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Target Reliability Levels for Existing Bridges Considering Emergency and Crisis Situations

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Abstract:

Specification of the target reliability levels is one of key issues required for the assessment of existing structures in emergency and crisis situations. International standards ISO 13822 and ISO 2394 indicate procedures for specification of the target reliability levels by optimisation of the total cost. This approach is applied in conjunction with the human safety criteria to estimate the target reliability levels of existing bridges considering emergency or crisis situations. For the reference period of one week obtained target reliabilities are in most cases within the range from 2.0 up to 3.5, thus significantly lower than those applied in the design of new structures.

Keywords:

Emergency situation, failure consequences, human safety, optimization, target reliability

1. Introduction

The target reliability levels in various national and international documents for new and existing structures are inconsistent in terms of the recommended values and the criteria according to which appropriate values are to be selected. Almost no recommendations are available for temporary structures [1] and this holds likewise for structures under temporary conditions including emergency and crisis situations.

This paper develops a general procedure for the assessment of target reliabilities of structures during emergency or crisis situations; according to specifications of the Ministry of Interior of the Czech Republic, the following definitions are accepted here:

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- An emergency situation is the situation caused by the threat of an origin of or as a consequence of an extraordinary event that is managed in a standard way by cooperation of the emergency services of the Integrated Rescue System, national security system, system of the protection of economy, defence etc., together with relevant authorities in the framework of their competences and common procedures, without the declaration of crisis states.
- A crisis situation is the situation that results in the declaration of a crisis state such as state of danger, emergency state, state of threat to the country or state of war. In such a situation the threat cannot be averted and/or the repair of the damage cannot be managed by a standard cooperation of public authorities, armed forces, emergency services, legal entities and civilians.

Extraordinary events can be caused by natural disasters, accidents, threat to a critical infrastructure, diseases, threat to the internal security of the state and economics.

In this paper a particular emphasis is put on road bridges exposed to loads due to crossings of heavy military and civilian traffic in response to the occurring situation. Target reliabilities related to emergency and crisis situations can be required for:

- Design of new bridges considering possible occurrence of the emergency or crisis situation (with considerations of low occurrence probability of the situation, potentially high consequences of bridge failure and relatively low costs of safety measures – improvements of structural resistance),
- Assessment of temporary bridges (special-purpose structures erected due to the emergency or crisis situation, with a given resistance and high costs of safety measures),
- Assessment of existing bridges when immediate decisions on permissions for crossing of heavy freights are needed (bridge resistance cannot be readily increased).

This paper focuses on the third case only. Some modifications would be required to adjust the proposed technique for the first two cases.

Hereafter an emergency or crisis situation is assumed to last only few days or weeks. However, applications of the proposed technique are in principle not constrained by the duration of the situation and even purpose of the structure. Though adjustments might be needed, e.g. for assessment of civilian buildings or industrial structures under emergency or crisis situations of longer durations.

2. Reliability assessment of existing Bridges

It is widely recognised that the reliability assessment of existing bridges differs from design of new structures in a number of aspects including:

- Increased safety levels usually involving more costs for existing bridges than for new bridges.
- The remaining working life of existing bridges often different from the standard design working life of 100 years assumed for new bridges.
- Information on actual structural conditions that may be available for assessment (inspections, tests, measurements).

When dealing with the reliability assessment under the emergency or crisis situations, the first aspect is of a particular interest since it might be difficult or even impossible to strengthen a bridge during a short duration of the situation. On the contrary, the second and third aspects may apply in the assessment under persistent design situations as the emergency or crisis situation is inherently of a shorter duration in comparison with service life of bridges. Moreover, in the emergency or crisis situation it is often impossible to obtain detailed information concerning the bridge conditions by means of inspections and testing.

At present, existing bridges are mostly verified using simplified deterministic procedures based on the partial factor method commonly applied in design of new bridges. Such assessments are often conservative and may lead to expensive upgrades. More realistic verification of actual performance of existing bridges can be achieved by probabilistic methods when uncertainties of basic variables are described by appropriate probabilistic models.

