAD valid in the country where the building or civil engineering works are located.

Matters specific to this Prestandard

(16) The scope of Eurocode 8 is defined in clause 1.1.1 of ENV 1998-1-1:1994 and the scope of this Prestandard is defined in 1.1. Additional Parts of Eurocode 8 which are planned are indicated in clause 1.1.3 of ENV 1998-1-1:1994.

(17) This Prestandard is divided into four sections. The first section presents the general rules applicable to the design for earthquake resistance of silos, tanks and pipelines. The other sections deal with the specific rules for silos (section 2), tanks (section 3) and pipelines (section 4).

(18) Attention shall be paid to the fact that this Prestandard has to be used in conjunction with ENV 1998-1-1 and in addition to the provisions of the other relevant Eurocodes.

(19) This Prestandard includes two informative annexes.

Intended future developments of this Prestandard

(20) An objective of this Prestandard is to ensure the consistency between seismic design rules used for silos, tanks and pipelines and rules used for other construction works. It should be understood that this is a longterm objective which demands a continuous progress and cannot be achieved in a single step.

(21) Parts in other Eurocodes dealing with the same structures as in this Prestandard are still in preparation.

(22) A number of aspects of the seismic behaviour of silos, tanks and pipelines are not yet well understood, and research on them is currently under way. It is expected that this Prestandard, and particular the design procedures and rules given in the Appendices will be updated in parallel with the advancement of the knowledge in the field.

1 General

1.1 Scope

(1) P This Prestandard aims at providing principles and application rules for the seismic design of the structural aspects of integrated facilities composed of pipeline systems and of storage tanks of different types and destinations, as well as for independent items, such as for example single water towers serving a specific purpose or groups of silos enclosing granular materials, etc. This Prestandard may also be used as a basis for evaluating the amount of strengthening needed by existing facilities to bring them up to present standards.

(2) P This Prestandard includes the additional criteria and rules required for the seismic design of these structures without restrictions on their size, structural types and other functional characteristics. For some types of tanks and silos, however, it also provides detailed methods of assessment and verification rules.

(3) P With reference to 1.1 of ENV 1998-1-1:1994, this Prestandard may not be complete for those facilities associated with large risks to the population or the environment, for which additional requirements shall be established by the competent authorities. This Prestandard is also not complete for those construction works which have uncommon structural elements and which require special measures to be taken and special studies are performed to ensure earthquake protection. In those two cases the present Prestandard gives general principles but not detailed application rules.

(4) The nature of lifeline systems which often characterises the facilities covered by this Prestandard requires concepts, models and methods that may differ substantially from those in current use for more common structural types. Furthermore, the response and the stability of tanks subjected to strong seismic actions may involve rather complex phenomena of soil-structure-fluid interaction, not easily amenable to simplified design procedures. Equally challenging may prove to be the design of a pipeline system having to cross areas with poor and possibly unstable soils. For the reasons given above, the organisation of this Prestandard is to some extent different from that of companion Parts of ENV 1998. This Prestandard is, in general, restricted to basic principles and methodological approaches, while detailed analysis procedures are given in Annexes for a number of typical situations.

(5) P For the formulation of the general requirements as well as for their implementation, a distinction is made among the facilities covered by the present Part 4, i.e.: independent structures and redundant networks.

(6) P A structure can be considered as independent when its behaviour during and after a seismic event is not influenced by that of other structures, and if the consequences of its failure relate only to the functions demanded from it.

1.2 Safety requirements

1.2.1 General

(1) P This Prestandard deals with structures which may differ widely in such basic features as:

- the nature and amount of stored product and associated potential danger
- the functional requirements during and after the seismic event
- the environmental conditions.

(2) Depending on the specific combination of the indicated features, different formulations of the general requirements are appropriate. For the sake of consistency with the general framework of the Eurocodes, the two limit states format is retained, with a suitably adjusted definition.

1.2.2 Serviceability limit state

(1) P Depending on the characteristics and the purposes of the structures considered one or both of the two following serviceability limit states may need to be satisfied:

- full integrity;
- minimum operating level.

