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RISK-BASED SEISMIC ASSESSMENT OF EXISTING STRUCTURES

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ABSTRACT: With every new code generations, requirements for seismic safety were substantially increased. In general, existing structures do not meet the new seismic criteria. Upgrading to the safety level for new structures may be very expensive and may lack cost efficiency even in zones of low to medium seismicity. The cost of upgrading may become disproportionately high in relation to the benefits of the achieved seismic risk reduction. To avoid inefficient allocation of resources, special risk-based rules are needed in seismic codes for existing structures. The decision to what extend existing structures have to be upgraded should be based on minimum requirements of individual and collective risks to persons as well as on maximum downtime of important infrastructure networks. With the simplified risk analysis according to Swiss Standard SIA 269/8 „Existing Structures – Earthquakes", the appropriate level of intervention can be determined. As a consequence, many structures in zones of low to medium seismicity can be accepted as sufficiently safe in the existing state without any intervention. Seismic upgrading may then be efficiently focussed on structures with high risks.

1. Introduction

In Switzerland, over 50 % of the existing building stock were constructed before seismic design rules were introduced in 1970 and approximately 90 % were built before modern seismic design rules were introduced in 2003. Most of these buildings would need to be retrofitted if one would impose the same requirements as today for new buildings. Case studies of retrofitted buildings in zones of low to medium seismicity in Switzerland by Wenk (2008) showed retrofitting costs up to 30 % of the building value. These costs may become disproportionally high in relation to the risk reduction that can be achieved by retrofitting. To avoid an inefficient allocation of resources, an efficient risk-based approach was introduced in the Swiss Prestandard SIA 2018 (2004) accepting lower performance levels for existing structures.

Already as a response to the 1989 seismic code change in Switzerland, first rules for seismic assessment and retrofitting were introduced. They considered a reduced seismic action in function of the remaining useful life of the existing structure (Wenk, 1997). These rules were based on the principles of Swiss Prestandard SIA 462 (1994) for the assessment of structural safety. The next code change in 2003 increased the seismic action even more. As a consequence, the question how to deal with the large stock of existing structures became even more important leading to the introduction of Swiss Prestandard SIA 2018 (2004) which will be replaced by Swiss Standard SIA 269/8 „Existing Structures – Earthquakes“, in 2016. A first version of SIA 269/8 has been published for public enquiry in 2014. In this paper, the background of the risk-based code procedures of SIA 269/8 (2014) for the seismic assessment of existing structures is presented.

2. RISK ACCEPTANCE

There was a consensus of opinion among experts that the decision on whether or not an existing structure should be retrofitted has to be based on cost-benefit considerations respecting minimum requirements for individual and collective risks to persons as explained by Wenk and Beyer (2014).

Similar risk criteria have already been used in Switzerland for preventive measures against other natural hazard and against man-made disasters such as fires in long tunnels through the Alps.

The minimum acceptable level of seismic safety is based on the assessment of the risks to persons. For this purpose, a distinction is made between individual and collective risks to persons, as proposed by Schneider (2000). The following paragraphs summarise briefly this Swiss approach; more detailed informations can be found in Koelz and Schneider (2005).

2.1. Individual Risk

The individual risk is the risk experienced by an individual person in certain situations. Table 1 summarises individual risks for various activities or exposures expressed as mean probability of death per year. Age dependent factors clearly dominate the individual risk as can be seen in Table 2. The level of risk that an average person considers as acceptable mainly depends on two factors: (i) whether the exposure to this risk is voluntary or involuntary; (ii) in case of a voluntary exposure if the risk can be reduced by appropriate behaviour. For involuntary exposures people accept only smaller levels of risk than for voluntary exposures. For involuntary exposures without the possibility to influence the risk, such as structural safety of existing buildings, an individual risk up to 10^{-5} per year is deemed acceptable according to the Swiss Standard SIA 269 (2011). This risk level was derived from comparisons with other risks to which people are involuntarily exposed.

New ordinary buildings designed according to the seismic specifications in the Swiss Standard SIA 261 (2014) with a return period of 475 years of the seismic design event lead to an individual risk of approximately 10^{-6} per year (SIA 269/8, 2014). Based on probabilistic seismic risk studies, it was concluded that a capacity of an existing building corresponding to about a quarter of the design forces or design displacements for new buildings would lead to an individual risk of 10^{-5} per year (Vogel and Koelz 2005). The ratio of the capacity of the existing building to the minimum capacity required for new buildings is called compliance factor α_{eff}. It is a measure which quantifies up to which level the existing building meets the seismic design requirements for new constructions. The compliance factor α_{eff} is a key quantity in the Swiss seismic assessment procedure for existing structures.