Specification of the target reliability levels is required for the probabilistic assessment of existing bridges. In addition, the target reliabilities can be used to modify the partial factors used in a deterministic assessment [2, 3]. It has been recognised that it would be uneconomical to specify for all existing buildings and bridges the same reliability levels as for new structures [4]. This is also demonstrated by the present practice in Canada, the Netherlands and USA where the target reliability indices for existing structures decrease by about 0.5-1.7 compared with indices for new structures [5, 6].

3. Target Reliability Levels in Codes

The target reliability levels recommended in EN 1990 [7] are primarily intended for design of new structures; reliability classes are associated with consequences of failure. More detailed classification is given in ISO 2394 [8] where relative costs of safety measures are also taken into account. The target reliability levels provided in both documents are partly based on calibrations to previous practice and should be considered as indicative only.

ISO 13822 [9] indicates a possibility to specify the target reliability levels for existing structures by optimisation of the total cost related to an assumed remaining working life. This approach in conjunction with the criteria for safety of people in accordance with ISO 2394 [8] is further developed here.

EN 1990 [7] recommends the target reliability index for two reference periods (1 and 50 years), see Tab. 1. These target reliabilities are intended to be primarily used in design of new structures.

The couples of β-values given in Tab. 1 for each reliability class correspond approximately to the same reliability level. For a bridge of RC2, the reliability index β = 3.8 should be thus used, provided that probabilistic models of basic variables are related to the reference period of 50 years. The same reliability level should be reached when β = 4.7 is applied using the theoretical models for one year. Note that the couples of β-values correspond to the same reliability level only when failure probabilities in individual time intervals (basic reference periods for variable loads) are independent. Target reliability index β = 3.8 could better be interpreted as corresponding to about 4.5 per year as complete independency of resistance and loads in subsequent years is not realistic [10].

Considering a reference period t_{ref}, it might be understood from EN 1990 [7] that the related reliability level can be derived as follows:

$$\beta_{t\mathrm{ref}} = \Phi^{-1}\{[\Phi(\beta_1)]^{t_{\mathrm{ref}}}\} \tag{1}$$

Tab. 1 Reliability classification for different reference periods in accordance with EN 1990 [7]

Reliability class	Failure consequences	β (1 y.)	β (50 y.)	Examples
RC3	high	5.2	4.3	bridges, public buildings
RC2	medium	4.7	3.8	residences, offices
RC1	low	4.2	3.3	agricultural buildings

where β_1 = the target reliability index taken from Tab. 1 for a relevant reliability class and the reference period t_{ref} = 1 year; Φ and Φ^{-1} = the cumulative distribution function of the standardised normal variable and its inverse function, respectively.

However, this concept seems to be hardly applicable for the emergency and crisis situations where the reference period can be very short and the reliability level excessively increases (for instance $\beta \approx 5.5$ should be considered for t_{ref} = 1/52 year = = 1 week and RC2).

A more detailed recommendation is provided by ISO 2394 [8] where the target reliability index is given for the working life and is related not only to the consequences but also to the relative costs of safety measures (Tab. 2). The target reliability might thus be selected independently of the reference period (duration of the emergency or crisis situation) which seems to be a more appropriate approach than that provided by EN 1990 [7]. Using Tab. 2 for existing structures, the target level usually decreases as it takes more effort to increase the reliability level [10]. So for a couple of similar new and existing structures, e.g. moderate costs of safety measures can be considered at a design stage while high costs may apply when assessing the existing structure.

In addition, Tab. 2 provides the classification of road bridges with respect to failure consequences according to the Technical Requirements of the Ministry of Transportation of the Czech Republic [11].