(2) P The "full integrity" requirement implies that the considered system, including a specified set of accessory elements integrated with it, remains fully serviceable and leak proof under a seismic event having an annual probability of exceedance whose value is to be established based on the consequences of its loss of function and/or of the leakage of the content.

(3) P The "minimum operating level" requirement implies that the considered system may suffer a certain amount of damage to some of its components, to an extent, however, that after the damage control operations have been carried out, the capacity of the system can be restored up to a predefined level of operation. The seismic event for which this limit state must not be exceeded shall have an annual probability of exceedance whose value is to be established based on the losses related to the reduced capacity of the system and to the necessary repairs.

1.2.3 Ultimate limit state

(1) P The ultimate limit state of a system is defined as that corresponding to the loss of operational capability of the system, with the possibility of partial recovery (in the measure defined by the responsible authority) conditional to an acceptable amount of repairs.

(2) P For particular elements of the network, as well as for independent structures whose complete collapse would entail high risks, the ultimate limit state is defined as that of a state of damage that, although possibly severe, would exclude, however, brittle types of failures and would allow for a controlled release of the content. When

the failure of the afore mentioned elements does not involve appreciable risks to life and property, the ultimate limit state can be defined as corresponding to total collapse.

(3) P The reference seismic event for which the ultimate limit state must not be exceeded shall be established based on the direct and indirect losses caused by the failure of the system.

1.2.4 Reliability differentiation

(1) P Pipeline networks and independent structures, either tanks or silos, shall be provided with a level of protection proportioned to the number of people at risk and to the economic and environmental losses associated with their performance level being not achieved.

(2) P Reliability differentiation shall be achieved by appropriately adjusting the value of the annual probability of exceedance of the design seismic action.

(3) This adjustment should be implemented by applying to the reference seismic action effects an importance factor γ_I , as defined in 2.1(3) of ENV 1998-1-1:1994. Specific values of the factor γ_I , necessary to modify the action effects so as to correspond to a seismic event of selected return period, are dependent on the seismicity of each region, and have therefore to be provided by the National Application Document.

(4) P For the structures within the scope of this Prestandard it is appropriate to consider 3 different levels of protection. Table 1.1 provides a framework for establishing differential levels of protection. In the column at left there is a classification of the more common uses of these structures, while the three columns at right contain the appropriate levels of protection in terms of the values of the importance factor γ_I for three classes of reliability (see ENV 1991-1:1994).

Table 1.1 Importance factors

Use of the structure/facility	Class		
	1	2	3
Potable water supply Non-toxic, non inflammable material	[1,2]	[1,0]	[0,8]
Fire fighting water Non-volatile toxic material Low flammability petrochemicals	[1,4]	[1,2]	[1,0]
Volatile toxic chemicals Explosive and other high flammability liquids	[1,6]	[1,4]	[1,2]

(5) P Class 1 refers to situations with a high risk to life and large environmental, economic and social consequences.

(6) P Situations with medium risk to life and considerable environmental, economic or social consequences belong to class 2.

(7) P Class 3 refers to situations where the risk to life is low and the environmental, economic and social consequences of failure are small or negligible.

(8) A more detailed definition of the classes, specific for pipeline systems, is given in 4.2.1

1.2.5 System versus element reliability

(1) P The reliability requirements set forth in 1.2.2 and 1.2.3 refer to the whole system under consideration, be it constituted by a single component or by a set of components variously connected to perform the functions required from it.

(2) P Although a formal approach to system reliability analysis is outside the scope of this Prestandard, the designer shall give explicit consideration to the role played by the various elements in ensuring the continued operation of the system, specially when it is not redundant. In the case of very complex systems the design shall be based on sensitivity analyses.

(3) P Elements of the network, or of a structure in the network, which are shown to be critical, with respect to the failure of the system, shall be provided with an adequate extra margin of protection, commensurate with the consequences of the failure. When there is no previous experience, those critical elements should be experimentally investigated to verify the acceptability of the design assumptions.

(4) If more rigorous analyses are not undertaken, the extra margin of protection for critical elements can be achieved by assigning these elements to a class of reliability one level higher than that proper to the system as whole.

