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NORMATIVE RISK-BASED ASSESSMENT OF EARTHQUAKE SAFETY

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Abstract

The building codes in Switzerland are published by the Swiss Society of Engineers and Architects (SIA). In 2004 SIA published the pre-standard SIA 2018 "Verification of the seismic safety of existing buildings" containing risk-based criteria for assessing the need for earthquake safety measures for existing buildings. At the end of 2017 the pre-standard SIA 2018 was replaced by the code SIA 269/8 "Existing structures – Earthquakes". SIA 269/8 adapts and extends this risk-based approach and extends the field of application to all structures.

The central concept of SIA 269/8 is the compliance factor α_{eff} which indicates the degree of compliance of an existing structure with the requirements for new structures. Below a minimum compliance factor, the safety of individuals is deemed unacceptable with an annual probability of death exceeding 10^{-5}. For buildings of importance classes I (common buildings) and II (mostly buildings with a high occupancy) α_{min} is 0.25. For critical buildings of the importance class III, as well as for school buildings and buildings or with an important infrastructure function (classes II-s and II-i), α_{min} is 0.40. If the compliance factor α_{eff} is below the threshold value of α_{min}, retrofit measures are necessary in order to reach a compliance factor after intervention α_{int} at least equal to α_{min}. If the compliance factor α_{eff} is above α_{min}, then retrofitting must be implemented as long as they are cost-efficient, meaning that the risk reduction is higher than the costs of the risk reduction. In SIA 269/8 the criterion used is the efficiency of measures EFM, which is the ratio between the risk reduction in Swiss francs per year and the annualized cost of measures computed with a discounting factor of 2 % over the remaining time of use. In SIA 269/8, risk reduction can be explicitly computed for casualty risk, risk of direct damage to the building and its content, business interruption and loss of infrastructure function.

Depending on the function and significance of the building as well as the requirements of the owner of the structure, the proportionality must or can be determined and assessed very differently. The owner is required in any case to take into consideration the benefit of reducing the casualty risk and in case of a critical infrastructure the benefit of reducing the risk of loss of infrastructure function. However, it is left to the owner's reflections and strategy to take into consideration the benefits of improving the protection of the structure, the contents or avoiding operational interruptions.

The paper shows how the risk criteria are applied. Using concrete examples, the risk-based assessment of earthquake safety is demonstrated and it will be discussed how the assessment of the cost-efficiency of safety measures depends on the protected objects under consideration and their values as well as on the key factors residual life time and discount rate.

Keywords: codes; risk assessment; commensurability; cost-efficiency

1 Introduction

In Switzerland, risk-based criteria for assessing the necessity of earthquake safety measures for existing buildings were introduced in 2004 with the pre-standard SIA 2018 “Verification of the seismic safety of existing buildings”. At the end of 2017 the pre-standard SIA 2018 was replaced by the code SIA 269/8 “Existing structures – Earthquakes”. SIA 269/8 adapts and extends this risk-based approach and extends the field of application to all structures.

If a structure meets the currently applicable standards at least to a certain degree, then further measures to approximate the requirements applicable to new structures are only explicitly required if they are proportionate. Depending on the function and significance of the structure and the requirements of the owner, the proportionality must - or can - be determined and assessed very differently.

According to SIA 269/8, the proportionality of an earthquake protection measure is assessed by comparing its benefit with its costs. A measure whose benefits outweigh its costs is called proportionate and must be implemented in all cases. It is always necessary to consider the improvement of personal safety on the benefit side. In addition, however, under certain conditions, the owner is also recommended to consider the benefits of improving the earthquake capacity of an existing structure, property protection and the avoidance of business interruptions.

While the risks associated with structures with "normal" functions can be estimated to a certain extent, this is hardly possible for structures with significant or vital infrastructure functions, because both the spatial extent, the duration of the possible consequences and the innumerable interdependencies between the various elements of an infrastructure function represent an extreme challenge that can hardly be met satisfactorily and with a reasonable amount of time for an individual structure. For this reason, a slightly different approach is chosen here, which can ultimately be integrated into the concept of efficiency of measures.