Tab. 2 Target reliability index (life-time, examples) in accordance with ISO 2394 [8] (classification of road bridges according to [11])

Classification of road bridges [11] (examples)	Bridges on sporadically used roads	Bridges of short spans on roads of II. and III. class	Common bridges	Long span bridges, bridges on highways and speedways
Relative costs of safety measures	Failure consequences			
	small	some	moderate	great
High	0	1.5	2.3	3.1
Moderate	1.3	2.3	3.1	3.8
Low	2.3	3.1	3.8	4.3

Similar recommendation is provided by the Probabilistic Model Code of the Joint Committee on Structural Safety (JCSS) [12]. Recommended target reliability indices are also related to both the consequences and to the relative costs of safety measures, however for the reference period of one year. These recommendations also seem to be less suitable for emergency and crisis situations.

ISO 13822 [9] indicates four target reliability levels for different consequences of failure (the ultimate limit states):

- Small consequences: 2.3,
- Some: 3.1,
- Moderate: 3.8,
- High: 4.3.

The related reference period is "a minimum standard period for safety (e.g. 50 years)".

In general ISO 2394 [8] seems to provide the most appropriate reliability differentiation for existing bridges in emergency and crisis situations since costs of safety measures are taken into account and the reliability levels are associated with a working life (duration of the emergency or crisis situation here).

The following comments concerning available approaches to the target reliabilities are provided:

- Costs of safety measures might be perceived as an unacceptable factor for the target reliability particularly of new structures.
- Several empirical models for the assessment of target reliabilities have been proposed in previous studies; Sykora and Holicky [13] provided a brief overview.

4. Basis of Cost Optimisation

Lower target reliability levels can be used if justified on the basis of social, cultural, economic, and sustainable considerations as indicated in ISO 13822 [9]. ISO 2394 [8] shows that the target level of reliability should depend on a balance between the consequences of failure and the costs of safety measures. From an economic point of view the objective is to minimize the total structural cost.

The expected total costs C_{tot} may be generally considered as the sum of the expected costs of inspections, maintenance, upgrades and costs related to failure of a bridge. The objective is to optimise relevant decision parameters d, represented by factors affecting the resistance, actions, serviceability, durability, maintenance, inspection, upgrade strategies, etc. Examples include:

- Design phase: sectional area of a steel beam, shear reinforcement ratio of reinforced concrete beam, concrete cover in durability design,
- Verification of an existing bridge: strategies to upgrade bridge resistance for a dominating failure mode (local strengthening by fibre-reinforced polymers, construction of a secondary load bearing structure), limits on traffic load (restrictions of vehicle weights, reduction of traffic lanes) etc.

In the present study, the decision parameter is assumed to concern mainly the immediate upgrade while inspection, maintenance and future repair or upgrade strategies are influenced marginally. This may be a reasonable assumption in many practical cases. Implications for the assessment in emergency and crisis situations are clarified in the following.

An upgrade of the bridge, immediately undertaken during the emergency or crisis situation, may in general lead to the following costs:

- Cost C_0 independent of the decision parameter – economic losses and potential societal consequences (injuries or fatalities) caused by temporary bridge closure in the emergency or crisis situation due to upgrade works immediately resulting from the decision to enhance bridge resistance,

- Marginal cost C_m per unit of the decision parameter.

Estimation of the cost C_0 may be a difficult task and expert judgements may be necessary. However, it is further assumed that the upgrade costs C_0 and C_m can be reasonably estimated.

The main reason for the existence of civil infrastructures is the public interest. Therefore, all related societal aspects should be considered when assessing the failure consequences C_f. Depending on the bridge concerned, failure may be associated with the following consequences:

- Potential societal consequences directly caused by the failure (collapse),
- Cost of repair or replacement,
- Economic losses and potential societal consequences caused by bridge closure due to repair works taken after the failure (possibly including also losses due to damage on detour routes),
- Other possible consequences, such as unfavourable environmental or psychological effects.

Estimation of the failure cost is a vital, but likely the most difficult step in the cost optimisation. It is important to include not only direct consequences of failure (those resulting from the failures of individual components), but also follow-up consequences (related to a loss of the functionality of a whole bridge). Background information for consequence analysis is provided in [14, 15] and by outcomes of the SeRoN project (seron-project.eu) focused on security of road transport network.