Table 1. Mean probability of death per person and year for various activities or exposures (adapted from Schneider, 2000)

Activity or exposure	Probability of death
Smokers: 20 cigarettes a day	$400 \cdot 10^{-5}$
Drinkers: 1 bottle of wine a day	$300 \cdot 10^{-5}$
Motorcycle sport	$150 \cdot 10^{-5}$
Delta flying or paragliding as hobby	$100 \cdot 10^{-5}$
20 to 24 years old car drivers	$20 \cdot 10^{-5}$
Pedestrians, household workers	$10 \cdot 10^{-5}$
10,000 km/year car driving	$10 \cdot 10^{-5}$
Mountain hiking	$5 \cdot 10^{-5}$
10,000 km/year motorway driving	$3 \cdot 10^{-5}$
Plane crash per flight	$1 \cdot 10^{-5}$
Living in buildings: Death by fire	$1 \cdot 10^{-5}$
10,000 km/year train travelling	$1 \cdot 10^{-5}$
Death by earthquakes in California	$0.2 \cdot 10^{-5}$
Lightning strike	$0.1 \cdot 10^{-5}$

Table 2. Mean probability of death of a person and year in function of its age (BFS, 2014)

Age group in years	Probability of death
1 - 14	$9 \cdot 10^{-5}$
15 - 44	$50 \cdot 10^{-5}$
45 - 64	$350 \cdot 10^{-5}$
65 - 84	$2300 \cdot 10^{-5}$
85 and older	$15000 \cdot 10^{-5}$

2.2. Collective Risk

The collective or societal risk is the total risk to persons considering all scenarios for a specific hazard with their probability of occurrence. In the case of seismic hazard, the collective risk for a certain area or building is usually expressed by the number of deaths per year due to earthquakes. Measures to reduce the collective risk should be executed as long as their cost does not become disproportional with respect to the achieved risk reduction. To find a reasonable value for the life saving costs, different safety measures to reduce man-made and natural risks are compared in Table 3. The life saving costs reflect a certain consensus within the society on how much should be spent for preventive measures to reduce the number of deaths in future disasters. The life saving costs are in general higher for man-made than for natural risks and they are much higher for very seldom, large events than for more frequent events where each single event causes only very few casualties. In addition, the degree of self-determination plays a major role in how risks are perceived and therefore on the life saving costs. As shown in Table 3, if persons are subjected completely involuntarily to the risk, the life saving costs are higher than for more voluntary conditions. Acceptable life saving costs for structural safety of buildings have to be on the higher end of the range of values in Table 3.

The Swiss Standard SIA 269 (2011) prescribes a large range between 3 and 10 million CHF for proportional life saving costs for the assessment and retrofitting of existing structures with respect to all kind of actions. According to Swiss Standard SIA 269/8 (2014), the upper limit of 10 million CHF should be assumed as a minimum value when computing the proportional seismic retrofitting costs. In other words, assessment and retrofitting costs up to 10 million CHF are considered proportional, if the retrofit saves one person's life during the remaining useful life of the building for the considered seismic hazard. Hence, retrofitting measures up to this limit should be executed. The risk analysis according to SIA 269/8 (2014) is based on the number of deaths without considering explicitly the number of injured persons, i.e. the life saving costs of 10 million CHF per life include the costs of injured people assuming that each death leads also to a certain number of injured people.

3. Assessment Procedure

3.1. Seismic Analysis

The main step of the assessment procedure consists of a structural analysis according to the current seismic Standards for new buildings. The analysis may be based on forces or on displacements. Based on the results of the analysis, the compliance factor $\alpha_{eff} = A_R/A_d$ is determined, where A_R is the seismic action when the design value of the resistance of the existing structure is reached and A_d the corresponding seismic design value of the seismic action for new structures. The critical compliance factor α_{eff} is the minimum value over all sections in the structural system and in the non-structural elements. The compliance factor measures up to what level the existing building complies with the requirements of the seismic design situation for new buildings. If the compliance factor α_{eff} is ≥ 1.0 then the code requirements for new buildings are fully satisfied. This case does not need any further consideration. However, existing building in general present a compliance factor α_{eff} < 1.0. Then it should be decided based on risk criteria whether or not structural interventions should be executed.