(5) P The designer shall take into consideration that, in some cases, increasing the strength of an element of a structure may decrease the global reliability of the structure.

1.2.6 Conceptual design

(1) P The design of a network or of an independent structure shall take into consideration the following general aspects for mitigation of earthquake effects:

- Quality control of the components;
- Redundancy of the systems;
- Easy access for inspection, maintenance and repair of damages;
- Absence of interaction of the mechanical and electrical components with the structural elements.

(2) P In redundant systems, in order to avoid spreading of damage due to interconnection of components it shall be made possible to isolate parts of the system so as to take advantage of the redundancies.

(3) In case of indispensable facilities vulnerable to earthquakes, of which damage recovery is difficult or time consuming, or the damaged portions may be hard to detect, they should either be divided into independent parts or spare facilities should be provided.

1.3 Seismic action

(1) P The seismic action to be used in the determination of the seismic action effects for the design of silos, tanks and pipelines shall be that defined in 4 of ENV 1998-1-1:1994 in the various equivalent forms of elastic, site dependent response spectra (4.2.2 of ENV 1998-1-1:1994), power spectrum (4.3.1 of ENV 1998-1-1:1994) and time-history representation (4.3.2 of ENV 1998-1-1:1994). In those cases where a behaviour factor q larger than unity is acceptable (see 1.4.2), the design spectrum for linear analysis shall be used (4.2.2 of ENV 1998-1-1:1994).

(2) P The two seismic actions to be used for checking the serviceability limit state and the ultimate limit state, respectively, shall be established by the competent National Authority on the basis of the seismicity of the different seismic zones and of the level of the importance category of the specific facility.

(3) Possible reduction factors to take into account the lower return period of the seismic event associated with the serviceability limits state are given in 4.3 of ENV 1998-1-2:1994.

1.4 Analysis

1.4.1 General

(1) P For the structures within the scope of this Prestandard the seismic actions effects shall in general be determined on the basis of linear behaviour of the structures and of the soil in their vicinity.

(2) P Nonlinear methods of analyses can be used to obtain the seismic action effects for those special cases where consideration of nonlinear behaviour of structure and surrounding soil is dictated by the nature of the problem, or where the elastic solution would be economically unfeasible. In those cases it shall be proved that the design obtained possesses at least the same amount of reliability as the structures explicitly covered by this Prestandard. The proof is deemed to be achieved if no failure is observed for realistically large variations of the mechanical properties adopted.

1.4.2 Behaviour factors

(1) P The structures covered by this Prestandard are not expected to dissipate appreciable amounts of energy through their inelastic behaviour. Hence the value of the behaviour factor q shall in general be taken as $q = 1$. Use of q factors >1 is only allowed provided the sources of energy dissipation are explicitly identified and quantified, and the capability of the structure to exploit them through appropriate detailing is demonstrated.

(2) P For fully elastic design ($q=1$) the design seismic action is defined by the elastic spectrum. If values of $q>1$ are adopted, the design spectrum for linear analysis shall be used.

(3) P Even if a value $q = 1$ is adopted for the overall response, structural elements shall be designed with some local ductility and constructed from ductile materials.

1.4.3 Damping

1.4.3.1 Structural damping

(1) If the damping values are not obtained from specific information or by direct means the following damping values should be used in linear analysis:

- a) Serviceability limit state:
 - reinforced concrete structures: 4%
 - prestressed concrete structures: 2%
 - steel structures: 2%
- b) Ultimate limit state:
 - reinforced concrete structures: 7%
 - prestressed concrete structures: 5%
 - steel structures: 4%

1.4.3.2 Contents damping

(1) The value $\xi = 0,5 \%$ may be adopted for water and other fluids unless otherwise determined.

(2) For granular materials an appropriate damping value should be used. In the absence of more specific information a value of 10% may be used.

1.4.3.3 Foundation damping

(1) Material damping varies with the nature of the soil and the intensity of shaking. When more accurate determinations are not available, the values given in Table 4.1 of ENV 1998-5:1994 should be used.