2 Risk-based approach of SIA 269/8

2.1 Computational evaluation of earthquake safety

The risk-based concept of SIA 269/8 is linked to the mathematical assessment of earthquake safety. This is done using the compliance factor α_{eff}, which is defined as follows in accordance with SIA 269/8:

$$\alpha_{eff} = \frac{A_R}{A_{d,act}} \tag{1}$$

Where A_R is the earthquake action that causes failure and $A_{d,act}$ is the verification value of the action. Other relevant variables are the importance class and the remaining useful life. The importance classes defined in [2] were supplemented with importance classes BWK II-s and BWK II-i for existing buildings (table 1). Each importance class is assigned a so-called minimum compliance factor α_{min}.

Table 1: Importance classes and minimum compliance factors α_{min}

Importance class	α_{min}
BWK I	0,25
BWK II (without BWK II-s or BWK II-i)	0,25
BWK II-s: Schools and kindergartens	0,40
BWK II-i: Structures with significant infrastructure function	0,40
BWK III: Structures with vital infrastructure function	0,40

The assessment of the need for action is based on the compliance factor, the class of structure and the remaining useful life as shown in table 2 and fig. 1.

Table 2: Definition of the need for action

Condition	Need for action
$\alpha_{eff} \geq 1{,}0$	No need for action
$1{,}0 > \alpha_{eff} \geq \alpha_{min}$	Measures required, if proportionate
$\alpha_{eff} < \alpha_{min}$	measures needed

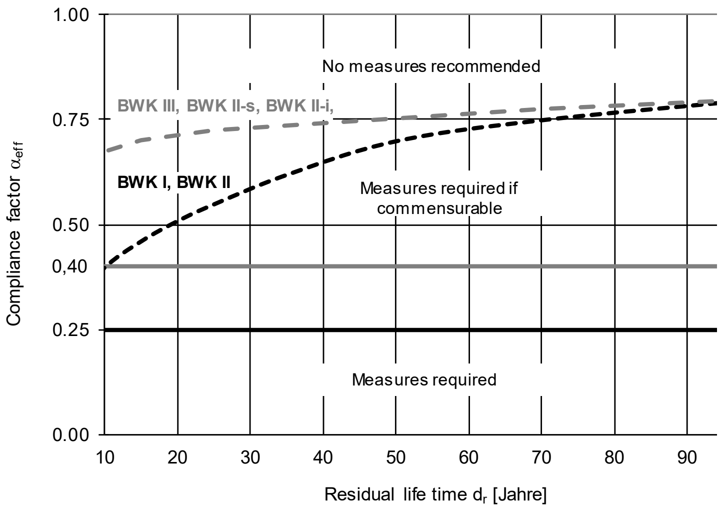

Fig. 1: Basis for the assessment of earthquake safety

2.2 Assessment of proportionality

The proportionality of a measure is assessed using the efficiency EF_M [3] of earthquake safety measures. In general, EF_M is defined as follows:

$$EF_M = \frac{\Delta R_M}{SC_M} \quad (2)$$

where ΔR_M is the annual reduction in risk measured in monetary units. ΔR_M includes at least the reduction of personal risk. If the assets to be protected are of high value, e.g. buildings, objects and operations, or if larger investments are planned, it is recommended that these assets be additionally taken into account in the risk reduction ΔR_M. SC_M stands for the annual costs of earthquake safety measures. For buildings with a vital (BWK III, emergency response: e.g. hospitals, fire brigade) or important (BWK II-i, basic infrastructure: e.g. power supply, transport) infrastructure function, EF_M is defined as follows:

$$EF_M = \frac{\Delta ZI_M + \Delta RP_M}{SC_M} \quad (3)$$

where ZIM represents the so-called willingness to pay of the Society for the Protection of Infrastructure Function and RPM represents the reduction of personal risk.

3 Risks to be considered in any case

3.1 Risk to people

The reduction of the risk to people ΔRP_M has always to be considered:

$$\Delta RP_M = \Delta PRF_M \cdot PB \cdot GK \tag{4}$$

with ΔPRF_M being the difference between the relevant personal risk factors (Fig. 3) which are derived from the respective values for the compliance factors with (α_{int}) and without (α_{eff}) retrofit measures. PB is the expected value of the occupancy (average number of people at risk). GK is estimated at CHF 10 million per human life saved.