Table 3 – Comparison of life saving costs per human life saved (adapted from Katarisk, 2003 and Schneider and Schlatter, 2007)

Safety measure	Life Saving Costs in CHF
Multiple vaccinations in the 3rd World	100
Installation of x-ray equipment	2‘000
Wearing motorcycle helmet	5‘000
Providing cardio-equipped ambulances	10‘000
Tuberculosis screening	20‘000
Deployment of rescue helicopters	50‘000
Seat belts in cars	100‘000
Rehabilitation of road intersections	200‘000
Providing kidney dialysis units	300‘000
Structural safety in buildings	500‘000
Road traffic safety US	500‘000
Railroad crossing safety in Germany	1‘000‘000
Swiss Structural Standard SIA 269	3‘000‘000
Tunnel safety in new Swiss alpine tunnels	5‘000‘000
Tunnel safety in new tunnels in Germany	5‘000‘000
Swiss Seismic Standard SIA 269/8	10‘000‘000
Transportation of hazardous materials by train in Switzerland	20‘000‘000
Mining safety USA	20‘000‘000
DC-10 grounding USA	50‘000‘000
Tall building regulations UK	100‘000‘000
Asbestos removal in school buildings in Switzerland	1‘000‘000‘000

3.2. Risk-Based Recommendation for Retrofitting Measures

In the final step following the seismic analysis, a simplified risk analysis has to be performed considering the average occupancy *PB*, the remaining useful life, and the compliance factor α_{eff} in the existing state. Three different cases have to be distinguished as shown in Figure 1 for buildings of importance class I (ordinary buildings) and importance class II (buildings with higher occupancy):

If the compliance factor α_{eff} falls in the white zone of Figure 1, i.e. α_{eff} greater than 0.4 to 0.8 depending on the selected remaining useful life, measures are in general not proportional. The building can be accepted as sufficiently safe in the existing state without any risk analysis. A detailed risk analysis for these combinations of compliance factor and remaining useful life would typically show that any possible retrofitting measures would not be proportional, i.e. to costly in relation to the seismic risk reduction. The remaining useful life is defined as the time span over which structural safety has to be guaranteed at the time of the examination of the existing building. At the end of the assumed remaining useful life, a new examination will have to be performed. A typical selection for the remaining useful life for buildings would be in the range of 30 to 40 years.

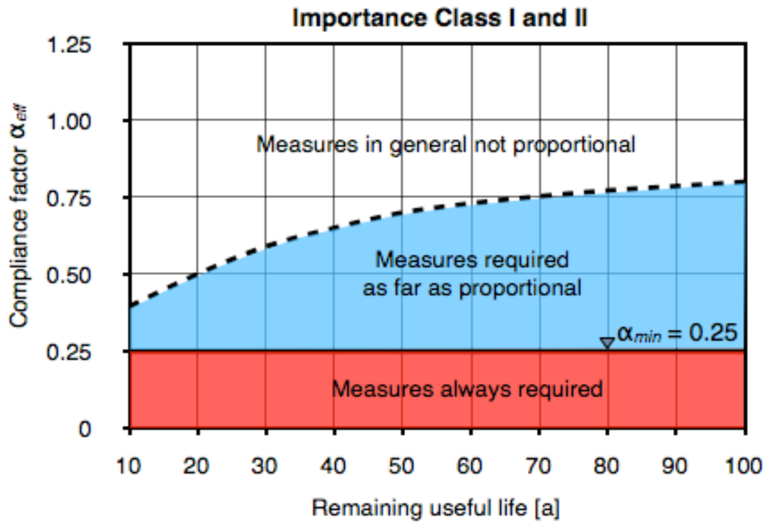

Figure 1 – Risk analysis according to SIA 269/8 (2014) for buildings of importance category I and II.

If the compliance factor α_{eff} falls in the blue zone in Figure 1, the building should be retrofitted as long as the costs of the structural intervention are proportional in relation to the achieved seismic risk reduction. Considering the criteria of collective risk to persons, a simplified risk analysis based on the average occupancy *PB* of the building and the compliance factor before and after the intervention as well as the remaining useful life has to be performed for this purpose.