In cost optimisations, discounting is commonly applied to express the upgrade and failure costs on a common basis [1]. Apparently such considerations are not needed in the case of situations of short-term durations.

Based on these assumptions, the expected total costs can be expressed as follows:

$$\text{In case of upgrade: } C_{tot}(d) = C_0 + C_m\, d + C_f\, p_f(d) \quad (2)$$

$$\text{No upgrade (accepting a present state): } C_{tot}(d_0) = C_f\, p_f(d_0) \quad (3)$$

where $p_f(\cdot)$ = the failure probability related to a reference period; and d_0 = the value of the decision parameter before an upgrade such as shear resistance of an as-built bridge girder.

From equation (2), the optimum value of the decision parameter d_{opt} (optimum upgrade strategy) can be obtained:

$$\text{minimum}_d\, C_{tot}(d) = C_{tot}(d_{opt}) \quad (4)$$

From an economic point of view, no upgrade is undertaken when the total cost according to equation (3) is less than the total cost of the optimum upgrade. It follows from equations (2) and (4) that d_{opt} is independent of C_0.

5. Target Reliabilities Based on Cost Minimisation

The optimum upgrade strategy should aim at the target reliability corresponding to d_{opt}, $\beta_{up} = -\Phi^{-1}[p_f(d_{opt})]$. However, the total costs given in equations (3) and (4) should be compared to decide whether to upgrade the bridge or not. The limiting value d_{0lim} of the decision parameter before the upgrade is then found as follows:

$$p_f(d_{0lim}) = C_0 / C_f + C_m\, d_{opt} / C_f + p_f(d_{opt}) \quad (5)$$

For $d_0 < d_{0\lim}$ the reliability level of an existing bridge is too low, failure consequences become high and the decision is to upgrade the bridge as the optimum upgrade strategy yields a lower total cost. For $d_0 > d_{0\lim}$ the present state is accepted from an economic point of view, since no upgrade strategy leads to a lower total cost than costs expected when no upgrade is taken. The minimum reliability index β_0 below which the bridge is unreliable and should be upgraded then corresponds to $d_{0\lim}$, $\beta_0 = -\Phi^{-1}[p_f(d_{0\lim})]$.

Realistically assuming $C_f >> C_m\, d_{opt}$ for important bridges in emergency and crisis situations, the minimum reliability index β_0 becomes:

$$\beta_0 \approx -\Phi^{-1}[C_0 / C_f + p_f(d_{opt})] \quad (6)$$

Assessment of the optimum repair strategy (d_{opt}) requires a case-specific approach and detailed information on this is beyond the scope of this paper.

During emergency or crisis situations it can be assumed that the target reliability will be dominantly affected by the ratio C_0 / C_f as these costs become comparable and the evaluation of the $p_f(d_{opt})$ is then of a minor importance.

To simplify the present analysis, results obtained in [16] are adopted and failure probabilities related to optimum upgrade strategies are considered as follows:

- Failure consequences small/some: $p_f(d_{opt}) \approx 0.03$ ($\beta(d_{opt}) \approx 1.9$),
- Medium: $p_f(d_{opt}) \approx 0.008$ ($\beta(d_{opt}) \approx 2.4$),
- High: $p_f(d_{opt}) \approx 0.003$ ($\beta(d_{opt}) \approx 2.8$).

Fig. 1 indicates variation of the minimum reliability index β_0 with the cost ratio C_0 / C_f. Apparently the cost ratio is a significant factor. It appears that for:

- $C_0 / C_f < 0.001$ the minimum reliability index is about 2.4 for CC2 and 2.7 for CC3,
- $C_0 / C_f > 0.01$ the minimum reliability index drops below two which is the reliability level commonly considered for the Serviceability limit states.

It is interesting to note that for high relative costs of safety measures, ISO 2394 [8] (Tab. 2) indicates $\beta = 2.3$ and 3.1 for moderate and great failure consequences, respectively.

