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Assessment of existing civil engineering structures

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Abstract. The upcoming CEN Technical Specification (TS) on assessment of existing structures is to be related to the probabilistic concepts and fundamental requirements of the EN Eurocodes. The document should concern all types structures made of concrete, steel and other materials, exposed to all kinds of actions. The final draft of the Technical specification was already submitted to the technical committee CEN TC250. It contains requirements, general framework of operational assessment, data updating, structural analysis (linear, nonlinear, dynamic), verifications (partial factors, probabilistic methods, risk assessment), past performance, interventions, annexes (flowchart, time-dependent reliability, assessment of heritage structures). The submitted contribution provides background information on the principles included in TS. Particular attention is paid to specifying appropriate target reliability levels and application of these values in engineering practice through adjustment of partial factors. It is shown that the operational assessment of existing concrete structures provides prediction of the remaining working life of a structure using a convenient reference period (commonly 50 years) taking into account durability aspects and mutual dependence of the failures in subsequent basic time periods (usually considered as one year).

1. Introduction

Assessment of existing structures is becoming a more and more important and frequent engineering task. Continued use of existing structures is of a great significance due to environmental, economic and socio-political assets, growing larger every year. These aspects are particularly relevant to public buildings that constitute a great social and economic value. General principles of sustainable development regularly lead to the need for extension of the life of a structure, in majority of practical cases in conjunction with severe economic constraints. That is why assessment of existing structures often requires application of sophisticated methods, as a rule beyond the scope of traditional design codes. Nevertheless, apart from few national codes (listed in JRC report (2015) [1]), three International Standards ISO 2394 (2015) [2], ISO 13822 (2010) [3] and ISO 12491 (1997) [4], related to assessment of existing structures, have been recently developed. Selected principles of Eurocede EN 1990 (2002) [5] are also applicable for assessment of existing structures. Additional information may be found in a number of scientific papers (listed in JRC report (2015) [1]) and publications, for example in [6], [7], [8] and [9].

The approach to assessment of an existing structure is in many aspects different from that taken in designing the structure of a newly proposed building. The effects of the construction process and subsequent life of the structure, during which it may have undergone alteration, deterioration, misuse, and other changes to its as-built (as-designed) state, must be taken into account. However, even though the existing building may be investigated several times, some uncertainty in behaviour of the basic variables shall always remain. Therefore, similarly as in design of new structures, actual variation in the basic variables describing actions, material properties, geometric data and model uncertainties are to be taken into account by any verification method.

Differences between the assessment of existing structures and the design of new structures as indicated in Table 1 should be considered when making decision.

Table 1. Differences between the assessment of existing structures and the design of new structures.

Aspect	Existing structures	New structures
Economic	Additional costs of reliability improvements are usually high	Additional costs of reliability improvements are usually low
Social	Restriction of the use and damage of cultural assets are significant	Restrictions are usually less significant than in existing structures
Sustainability	Allowance for sustainability is made using original materials	As a rule new materials are used and aspect of sustainability is complicated

In general, an existing structure is subjected to the assessment of its actual reliability in case of:

- rehabilitation of an existing constructed facility during which new structural members are added to the existing load-carrying system;
- adequacy checking in order to establish whether the existing structure can resist loads associated with the anticipated change in use of the facility, operational changes or extension of its design working life;
- repair of an existing structure, which has deteriorated due to time dependent environmental effects or which has suffered damage from accidental actions, for example, earthquake;
- doubts concerning actual reliability of the structure.

In some circumstances assessments may also be required by authorities, insurance companies or owners or may be demanded by a maintenance plan.

2. Principles and general framework of assessment

Two main principles are usually accepted when assessing existing structures:

- Currently valid codes for verification of structural reliability should be applied, historic codes valid in the period when the structure was designed should be used only as guidance documents.
- Actual characteristics of structural materials, actions, geometric data and structural behaviour should be considered, the original design documentation including drawings should be used as guidance documents only.

The first principle should be applied in order to achieve similar reliability level as in case of newly designed structures. The second principle should avoid negligence of any structural condition that may affect actual reliability (in favourable or unfavourable way) of a given structure. Most of the current codes are developed assuming the concept of limit states in conjunction with the partial factor method. In accordance with this method, which is mostly considered here, basic variables are specified by characteristic or representative values. The design values of the basic variables could be determined from the characteristic (representative) values and appropriate partial factors or on the bases of more advanced reliability methods.