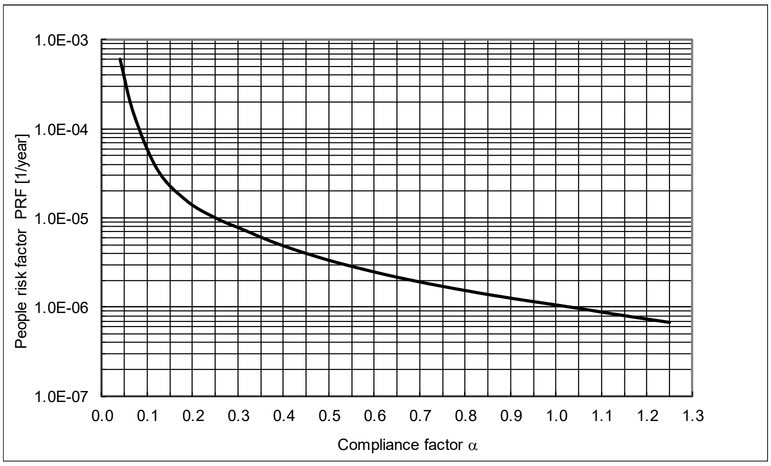

Fig. 2: Structure risk factor BRF for estimating the reduction of the risk of damage to structures

3.2 Risk to infrastructure function

The minimum compliance factor for vital infrastructure functions was set at 0.4. For many infrastructure functions, however, the number of people using them is very low. If the effective compliance factor was larger than the minimum compliance factor, this usually meant that no further proportionate measures could be found. Furthermore, infrastructure functions are usually embedded in relatively complex systems with corresponding dependencies. It is difficult to determine the consequences of the failure of such a function and thus also the monetarized risk reduction associated with an appropriate earthquake safety measure. For this reason, the approach described below was chosen in standard SIA 269/8.

A distinction is made between vital (BWK III) and important (BWK II-i) infrastructure functions. While BWK III can be assumed to be well known, the intention regarding BWK II-i requires explanation. According to SIA 269/8, a significant infrastructure function after an earthquake is essential for rapid reconstruction and regeneration. Their impairment leads to serious effects on society, the economy and the state. These are thus in particular, structures of traffic routes as well as structures, installations and facilities for supply, disposal and telecommunications, provided that they are not assigned to importance class III.

To determine the efficiency of the measures, the willingness to pay is to be estimated as follows:

$$\Delta ZI_M = \Delta IS \cdot BSW \quad (5)$$

where ΔIS is the difference between the applicable infrastructure rates and BSW comprises the value of the structure and the items directly affected. IS is determined according to Fig. 3 depending on the compliance factors before and after measures.

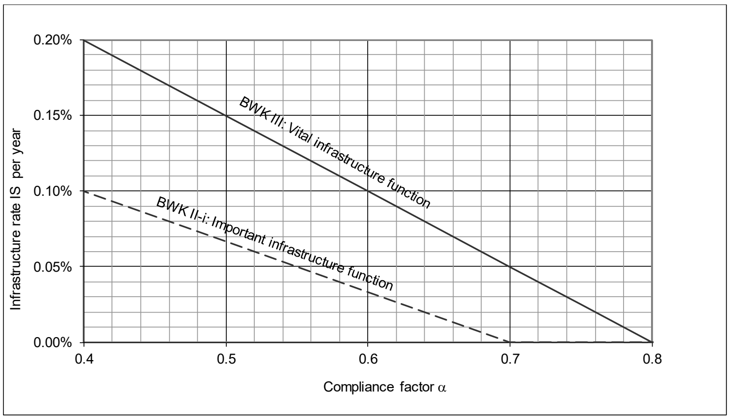

Fig. 3: Infrastructure rates to determine willingness to pay.

3.3 Risk to environment

The standard SIA 269/8 does not give a lot of recommendations associated to structures linked up to environmental risks. In particular, if there is a significant potential environmental risk, consultation with the regulatory authorities is required. SIA 269/8 therefore declares itself, in accordance with the standard SIA 261, not to be responsible for setting the requirements for establishments subject to the Major Accidents Ordinance.

3.4 Risk to cultural heritage

The requirements for personal safety must be met in any case. In addition, reference is made to a differentiated assessment of proportionality with reference to the preservation of historical monuments.

4 Further risks recommended to be considered

4.1 Enhancing the efficiency of measures

The objective of the standard SIA 269/8 is to provide the possibility to take into account the risk to the structure, the risk to contents and the risk associated to business interruption. By the help of SIA 269/8 these risks can be quantitatively taken into account in the assessment of the efficiency of measures. In this sense, the efficiency of measures is extended as follows:

$$EF_M = \frac{\Delta RP_M + \Delta RB_M + \Delta RS_M + \Delta RU_M}{SC_M} \quad (6)$$

with ΔRP_M the known reduction of risk to persons, ΔRB_M the reduction of risk to the structure, ΔRS_M the reduction of risk to contents and ΔRU_M the reduction of risk to operations (risk from business interruption).