6. Requirements on Human Safety

The cost optimisation is commonly perceived to aim at finding the optimum decision from the perspective of a bridge owner. However, society commonly establishes limits for human safety. General guidelines for the assessment of the target reliabilities with respect to human safety are provided in ISO 2394 [8]. In principle structural design and assessment of existing bridges are not distinguished.

ISO 2394 [8] states that structural reliability is important first and foremost if people may be killed or sustain injuries as a result of the collapse. An acceptable maximum value for the failure probability might be found from a comparison of risks resulting from other activities. Individual lethal accident rates ranging between 10^{-6} and 10^{-5} per year, as accepted in [16, 17], seem to be reasonable for structures in persistent design situations, when compared to the typical rates in industries, e.g.:

- 10^{-4} per year for work in all industries (2×10^{-4} for users of motor vehicles),
- 10^{-5} per year for third parties in ship industry (passengers or public ashore).

The overall individual lethal accident rate of 10^{-4} per year is a common value of reference; rates over 10^{-3} are deemed unacceptably high [18].

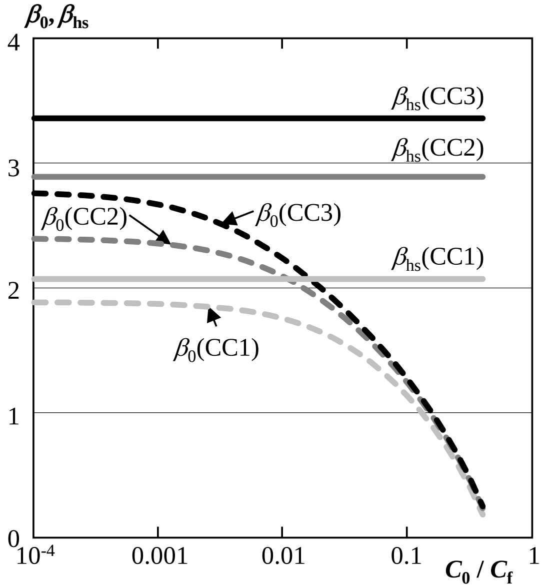

Fig. 1 Variation of the target reliability indices based on the economic (β_0) and human safety (β_{hs}) criteria with the cost ratio C_0 / C_f for the different consequence classes and reference period of one week

However, in emergency and crisis situations higher risks may be acceptable, since they may be compensated by mitigation of consequences in endangered areas. Therefore, a tentative value of 10^{-3} per year is considered hereafter that may be associated with uncommon accidents [19] (tacitly assuming that safety of the members of rescue corps is endangered).

The concept of individual risk provided in ISO 2394 [8] then yields the following relationship between the target failure probability $p_{ft,hs}$ and the conditional probability of occupant fatality p_1, given the structural failure in emergency or crisis situation:

$$p_{ft,hs} \text{ (per year)} \leq 10^{-3} \text{ per year} / p_1 \quad (7)$$

With respect to the loss of human life, EN 1990 [7] distinguishes among low, medium, or high consequences (Consequence Classes CC1-CC3, respectively). The Consequence Classes may be associated with the Reliability Classes indicated in Tab. 1. Based on a literature review [20] the following conditional probabilities for assessment of bridges might be accepted:

- p_1 = 0.05 for CC3,
- p_1 = 0.01 for CC2,
- p_1 = 0.001 for CC1.

For emergency and crisis situations, the target failure probabilities of a structural members, related to a reference period t_{ref} (duration of a situation << 1 year), become from equation (7) (with t_{ref} in years):

$$\text{CC1: } p_{ft,hs} \leq t_{ref}; \text{ CC2: } p_{ft,hs} \leq 0.1t_{ref}, \text{ CC3: } p_{ft,hs} \leq 0.02t_{ref} \quad (8)$$

Fig. 1 indicates the target reliability index β_{hs} (obtained from equations (6) and (8)) for the different consequence classes and t_{ref} = 1 / 52 year = 1 week. The human safety criterion is apparently dominating the target reliability over the minimum reliability level based on the cost ratio C_0 / C_f.