(2) P Radiation damping depends on the direction of motion (horizontal translation, vertical translation, rocking, etc.), on the geometry of the foundation, on soil layering and soil morphology. The values adopted in the analysis shall be compatible with actual site conditions and shall be justified with reference to acknowledged theoretical and/or experimental results. The values of the radiation damping used in the analysis shall not exceed the value: $\xi = [20 \text{ \%}]$. Guidance for the selection and use of damping values associated with different foundation motions is given in Annex B of ENV 1998-3:1996, and in Annex A of this Prestandard.

1.4.4 Interaction with the soil

(1) P Soil-structure interaction effects shall be addressed in accordance with 6 of ENV 1998-5:1994.

(2) Additional information on procedures for accounting for soil-structure interaction is given in Annex C of ENV 1998-3:1996, and Annex A of this Prestandard.

1.4.5 Weighted damping

(1) A procedure for accounting of the contributions of the different materials/elements to the global average damping of the whole system is given in Annex B of ENV 1998-3:1996.

1.5 Safety verifications

1.5.1 General

(1) P Safety verifications shall be carried out for the limit states defined in 1.2, following the specific provisions in 2.4, 3.5 and 4.5.

(2) In case plate thickness is increased to account for future corrosion effects the verifications shall be made for both the nonincreased and the increased thickness.

1.5.2 Combinations of seismic action with other actions

(1) P Verifications shall be performed using the combination of seismic action effects with the other actions as prescribed in 4.4 (1) of ENV 1998-1-1:1994.

$$\Sigma G_{kj} + \gamma_1 A_{Ed} + P_k + \Sigma \psi_{2i} Q_{ki} \quad (1.1)$$

where:

- γ_I importance factor as defined in 1.2.4
- A_{Ed} seismic action effects as defined in 1.3
- G_{kj} permanent loads at their characteristics values. These will include the weight of the structure and in case of partially backfilled or buried tanks, it includes earth cover and permanent external pressures due to the water table
- P_k characteristic value of the prestressing action
- Q_{ki} variable loads at their characteristic values. Among these the effects of the liquid should be considered for various levels of filling
- ψ_{2i} combination coefficient for quasi permanent value of variable action i . The ψ_{2i} values depend on the specific conditions of use and of functioning of the structure. Guidance on these values is given in ENV 1991-1:1994.

(2) P In the case of groups of silos and tanks, different likely distributions of full and empty reservoirs shall be considered according to the operation rules of the facility. At least, the cases where all reservoirs are either empty or full must be considered.

2 Specific rules for silos

2.1 Dynamic overpressure

(1) P Under dynamic conditions, the pressure exerted by the material on the walls, the hopper and the bottom, increases over the value relative to the condition at rest. This increased pressure must be considered concurrently with the effects of the inertia forces due to the seismic excitation.

(2) P Design pressures in combination with earthquake load shall be obtained by multiplying the static pressure by the appropriate over-pressure correction factor C_d . Minimum required values of factors C_d are given in Table 2.1. (For values of H/d between 2 and 4 linear interpolation may be used).

Table 2.1 Minimum values of over-pressure factor C_d

	$H/d \leq 2$	$H/d \geq 4$
$0,75 < \zeta < 1$	1,20	1,35
$0,5 < \zeta < 0,75$	1,45	1,60
$0,25 < \zeta < 0,5$	1,65	1,85
$0,25 < \zeta < 0$	1,65	1,85
hopper depth	1,65	1,85
bottom, concrete	1,50	1,50
bottom, steel	1,75	1,75

where:

- H maximum height of contained material above hopper
- d diameter of the silo
- ς non-dimensional vertical ordinate $\varsigma = z / (H - H_1)$
- z vertical ordinate, with origin at the level of the hopper
- H_1 1,5 (H - H_m), where H_m is the equivalent height of contained material above hopper (accounting for the possible non-levelled surface at the top of the material)

2.2 Combination of ground motion components

- (1) P Silos shall be designed assuming the concurrent presence of one horizontal component of the seismic motion, which acts along the worst direction in plan for the element considered, and of the vertical component.
- (2) When approximate methods are used, (for example, response spectrum modal analysis) the global maximum response can be obtained by combining the individual peak contributions (separately obtained for the horizontal and the vertical excitation) by means of the "square root of the sum of the squares" (SRSS) rule.
- (3) P When accurate methods of analysis are used, the peak values of the total response under the combined action of the horizontal and vertical excitation obtained from the analysis shall be used in accordance with 4.3.2 of ENV 1998-1-1:1994 and 3.3.4 of ENV 1998-1-2:1994.