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It follows from the second principle that a visual inspection of the assessed structure should be made whenever possible. Practical experience shows that inspection of the site is also useful to obtain a good feel for actual situation and state of the structure. As a rule the assessment need not to be performed for those parts of the existing structure that will not be affected by structural changes, rehabilitation, repair, change in use or which are not obviously damaged or are not suspected of having insufficient reliability.

In general, the assessment procedure consists of the following steps:

- specification of the assessment objectives required by the client or authority;
- scenarios related to structural conditions and actions;
- preliminary assessment:
  - study of available documentation;
  - preliminary inspection;
  - preliminary checks;
  - decision on immediate actions;
  - recommendation for detailed assessment;
- detailed assessment:
  - detailed documentary search;
  - detailed inspection;
  - material testing and determination of actions;
  - determination of structural properties;
  - structural analysis;
  - verification of structural reliability;
- report including proposal for construction intervention;
- repeat the sequence if necessary.

When the preliminary assessment indicates that the structure is reliable for its intended use over the remaining life a detailed assessment may not be required. Conversely if the structure seems to be in dangerous or uncertain condition immediate interventions and detailed assessment may be necessary.

3. Investigation

Investigation of an existing structure is intended to verify and update the knowledge about the present condition (state) of a structure with respect to a number of aspects. Often, the first impression of the structural condition will be based on visual qualitative investigation. The description of possible damage of the structure may be presented in verbal terms like: 'unknown, none, minor, moderate, severe, destructive'. Very often the decision based on such an observation will be made by experts in purely intuitive way.

A better judgement of the structural condition can be made on the basis of (subsequent) quantitative inspections. Typically, assessment of existing structures is a cyclic process when the first inspection is supplemented by subsequent investigations. The purpose of the subsequent investigations is to obtain a better feel for the actual structural condition (particularly in the case of damage) and to verify information required for determination of the characteristic and representative values of all basic variables. For all inspection techniques, information on the probability of detecting damages if present, and the accuracy of the results should be given.

The statement from the investigation contains, as a rule, the following data describing

- actual state of the structure;
- types of structural materials and soils;
- observed damages;
- actions including environmental effects;

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- available design documentation.

A proof loading is a special type of investigation. Based on such tests one may draw conclusions with respect to:

- the bearing capacity of the tested member under the test load condition;
- other members;
- other load conditions;
- the behaviour of the system.

The inference in the first case is relatively easy; the probability density function of the load bearing capacity is simply cut off at the value of the proof load. The inference from the other conclusions is more complex. Note that the number of proof load tests needs not to be restricted to one. Proof testing may concern one element under various loading conditions and/or a sample of structural elements. In order to avoid an unnecessary damage to the structure due to the proof load, it is recommended to increase the load gradually and to measure the deformations. Measurements may also give a better insight into the behaviour of the system. In general proof loads can address long-term or time-dependent effects. These effects should be complemented by calculation.

4. Basic variables

In accordance with the above-mentioned general principles, characteristic and representative values of all basic variables shall be determined taking into account the actual situation and state of the structure. Available design documentation is used as a guidance material only. Actual state of the structure should be verified by its inspection to an adequate extent. If appropriate, destructive or non-destructive inspections should be performed and evaluated using statistical methods.
For verification of the structural reliability using partial factor method, the characteristic and representative values of basic variables shall be considered as follows:

(a) Dimensions of the structural elements shall be determined on the basis of adequate measurements. However, when the original design documentation is available and no changes in dimensions have taken place, the nominal dimensions given in the documentation may be used in the analysis.

(b) Load characteristics shall be introduced with the values corresponding with the actual situation verified by destructive or non-destructive inspections. When some loads have been reduced or removed completely, the representative values can be reduced or appropriate partial factors can be adjusted. When overloading has been observed in the past it may be appropriate to increase adequately representative values.

(c) Material properties shall be considered according to the actual state of the structure verified by destructive or non-destructive inspections. When the original design documentation is available and no serious deterioration, design errors or construction errors are suspected, the characteristic values given in original design may be used.

(d) Model uncertainties shall be considered in the same way as in design stage unless previous structural behaviour (especially damage) indicates otherwise. In some cases model factors, coefficients and other design assumptions may be established from measurements on the existing structure (e.g. wind pressure coefficient, effective width values, etc.).