However, it is questionable whether the target level should be selected on the basis of the human safety criterion since it regards only safety of users of a bridge and fails to consider additional costs in form of life losses related to temporary bridge closure (cost C_0) if the criterion is not fulfilled. The decision regarding the permission of heavy freight crossing depends on case-specific conditions. In general it should aim at balancing risks of users and risks of people endangered when the crossing is not permitted (see the example below).

Note that besides the individual risk concept, ISO 2394 [8] indicates that in many cases authorities explicitly intend to avoid accidents with a large number of fatalities and proposes an additional societal risk criterion based on a so-called *F-N* curve, ISO 13824 [21]. However, application of this criterion requires a case-specific approach and it is out of the scope of this paper to provide a general guidance in this regard. Moreover, the individual risk criterion is dominating over the societal criterion except failures with vast collapsed areas [16]. Therefore, the societal risk criterion is not considered in this paper.

7. Examples

7.1. Human Safety not Endangered when Transport is not Permitted

Application of the derived target reliabilities in conjunction with the partial factor method (EN 1990 [7]) is illustrated by a simple example. An excessively heavy freight is to be transported over a reinforced concrete bridge. It is assumed that:

- Duration of an emergency situation is two weeks and the crossing is to be allowed at any time of this period, $t_{ref} = 0.038$ y.
- The bridge is classified in CC3 (high consequence for loss of human life in case of failure). Note that the class CC3 means that there is high conditional probability p_1. In such a case failure can occur without previous warning (e.g. shear failure of reinforced concrete beam or buckling of bridge piers) and subsequent collapse is likely.
- Considering economic and societal consequences, the cost ratio C_0 / C_f is estimated to be 0.01 and $\beta_0 \approx 2.2$ (see Fig. 1).
- Human safety is not endangered when the transport is not permitted. However, safety of a driver is to be considered in the case of crossing. Equation (8) leads to $p_{ft,hs} \leq 0.02 \times 0.038 = 7.6 \times 10^{-4}$ and then $\beta = \beta_{hs} = 3.2 > \beta_0 = 2.2$.
- It is impossible to conduct measurements and tests on the structure.

For the assessment the partial factors for material properties are needed. The partial factor of a material property γ_M can be obtained as [2, 3]:

$$\gamma_M = \gamma_{Rd}\, \gamma_m = \gamma_{Rd1}\, \gamma_{Rd2}\, \gamma_m \qquad (9)$$

where γ_{Rd1} = the partial factor accounting for model uncertainty; γ_{Rd2} = the partial factor accounting for geometrical uncertainties; γ_m = the reliability-based partial factor accounting for variability of the material and statistical uncertainty.

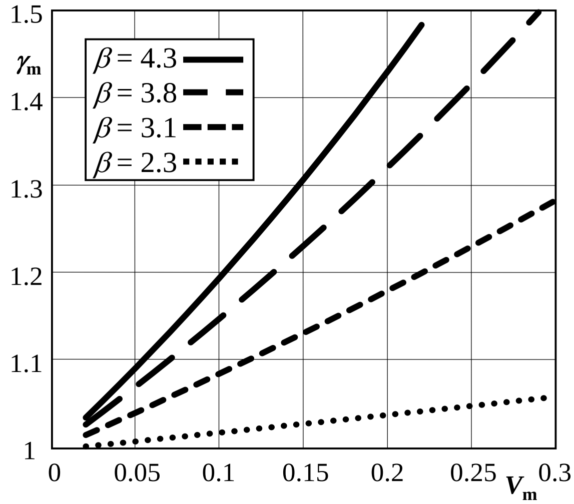

Fig. 2 Variation of the partial factor γ_m with the coefficient of variation V_m for β = 2.3, 3.1, 3.8 or 4.3 (adapted from [2, 3])

The following uncertainty factors can be recommended [2, 3]:

- γ_{Rd1} = 1.05 for concrete strength and γ_{Rd1} = 1.025 for reinforcement,
- γ_{Rd2} = 1.05 for geometrical uncertainties of the concrete section size or reinforcement position when measurements are not available.