If the compliance factor $\alpha_{eff} < \alpha_{min} = 0.25$ measures are always required (red zone in Figure 1) based on the criteria on individual risk to persons. If retrofitting measures are too costly or not possible to be executed, the number of people in the building has to be limited by organisational measures to a very small number in order to guarantee an acceptable level of individual risk. According to SIA 269/8 (2014), the average occupancy *PB* has to be kept below 0.2 persons and the maximum number of people in the building below 10 persons at all times. The limitation of the number of persons in the building serves as an alternative way to reduce the seismic risk if the vulnerability of the building cannot be reduced by retrofitting measures.

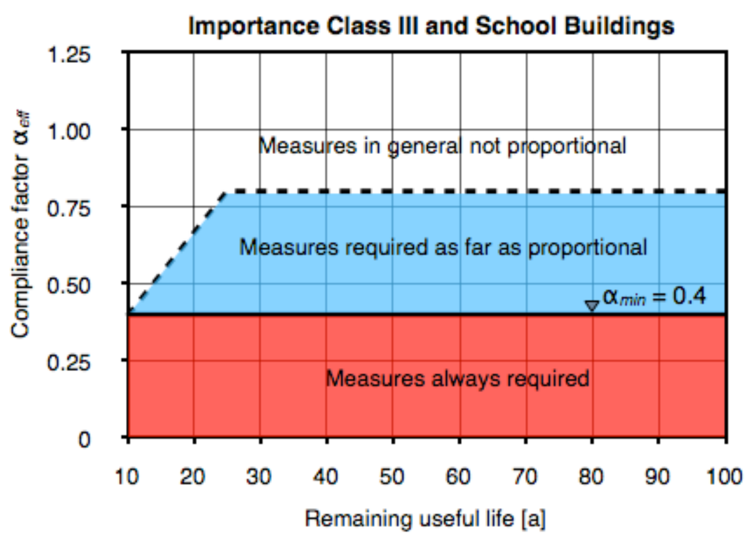

Figure 2 – Risk analysis according to SIA 269/8 (2014) for essential facilities and school buildings.

The minimum compliance factor α_{min} = 0.25 in Figure 1 separates the zone where measures are always required from the zone where proportional measures are required. The factor α_{min} = 0.25 corresponds to the maximum level of acceptable individual risk of 10^{-5} per person and per year as explained in chapter 2.1. This relatively low value of α_{min} = 0.25 was introduced in SIA 2018 (2004) based on requests during the public enquiry (Wenk, 2014). For the prevailing low to medium seismicity in Switzerland, a return period of approximately 50 years leads to approximately 25 % of the spectral acceleration corresponding to a return period of 475 years. Hence, the minimum safety level for individual risk in an existing building is reached if the life safety requirements are fulfilled for a return period of 50 years instead of 475 years for new buildings (Wenk and Beyer, 2014). For zones of higher seismicity, the minimum compliance factor corresponding to a return period of 50 years would be about α_{min} = 0.3 to 0.35 instead of 0.25.

For essential facilities and for school buildings the minimum compliance factor was raised from α_{min} = 0.25 to α_{min} = 0,4 to provide a higher minimum level of protection as shown in Figure 2. For essential facilities, it is important to maintain a higher level of operationality after an earthquake independent of the individual risk criterion. For school buildings, the intention is to provide a higher level of protection to children. In the last years, the mean probability of death of children in Switzerland dropped to $9 \cdot 10^{-5}$ per year (Table 2). An additional individual risk of 10^{-5} per year just for seismic events was considered too high.

4. Live Saving Costs

To determine, if the costs of a certain intervention measure are proportional, a simplified risk analysis has to be performed. In general, the total risk is dominated by the risk to persons and the other factors such as material damage of the building structure and of non-structural elements as well as interruption of production can be neglected. The risk analysis with respect to personal risks in a building comprises the following steps:

In the first step, the risk reduction ΔRM is estimated as product from the average occupancy PB of the building and the difference of personal risk factors ΔRPF before and after execution of the considered structural intervention: $\Delta RM = \Delta RPF \cdot PB$ expressed in lives saved per year. The personal risk factor RPF corresponds to the probability of death by earthquake consequences of a person staying the whole year in a building with a certain compliance factor α. The values of RPF are specified in function of the compliance factor α in SIA 269/8 (2014) and are reproduced in Figure 3. The curve in Figure 3 has two anchor points marked in pink: For the minimum compliance factor α_{min} = 0.25, the personal risk factor becomes $RPF = 10^{-5}$, i.e. RPF is equal to the maximum value of the acceptable individual risk of 10^{-5} per person and per year. For the compliance factor of a building satisfying the requirements for new buildings, i.e. α = 1.0, the personal risk factor becomes $RPF = 10^{-6}$. Therefore, it is assumed that a building designed for the seismic requirements for new buildings provides a personal risk factor ten times smaller than the minimum value for existing buildings.