Thus reliability verification of an existing structure should be backed up by inspection of the structure including collection of appropriate data. Evaluation of prior information and its updating using newly obtained measurements is one of the most important steps of the assessment.

5. Data updating

Using results of an investigation (qualitative inspection, calculations, quantitative inspection, proof loading) the properties and reliability estimates of the structure may be updated. Two different procedures of updating can be distinguished:

(1) Updating of the structural failure probability.
(2) Updating of the probability distributions of basic variables.

Direct updating of the structural reliability can formally be carried out using the following basic formula of probability theory:

$$\mathrm{P}(F|I) = \mathrm{P}(F \cap I)/\mathrm{P}(I) \tag{1}$$

where P denotes probability, F local or global failure, I inspection information, and $\cap$ intersection of two events. The inspection information I may consist of the observation that the crack width at the beam B is smaller than at the beam A. An example of probability updating using equation (1) is presented for example in [7] and [9].

The updating procedure of a univariate or multivariate probability distribution (equation (2)) is given formally as:

$$\mathrm{f}_X(x|I) = K\,\mathrm{P}(I|x)\,\mathrm{f}_X(x) \tag{2}$$

where $\mathrm{f}_X(x|I)$ denotes the updated probability density function of X, $\mathrm{f}_X(x)$ denotes the probability density function of X before updating, X a basic variable or statistical parameter, I inspection information, K normalising constant, and $\mathrm{P}(I|x)$ likelihood function.

An illustration of equation (2) is presented in Fig. 1. In this example updating leads to a more favourable distribution with a greater design value x_d than the prior design value x_d. In general, however, the updated distribution might be also less favourable than the prior distribution.

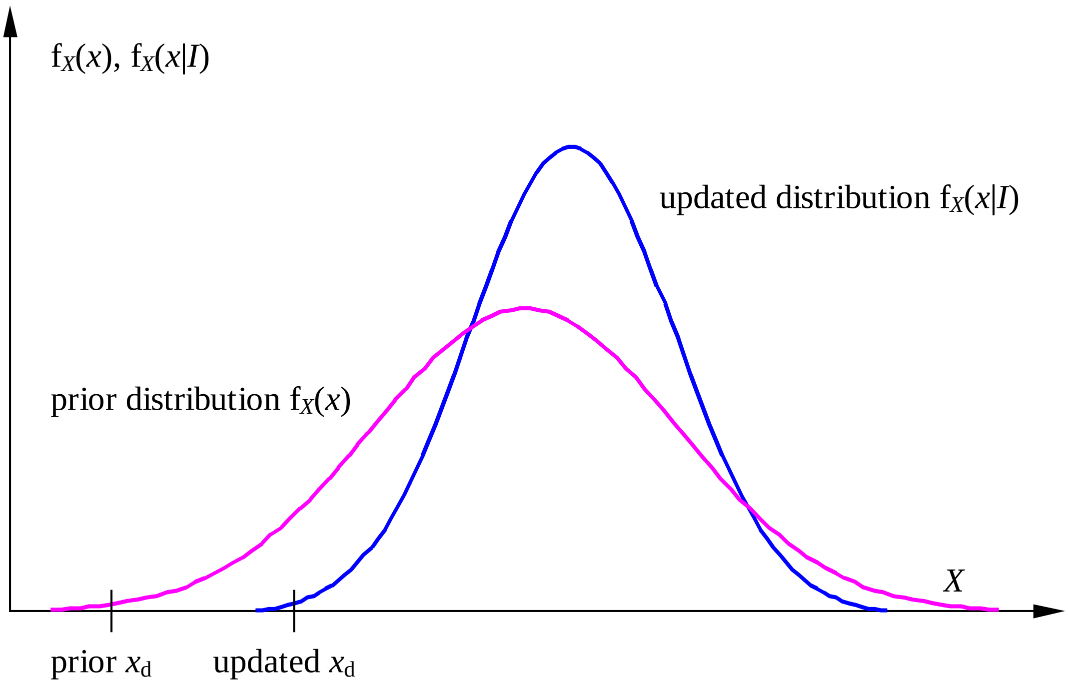

Figure 1. Updating of probability density function and design value x_d of a variable X.