Variation of the partial factor γ_m with the coefficient of variation of the material property V_m is shown in Fig. 2 for selected target reliabilities (adapted from [2, 3]). Considering common values V_c = 0.15 and V_s = 0.05 [2] the following partial factors are obtained for β = 3.2:

$$\gamma_C = 1.05 \times 1.05 \times 1.15 = 1.27; \gamma_S = 1.025 \times 1.05 \times 1.05 = 1.13 \quad (10)$$

In a similar way, the partial factor for permanent load can be obtained [2, 3] and partial factor for load effect due to heavy transport [22].

7.2. Human Safety Endangered when the Transport is not Permitted

Now it is assumed that the human safety is endangered when the transport is not allowed. This can be represented by the transport of decontamination units in the case of industrial or chemical explosion when immediate response is needed. Another example is the transport of portable flood barriers.

Two hazard scenarios are considered in the case when the transport is not permitted; an expert judgement suggests that:

- It is “very unlikely” that there is a single fatality in the endangered area; the qualitative term “very unlikely” may be associated with probability of having a single fatality of about 0.15 [23].
- It is “impossible” that there are ten fatalities in the endangered area (associated with probability of about 0.02 [23]).

The decision “not to permit the transport” is thus related to the risk R = 1 × 0.15 (1 – 0.02) + 10 × 0.02 = 0.35 (in terms of the expected number of fatalities).

When the transport is permitted, related risk should be lower than in the previous case:

$$p_f(1 \times p_1 + R) \leq R \quad (11)$$

where p_f = the failure probability given the crossing. The term in brackets in equation (11) represents risks given failure of the bridge. Only a driver is assumed to be present on the bridge during the crossing. For p_1 = 0.05 (CC3) and R = 0.35, equation (11) yields an excessively high failure probability, $p_f \leq 0.875$ ($\beta_{hs} < 0$). In this case the target reliability is thus dominated by the value β_0 that should be determined considering all factors affecting the C_0 and C_f costs, as discussed in Section 4.

8. Conclusions

The target reliability levels recommended in various standards for new and existing structures are inconsistent; almost no recommendations are available for structures under temporary conditions including emergency and crisis situations. Target reliabilities related to these situations can be required for (1) design of new bridges considering possible occurrence of the emergency or crisis situation, (2) assessment of temporary bridges or (3) assessment of existing bridges when immediate decisions on permissions for the crossings of heavy freights are needed. Concerning the third case the following conclusions can be made:

- It is uneconomical to require that existing bridges comply with the target reliability levels specified for new bridges; lower target reliability levels can be justified by social, cultural, economic, and sustainability considerations.
- Decisions in the assessment can result in the acceptance of an actual state or in the upgrade of a bridge; in principle two target reliability levels are needed - the minimum level below which the bridge is unreliable and should be upgraded (β_0), and the level indicating the optimum upgrade strategy (β_{up}).
- In particular situations it needs to be clarified whether and what minimum levels of human safety should be considered.
- Critical issue in the assessment of the minimum reliability level β_0 is estimation of the cost ratio of upgrade and failure consequences (C_0 / C_f).
- For C_0 / C_f > 0.01 the reliability level β_0 drops below 2.0 which is the reliability level commonly considered for the Serviceability Limit States.
- Human safety criterion leads to target reliabilities within the range from 2.0 to 3.5 for a reference period of one week.

References

[1] HOLICKÝ, M. Optimisation of the target reliability for temporary structures. *Civ Eng Environ Syst*, 2013, vol. 30, no. 2, p. 87-96.

[2] CASPEELE, R, ALLAIX, DL, STEENBERGEN, RDJM and SYKORA, M. On a partial factor approach for existing concrete structures: the Design Value Approach and Adjusted Partial Factor Method (accepted for publication). *Struct Eng Int*, 2013.