4.2 Risk to the structure

The potential structural damage was worked out for consideration in the assessment of proportionality and prepared in a normative manner for application. The estimation of the risk for the structure is carried out analogously to the estimation of the personal risk on the basis of a relationship established between the compliance factor and a structure risk factor (see Fig. 4). The reduction of the building risk is determined as follows:

$$\Delta RB_M = \Delta BRF_M \cdot BW \tag{7}$$

with ΔBRF_M the difference between the relevant building risk factors and BW the value of the structure.

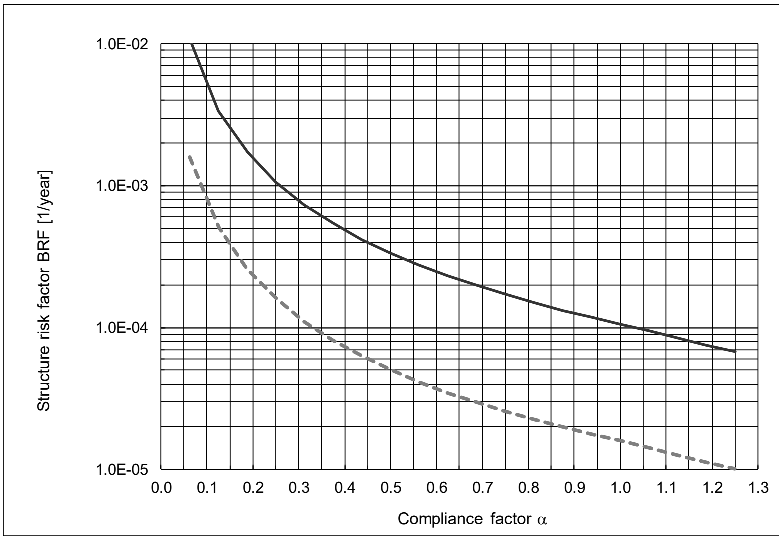

Fig. 4: Structure risk factor BRF for estimating the reduction of the risk of damage to structures

The structure risk factor BRF is an estimate of the damage to the structure risk per money unit of the structure value over one year. The value of the structure BW includes the value of the structure and all secondary components as well as the values of other elements such as cladding, windows, doors directly connected to the structure or secondary components. The replacement value can be used here. For buildings in particular, an estimate based on the insured value should be sufficient in many cases.

The upper curve in Fig. 4 applies to structures with a significant proportion of secondary components (e.g. common buildings such as residential and commercial buildings, administrative buildings, schools, museums). The lower curve applies to structures with an insignificant proportion of secondary components (e.g. bridges, retaining walls, reservoirs). Depending on the concrete design of the structure, values between the curves can be interpolated according to [4].

4.3 Risk to property value

Failing parts of a structure can damage objects located in the area of the structure affected by the failure. An example is a server rack which is destroyed by a falling wall. The material damage thus caused was also processed for consideration in the assessment of proportionality. The risks property values must be taken into account if their value is at least of the same order of magnitude as the value of the structure. The reduction of the risk to property ΔRS_M can be estimated using formula 8:

$$\Delta RS_M = SRF \cdot \Delta BRF_M \cdot SW \tag{8}$$

where SRF is the property risk factor, which can be assumed to be in a range of 0.05 to 0.2 and ΔBRF_M is the difference between the relevant structure risk factors (see 4.2) and SW is the value of the property concerned.

As already mentioned, only those property damages are taken into account which can be caused by a failure of the structure. Damage caused by failure of the object itself due to accelerations and displacements which the object experiences as a result of the earthquake is not covered. An example is the overturning of a top-heavy server rack that topples over although the server room remains intact. If one wanted to find out whether it would be proportionate to stabilise the server rack accordingly, one could calculate a compliance factor for the rack and, under certain circumstances, use the structure risk factor to roughly estimate the risk of material damage to the rack. However, the more suitable approach is to stabilize the cabinet accordingly or to decouple it seismically.

4.4 Risk of operation interruption

Serious damage to or collapse of a structure results in the interruption or at least impairment of the operation for which the structure is intended. This impairment results in loss of income and costs to maintain operations, the so-called interruption costs UK. In addition to the risks of structural damage and property damage, the risk of interruption was prepared for inclusion in the assessment of proportionality in a normative application. It is recommended to take into account the risk of interruption if the cost of interruption is more than 20% of the value of the structure.