The updating procedure can be used to derive updated characteristic and representative values (fractiles of appropriate distributions) of basic variables to be used in the partial factor method or to compare directly action effects with the limit values (cracks, displacements). More information on updating including Bayesian method for fractile updating may be found in ISO 12491 (1998) [4].

Once the updated distributions for the basic variables $f_X(x)$ have been found, the updated failure probability $P(F|I)$ may be determined by performing a probabilistic analysis using common method of structural reliability for new structures. Symbolically it can be written

$$P(F|I) = \int_{G(x)<0} f_X(x|I)\,\mathrm{d}x \tag{3}$$

where $f_X(x|I)$ denotes the updated probability density function and $g(x) < 0$ denotes the failure domain ($g(x)$ being the limit state function). It should be proved that the probability $P(F|I)$, given the design values of the basic variables, does not exceed a specified target value.

A more operational procedure is to determine updated design values for each basic variable (equation (2)). For a resistance parameter X, the design value can be obtained using operational formula of ISO 2394 (2015) [2]. For normal and lognormal random variable it holds

$$x_\mathrm{d} = \mu\left(1-\alpha\beta \mathrm{V}\right) \tag{4}$$

$$x_\mathrm{d} = \frac{\mu}{\sqrt{1+V^2}}\exp\left(-\alpha\beta\sqrt{\ln(1+V^2)}\right) \tag{5}$$

where x_d is the updated design value for X, μ updated mean value, α FORM sensitivity factor, β the target reliability index and V updated coefficient of variation.

The value of the target reliability index β is discussed in ISO 13822 (2010) [3], the values of α can be taken equal to those commonly used for new structures (– 0.7 for the dominating load parameter, 0.8 for the dominating resistance parameter and reduced values by factor 0.4 for non-dominating variables according to ISO 2394 (2015)) [2] and EN 1990 (2002) [5].

6. Alternative data updating

As an alternative to updating procedure (2), one might also determine the characteristic value x_k first and calculate the design value x_d by applying the appropriate partial factor γ_m:

$$x_\mathrm{d} = x_\mathrm{k}/\gamma_\mathrm{m} \tag{6}$$

For normal and lognormal random variable X the characteristic values x_k follow as

$$\frac{x_\mathrm{k}}{x_\mathrm{d}} = \frac{\mu-k\sigma}{\mu-\alpha\beta\sigma} \tag{7}$$

$$x_\mathrm{k} = \frac{\mu}{\sqrt{1+V^2}}\exp\left(-k\sqrt{\ln(1+V^2)}\right) \tag{8}$$

where $k = 1.64$ (5% fractile of the standardised normal distribution) is usually used. It may be helpful to consider both methods and to use the most conservative result. In case of a limited sample size, the value of k will increase with decreasing number of observations. This procedure may be applied for all basic variables. However, for geomechanical properties and variable loads usually other distributions apart from the normal and lognormal distribution may be more suitable (e.g. Gumbel, three-parameter lognormal distribution).

Note that a lower acceptable reliability level can be reflected by reducing β values for probabilistic design and reducing γ values in the partial factor method. For a material property X described by a normal distribution the partial factor γ_{m} may be estimated using relationship

$$\gamma_{\mathrm{m}} = \frac{x_k}{x_d} = \frac{\mu - k\sigma}{\mu - \alpha\beta\sigma} \tag{9}$$

which follows from general equation (6). All the symbols used in equation (8) are defined above (k = 1.64 is usually applied for the characteristic strength). Similar relationships between γ_{m} and β may be derived for lognormal or other distributions.

7. Structural analysis

Structural behaviour should be analysed using models that describe actual situation and state of an existing structure. Generally the structure should be analysed for ultimate limit states and serviceability limit states using basic variables and taking into account relevant deterioration processes. All basic variables describing actions, material properties, load and model uncertainties should be considered as mentioned above. The uncertainty associated with the validity and accuracy of the models should be considered during assessment, either by adopting appropriate factors in deterministic verifications or by introducing relevant probabilistic model factors in reliability analysis.

When an existing structure is analysed, conversion factors reflecting the influence of shape and size effect of specimens, temperature, moisture, duration-of-load effect, etc., should be taken into account. The level of knowledge about the condition of components should be also considered. This can be achieved by adjusting the assumed variability in either the load carrying capacity of the components or the dimensions of their cross sections, depending on the type of structure.