2.3 Analysis

- (1) P The model to be used for the determination of the seismic effects shall reproduce accurately the stiffness, mass and geometrical properties of the containment structure, shall account for the response of the contained material and for the effects of interaction with the foundation soil.
- (2) If more accurate evaluations are not undertaken, total mass of the granular material inside the silos can be assumed as moving rigidly with the silos shell.
- (3) P Silos shall be analysed considering an elastic behaviour, unless proper justification is given.

2.4 Verifications

2.4.1 Serviceability limit state

- (1) P Under the seismic load combination given by expression 1.1 of 1.5.2 the silo structure shall be checked to satisfy the serviceability limit state verifications required by ENV 1992-4 and ENV 1993-4.

(2) For steel silos, adequate reliability with respect to the occurrence of elastic or inelastic buckling phenomena is assured if the verifications regarding these phenomena are satisfied under the seismic loading for the ultimate limit state.

2.4.2 Ultimate limit state

2.4.2.1 Global stability

(1) P Overturning and sliding shall not occur for the design seismic action. The resisting shear force, which can be mobilized at the interface between the base of the silo and its foundation, shall be evaluated taking into account the effects of the vertical component of the seismic action.

(2) P Uplift is acceptable if it is adequately taken into account in the analysis and in the subsequent verifications of both the structure and of the foundation.

2.4.2.2 Shell

(1) P The maximum action effects (axial and membrane forces and bending moments) induced by the pertinent seismic load combination shall be less or equal to the ultimate strength capacity of the shell, evaluated as for non seismic situations. This includes all types of failure modes such as yielding, buckling, etc.

(2) Verifications are to be carried out in accordance with ENV 1992-4 and ENV 1993-4.

2.4.2.3 Anchors

(1) P Anchoring systems shall be designed to remain elastic under the pertinent seismic load combination. They shall also be provided by an adequate amount of ductility, so as to avoid brittle failures.

2.4.2.4 Foundations

(1) P The forces transmitted to the soil by the silo acted upon by the pertinent seismic load combination shall not exceed the bearing capacity of the soil, evaluated in accordance with the procedures given in ENV 1998-5.

3 Specific rules for tanks

3.1 Compliance criteria

3.1.1 General

(1) P The general requirements set forth in 1.2. are deemed to be satisfied if, in addition to the verifications specified in 3.4, the complementary measures indicated in 3.5 are also satisfied.

3.1.2 Serviceability limit state

(1) P It shall be ensured that under the relevant design seismic action and in respect to the “full integrity” limit state or “minimum operating level” limit state:

- The tank system maintains its tightness against leakage of the content. Adequate freeboard shall be provided, in order to prevent damage to the roof due to the pressures of the sloshing liquid or, if the tank has no rigid roof, to prevent the liquid from overstepping;
- The hydraulic systems which are part of, or are connected to the tank, are capable to accommodate stresses and distortions due to tank displacements relative to each other and to the soil, without impairment of their functions;
- Local buckling, if it occurs, does not initiate collapse and is reversible; for instance, local buckling of struts due to stress concentration is acceptable.

3.1.3 Ultimate limit state

(1) P It shall be ensured that under the relevant design seismic action:

- The overall stability of the tank is satisfied with respect to collapse. The overall stability refers to rigid body behaviour and may be impaired by sliding or overturning;
- The spread of inelastic behaviour is restricted within limited portions of the tank, and the ultimate deformations of the materials are not exceeded;
- The nature and the extent of buckling phenomena in the shell are adequately controlled;
- The hydraulic systems which are part of, or connected to the tank are designed so as to prevent loss of the tank content following the failure of some of its components;
- The foundation shall not attain a failure mechanism before failure of the tank.