[3] SÝKORA, M, HOLICKÝ, M and MARKOVÁ, J. Verification of existing reinforced concrete bridges using the semi-probabilistic approach. *Eng. Struct.*, 2013, vol. 56, no. 0, p. 1419-1426.

[4] VROUWENVELDER, ACWM and SCHOLTEN, N. Assessment Criteria for Existing Structures. *Struct Eng Int*, 2010, vol. 20, no. 1, p. 62-65.

[5] CASAS, JR and WISNIEWSKI, D. Safety requirements and probabilistic models of resistance in the assessment of existing railway bridges. *Struct Infrastruct E*, 2013, vol. 9, no. 6, p. 529-545.

[6] MALJAARS, J, STEENBERGEN, R, ABSPOEL, L and KOLSTEIN, H. Safety Assessment of Existing Highway Bridges and Viaducts. *Struct Eng Int*, 2012, vol. 22, no. 1, p. 112-120.

[7] EN 1990, *Eurocode – Basis of structural design.*

[8] ISO 2394, *General principles on reliability for structures.*

[9] ISO 13822, *Bases for design of structures – Assessment of existing structures.*

[10] VROUWENVELDER, ACWM. Developments towards full probabilistic design codes. *Struct Saf*, 2002, vol. 24, no. 2-4, p. 417-432.

[11] TP 224. *Ověřování existujících betonových mostů pozemních komunikací* (*in Czech – Assessment of existing concrete road bridges*). Prague: Ministry of Transportation of the Czech Republic, 2010. p. 53.

[12] JCSS. *JCSS Probabilistic Model Code.* Zurich: Joint Committee on Structural Safety, 2001.

[13] SÝKORA, M, HOLICKÝ, M and MARKOVÁ, J. Target reliability levels for assessment of existing structures. In *Proc. ICASP11.* Leiden: CRC Press/Balkema, 2011, p. 1048-1056.

[14] IMAM, BM and CHRYSSANTHOPOULOS, MK. Causes and Consequences of Metallic Bridge Failures. *Struct Eng Int*, 2012, vol. 22, no. 1, p. 93-98.

[15] THOFT-CHRISTENSEN, P. Life-cycle cost-benefit (LCCB) analysis of bridges from a user and social point of view. *Struct Eng Int*, 2009, vol. 5, no. 1, p. 49-57.

[16] SYKORA, M and HOLICKY, M. Target reliability levels for the assessment of existing structures - case study. In *Proc. IALCCE 2012.* Leiden: CRC Press/Balkema, 2012, p. 813-820.

[17] STEENBERGEN, RDJM and VROUWENVELDER, ACWM. Safety philosophy for existing structures and partial factors for traffic loads on bridges. *Heron*, 2010, vol. 55, no. 2, p. 123-139.

[18] STEWART, MG. Life-safety risks and optimisation of protective measures against terrorist threats to infrastructure. *Structure and Infrastructure Engineering*, 2011, vol. 7, no. 6, p. 431-440.

[19] MELCHERS, RE. *Structural Reliability Analysis and Prediction.* Chichester, England: John Wiley and Sons Ltd., 2001. p. 437.

[20] SÝKORA, M, HOLICKÝ, M and MANAS, P. Target Reliability for Bridges in Emergency Situations. In *Proc. ICMT'13.* Brno: University of Defence, 2013, p. 371-382.

[21] ISO 13824, *Bases for design of structures – General principles on risk assessment of systems involving structures.*

[22] LENNER, R, SYKORA, M and KEUSER, M. Partial factors for military loads on bridges. In *Proc. ICMT'13.* Brno: University of Defence, 2013, p. 409-418.

[23] BUDESCU, DV and WALLSTEN, TS. Consistency in interpretation of probabilistic phrases. *Organ Behav Hum Decis Process*, 1985, vol. 36, no. 3, p. 391-405.

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