8. Verification

8.1 General

Reliability verification of an existing structure shall be made using valid codes of practice, as a rule based on the limit state concept. Attention should be paid to both the ultimate and serviceability limit states. Verification may be carried out using partial safety factor or structural reliability methods with consideration of structural system and ductility of components. The reliability assessment shall be made taking into account the remaining working life of a structure, the reference period, and anticipated changes in the environment of a structure. The conclusion from the assessment shall withstand a plausibility check. In particular, discrepancies between the results of structural analysis (e.g. insufficient safety) and the real structural condition (e.g. no sign of distress or failure, satisfactory structural performance) must be explained. It should be kept in mind that many engineering models are conservative and cannot be always used directly to explain an actual situation.

The target reliability level used for verification can be taken as the level of reliability implied by acceptance criteria provided in valid design codes. The target reliability level shall be stated together with clearly defined limit state functions and specific models of the basic variables. The target reliability level can also be established taking into account the required performance level for the structure, the reference period and possible failure consequences. In accordance with ISO 2394 [2], the performance requirements applied in assessment of existing structures are the same as those used in design of new structures. Lower reliability targets for existing structures may be used if they can be justified on the basis of economic, social and sustainable consideration (Annex F to ISO 13822 [3]).

An adequate value of the reliability index β should be in general determined considering appropriate reference period. For serviceability and fatigue the reference period equals the remaining working life, while for the ultimate limit states the reference period is in principle the same as the design working life specified for new structures (50 years for buildings). This general approach should be in specific cases supplemented by detailed consideration of the character of serviceability limit states (reversible, irreversible), fatigue (detectable, not detectable) and consequences of ultimate limit states (economic consequences, number of endangered people).

Reliability of a structure given by condition $g(X_i) > 0$ (in a simplified form $R - E > 0$) can be verified by various methods. The following procedures are included in the draft of upcoming CEN Technical specification.

8.2. Partial factor method

The requirement $g(X_i) > 0$ is substituted by

$$g(x_{di}) = g(x_{d1}, x_{d2}, x_{d3}, ...) > 0, \; x_{di} = x_{ki} \text{ or } x_{di} = x_{ki}\,\gamma \text{ or } x_{di} = x_{ki}/\gamma \quad (10)$$

Here x_{di} denotes the design values of basic variables x_i determined using the characteristic values x_{ki} and relevant partial factors γ.

8.3. Design value method

The requirement $g(X_i) > 0$ is substituted by

$$g(x_{di}) = g(x_{d2}, x_{d2}, x_{d3}, ...) > 0, , \Phi_{Xi}(x_{di}) = \Phi(-\alpha_i\,\beta) \quad (11)$$

Here α_i denotes the FORM sensitivity factors and Φ the normal distribution function.

8.4. Probabilistic method

The requirement $g(X_i) > 0$ is examined by failure probability

$$P_f = P\{g(X_i) < 0\} < P_{f,t} \quad (12)$$

Here $P_{f,t}$ denotes the target probability of failure, that is to be specified taking into account economic and societal consequences of failure and costs of improving structural reliability.

8.5. Risk assessment approach

The reliability is examined by acceptable risk expressed in a symbolic form as

$$R = P_f\ C = P\{g(X_i) < 0\}\ C < R_t \quad (13)$$

Here *C* generally represents any type of economic and societal consequences and R_t the relevant target risk level. Appropriate target risk level R_t is to be specified individually taking into account specific condition of an assessed structure. This may be complicated task particularly in case of heritage buildings when in addition to economic consequences historical and artistic aspects are usually involved. A general flowchart of risk assessment procedure accepted in the first draft of the upcoming Technical specification is shown in Fig. 2.

9. Concluding remarks

The main principles of the upcoming European document on assessment of existing structures harmonised with the valid Eurocode EN 1990 [5] and ISO standards [2], [3] and [4] can be summarized as follows:

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- Currently valid codes for verification of structural reliability should be applied, historic codes valid in the period when the structure was designed, should be used as guidance documents only;
- Actual characteristics of structural material, action, geometric data and structural behaviour should be considered; the original design documentation including drawing should be used as guidance material only.