3.2 Combination of ground motion components

(1) P Tanks shall be designed assuming the concurrent presence of one horizontal component and of the vertical component of the seismic motion.

(2) When the peak responses due to horizontal and vertical motions are determined separately, the most unfavourable combined effect can be obtained by means of the following expression:

(3)

$$p = p_{st} \pm p_h \pm p_v, \quad (3.1)$$

where:

p_{st} is the static pressure, and
 p_h , p_v are the peak values of the horizontal and vertical pressure, respectively. The signs of the terms in the combination should be selected so as to obtain the most critical effects in the various parts of the tank.

(3) P When accurate methods of analysis are used, the most unfavourable of the total response under the combined action of the horizontal and vertical excitation obtained from the analysis shall be used in accordance with 4.3.2 of ENV 1998-1-1:1994, and 3.3.4 of ENV 1998-1-2:1994.

3.3 Methods of analysis

3.3.1 General

(1) P The model to be used for the determination of the seismic effects shall reproduce accurately the stiffness, mass and geometrical properties of the containment structure, shall account for the hydrodynamic response of the contained fluid and the effects of interaction with the foundation soil.

(2) P Tanks shall be analysed considering an elastic behaviour, unless proper justification is given for particular cases.

(3) P The localized non linear phenomena admitted under the ultimate limit state design seismic action (see 3.1.3) shall be restricted so as to not affect the global dynamic response of the tank to any significant extent.

(4) Possible interaction between tanks due to connecting pipings shall be considered whenever appropriate.

(5) Methods for seismic analysis of tanks of usual shapes are given in Annex A.

3.3.2 Behaviour factors

(1) P Tanks of type and importance other than those mentioned below shall be either designed for a fully elastic response ($q=1$), or, for properly justified cases, (see 1.4.1(2)) the admissibility of their inelastic response shall be adequately demonstrated.

(2) P For elevated tanks, the supporting structure may be designed to respond beyond the yield level under the ultimate limit state design earthquake.

(3) For simple support and simple geometry and for tanks belonging to class of reliability 3, the values of q given in ENV 1998-1-3:1995 relative to inverted pendulum structures can be adopted.

(4) When the conditions above are not satisfied the energy dissipation corresponding to the selected value of q shall be properly substantiated and the necessary ductility provided through ductile design. The full elastic design action (i.e., $q = 1$), however, shall in all cases be used for the evaluation of the convective part of the fluid response.

3.3.3 Hydrodynamic effects

(1) P A rational method based on the solution of the hydrodynamic equations with the appropriate boundary conditions shall be used for the evaluation of the response of the tank system under the design seismic actions as defined in 1.3.

(2) P In particular, the analysis shall properly account for the following, where relevant:

- the convective and the impulsive components of fluid motion;
- the deformation of the tank shell due to the hydrodynamic pressures, and the interaction effects with the impulsive component;
- the deformability of the foundation soil and the ensuing modification of the response.

(3) For the purpose of evaluating the dynamic response under seismic actions the fluid can be generally assumed as incompressible.

(4) Accurate evaluation of the maximum hydrodynamic pressures induced by horizontal and vertical excitation requires the use of time-history analysis as indicated in 4.3.2 of ENV 1998-1-1:1994 or, equivalently, the adoption of harmonic analysis and synthesis procedures with the power spectral densities indicated in 4.3.1 of ENV 1998-1-1:1994 as input.

(5) Simplified methods based on mechanical analogues of the fluid behaviour and allowing for a direct application of the traditional response spectrum approach can be used, provided suitable conservative rules for the combination of the peak modal contributions are adopted and provided the approximation introduced with these methods is shown to be adequate for the particular case considered. Acceptable procedures accounting for the above mentioned effects are given in Annex A.

(6) P In order to provide adequate freeboard against liquid overstepping or impacting with the roof, the maximum vertical displacement of the liquid surface shall be calculated.

(7) Appropriate expressions are given in Annex A.