The cost of interruption is estimated using the so-called threatened income due to interruption. The threatened income is determined as the difference between total sales and variable costs. Variable costs are those costs that practically cease to exist at the time of the interruption or shortly thereafter. In the case of service companies and operations that are expected to provide their services as uninterruptedly as possible, the costs that must be incurred in order to continue to provide the service are to be recognised.

The reduction of the risk of business interruption ΔRUM in Swiss francs per year as a result of the possible collapse or serious damage to a structure can be estimated in a simplified way using the following relationship:

$$\Delta RU_M = URF \cdot \Delta BRF_M \cdot UK \tag{9}$$

where URF is the dimensionless interruption risk factor, ΔBRF_M is the difference between the relevant construction risk factors (see 4.2) and UK is the interruption cost in monetary units.

Assuming that the interruption of operations due to serious damage to the structure corresponds to a total loss of one year, the interruption risk factor URF can be assumed to be 0.5. For shorter or longer business interruptions due to severe damage to the structure, the interruption risk factor can be adjusted proportionally.

5 Safety costs

Safety costs SC_M are the costs of an earthquake protection measure that are discounted to one year taking into account a discount factor. The safety costs are defined as follows:

$$SC_M = DF \cdot SIC_M \tag{9}$$

with the discount factor DF and the safety-related investment costs SIC_M of the earthquake safety measure. The safety-related investment costs represent the costs of measures that are exclusively attributable to earthquake safety. It should be noted that according to SIA 269/8, when estimating these safety costs, all direct and indirect costs associated with their implementation should be included. This means that the safety-related investment costs to be estimated can be several times higher than the pure construction costs of the earthquake protection measures. It is obvious, however, that costs should not be offset if the corresponding avoided costs are not taken into account on the benefit side. For example, costs resulting from business interruption and other indirect costs (e.g. for resources used by the developer) should not be taken into account if corresponding risk reductions are also not taken into account on the benefit side. If only the reduction of the risk to people is taken into account on the benefit side, only those costs that are necessary to implement the earthquake safety measures and make the structure usable again should therefore be considered on the cost side.

The discount factor DF is calculated from the agreed residual lifetime d_r and the discount rate i as follows

$$DF = \frac{i(1+i)^{d_r}}{(1+i)^{d_r}-1} \tag{10}$$

where the discount rate is set to 2% per year.

6 Examples

6.1 Administration building

The relevant data is given in the Table 3.

Table 3: Data for administrative building example

BWK	II
d_r	fifty years
PB	80 persons
BW	78.5 million CHF
SW	2.5 million CHF
UK	CHF 5 million
α_{eff}	0,25
α_{int}	0,5
SRF	0,2
URF	0,5
SIC_M	230'000 CHF
SC_M	8'000 CHF/year
ΔRP_M	5'300 CHF/year
ΔRB_M	58'000 CHF/year
ΔRS_M	400 CHF/year
ΔRU_M	1'900 CHF/year
$\Sigma\Delta R_M$	66'000 CHF/year
EF_M (ΔRP_M)	0,7
EF_M ($\Sigma\Delta R_M$)	8,0

The example shows that the efficiency of measures would not be achieved if only the risk to people were taken into account. Nevertheless, it would be advisable to implement the measures even if only the risk to people were taken into account, firstly because the efficiency of the measures is still relatively high and secondly because it must be borne in mind that the risk assessment can be associated with considerable uncertainty.

The large contribution of the reduction of the risk to the structure to the total amount of risk reduction is certainly in need of explanation. The contribution is so high on the one hand because the value of the building itself is already very high. On the other hand, it should be noted that when calibrating the structural risk, it was assumed that severe damage (without the risk of collapse) would in many cases lead to the demolition of the structure. This took account of the specific conditions in Switzerland.

The property value is comparatively small. According to SIA 269/8, it only makes sense to take it into account if it is in the order of magnitude of the value of the building. Even if the value of the property were much higher, this would only make a modest contribution to the risk reduction. A major reason for this is that the items only suffer significant damage from structural failure when at least a partial collapse occurs.

The costs for the interruption of operations are within the expected range for an administrative building.

6.2 Hospital

The relevant data are given in the Table 4.