The most important step of the whole assessment procedure is evaluation of available data and updating of prior information concerning actions, strength and structural reliability. It appears that a Bayesian approach can provide an effective tool.

Typically, assessment of existing structures is a cyclic process in which the first preliminary assessment is often supplemented by subsequent detailed investigations, data evaluation and updating. A report on structural assessment prepared by an engineer assessing the structure should include a recommendation on possible structural and operational interventions. However, the client in collaboration with the relevant authority should make the final decision concerning possible interventions.

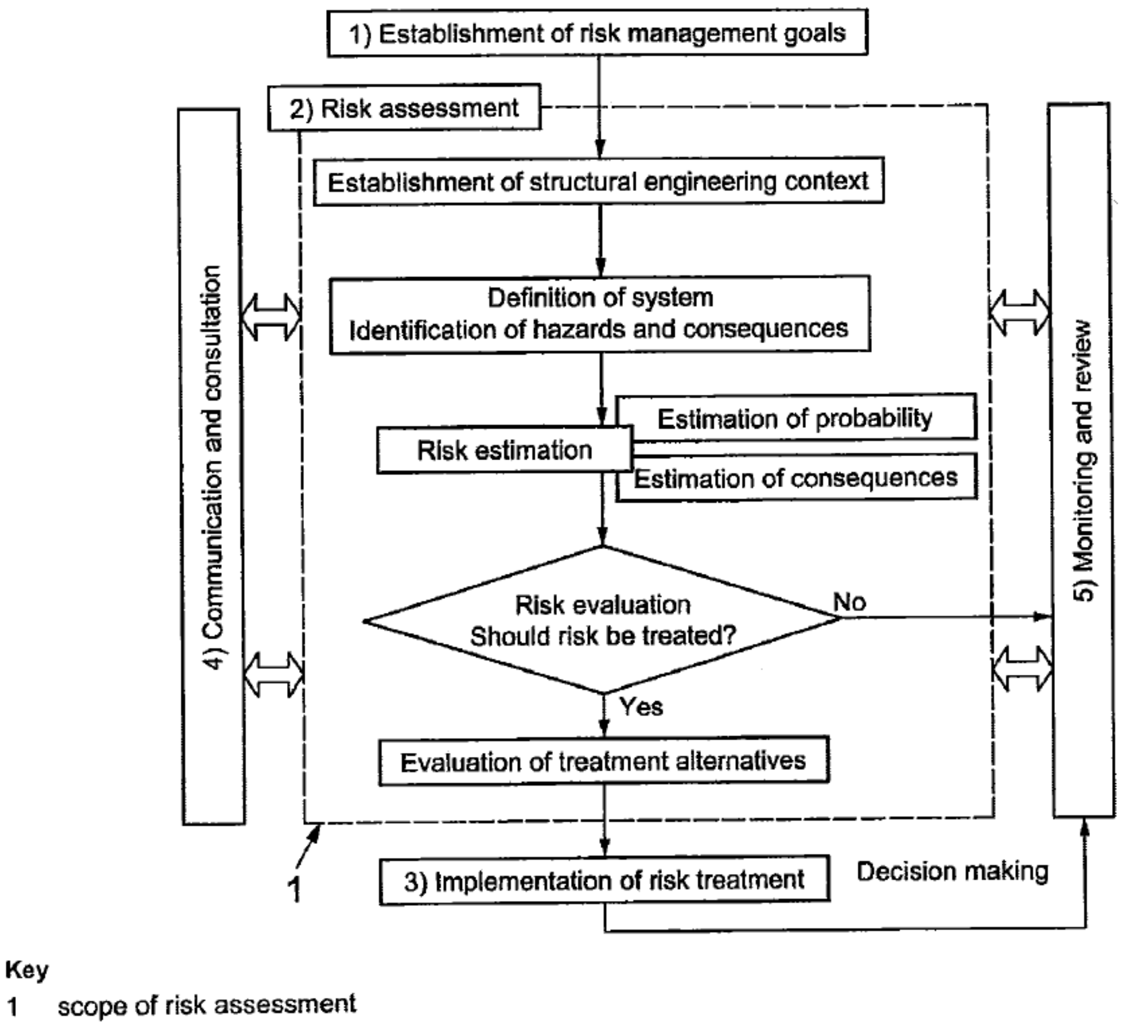

Figure 2. Flowchart of risk assessment procedure.

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