Table 4: Data Example acute hospital

BWK	III
d_r	fifty years
PB	110 persons
BW	CHF 135 m
SW	CHF 55 million
α_{eff}	0,4
α_{int}	1,0
SIC_M	2'000'000 CHF
SC_M	60'000 CHF/year
ΔRP_M	27'000 CHF/year
ΔZI_M	380'000 CHF/year
EF_M	6,8

The key data show that the earthquake protection measures are highly efficient based on the willingness to pay for the maintenance of the infrastructure function. Despite the high number of people involved, not even half of the costs of the measures are covered by the reduction of the risk to people. Due to the infrastructure function, the goal of achieving a compliance factor of 1.0 will in many cases be recommended as a proportionate measure in the future.

6.3 Bridge

The following example is a bridge. It is the neuralgic point of a central connection to a closed area. The replacement of the bridge takes a considerable amount of time and there are only limited possibilities to compensate for the failure in useful time. The bridge is therefore classified as an important infrastructure function (importance class BWK II-i). The relevant data is given in the Table 5.

Table 5: Data bridge example

BWK	II-i
d_r	80 years
PB	1 person
BW	CHF 20 million
SW	0.1 million CHF
α_{eff}	0,4
α_{int}	1,0
SIC_M	400'000 CHF
SC_M	13'000 CHF/year
ΔRP_M	0
ΔZI_M	21'000 CHF/year
EF_M	1,6

The example shows that the direct personal risk due to the negligible number of people is not a motive to improve the earthquake safety of the bridge. In contrast, the specifications for maintaining the infrastructure function justify upgrading the bridge to a compliance factor of 1.0. The value of 1.6 for the efficiency of measures indicates that even higher costs for earthquake safety measures would be justified.

8. Recommendation for measures

8.1 Goals for seismic retrofit

SIA 269/8 requires that a compliance factor of 1.0 be aimed for. If this goal cannot be achieved with a proportionate use of resources, the most far-reaching sub-measure, which is just about proportionate, is to be implemented. Figure 4 illustrates this approach systematically.

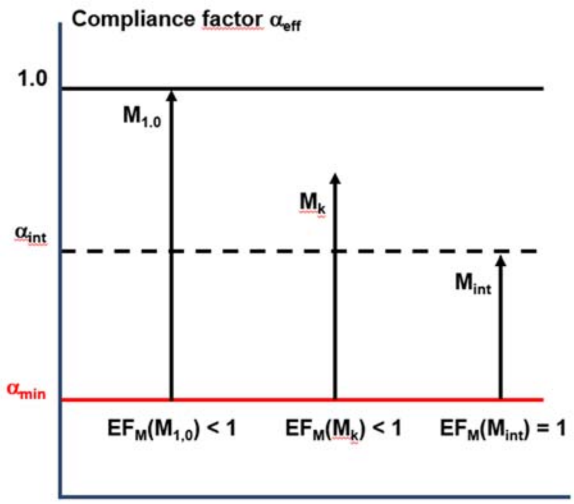

Fig. 5: Goals for seismic retrofit

8.3 Not proportionate according to SIA 269/8, disproportionate?

The requirement of the SIA 269/8 standard, according to which a compliance factor α_{int} of 1.0 is to be aimed for, applies in principle. This requirement may be deviated from if the earthquake protection measures are not proportionate due to the efficiency of the measures. There are, however, situations in which, despite insufficient efficiency of the measures, a compliance factor int of 1.0 should be aimed for.

For example, there is a situation similar to that of a new building, for example, because the building is reduced to the shell. Then the compliance factor to be striven for can be determined independently of the proportionality according to SIA 269/8.

If the investments in the structure are so high that the costs for earthquake protection measures are practically negligible, these should be implemented.

In general, it should be taken into account that the risk assessment is associated with considerable uncertainties. The approach to assessing proportionality should be to avoid measures that are really very disproportionate.

9. Conclusion

The standard SIA 269/8 has been widely accepted by the engineers. In the standard SIA 269/8, the risk to the structure, property and operation were newly introduced and recommended for consideration in the assessment of proportionality. As a rule, however, only the structue value has a significant favourable influence on the proportionality. In addition to these risk-based criteria for the assessment of proportionality, other criteria such as the total investment sum of a conversion or repair project must also be taken into account in order to achieve the objective set out in standard SIA 269/8 "In principle, a compliane factor of at least 1.0 after implementation of measures must be aimed for" to be fair.

10. Literature

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