Then, the safety costs SK_M per year are determined by investment considerations over the remaining useful life of the building. The initial investment costs of SIK_M of safety measures will be amortised over the remaining life of the building considering a discount rate of 2 %. The resulting safety costs per year amount to: $SK_M = DF \cdot SIK_M$. The discount factor DF can be found in SIA 269/8 (2014). The shorter the remaining useful life is selected, the higher are the discount rate DF and the safety costs per year SK_M for given initial investment costs SIK_M. The investment costs SIK_M include all direct and indirect costs involved with the realisation of a structural intervention to increase the seismic safety.

In the final step, the efficiency RK_M of the considered safety measures is determined by the ratio of the safety costs to the risk reduction: $RK_M = SK_M / \Delta RM$. The efficiency is measured in monetary units per live saved. According to SIA 269/8 (2014), the safety costs are considered *proportional* if this ration RK_M does not exceed 10 million CHF per live saved. If the safety costs exceed 10 million CHF per live saved, they are considered *disproportional*. Then, the existing state of the building can be accepted as sufficiently safe without any intervention as long as the compliance factor α_{eff} is already above the minimum value α_{min}, i. e. $\alpha_{eff} \geq \alpha_{min}$ = 0.25 for ordinary buildings in importance class I and II or $\alpha_{eff} \geq \alpha_{min}$ = 0.4 for essential facilities and school buildings. If $\alpha_{eff} < \alpha_{min}$ a structural intervention has to be executed independent of costs, i.e. also if the costs are disproportional. As an exception, an existing state with $\alpha_{eff} < \alpha_{min}$ can still be accepted as sufficiently safe if the occupancy is limited by organisational measures to a very small number of persons as mentioned above.

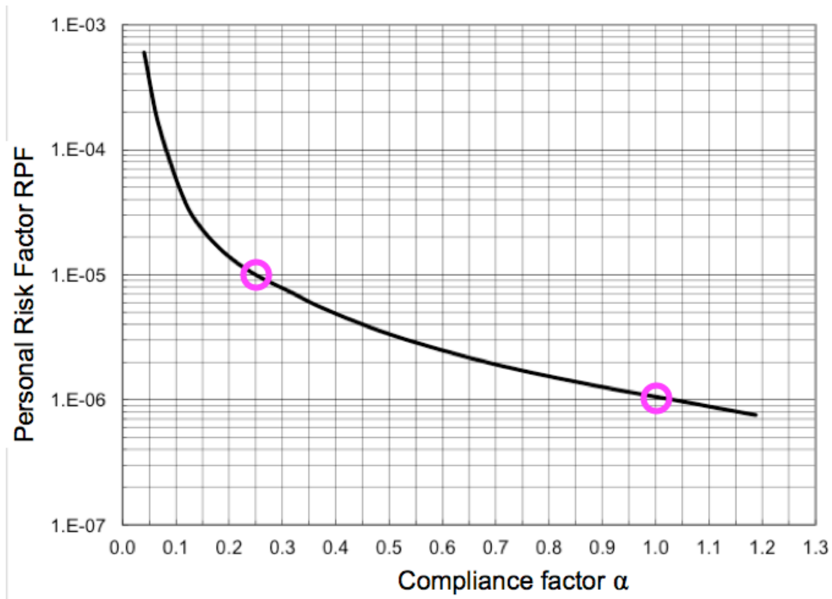

Figure 3 – Personal risk factor *RPF* vs. compliance factor *α* (SIA 269/8, 2014)

5. Case Study of Building with Unit Occupancy

A case study of a small building of building class I with a theoretical unit average occupancy *PB* = 1 person and a typical remaining useful life of 40 years illustrates the order of magnitude of the parameters involved. The average occupancy of a single family home for four people typically reaches an average occupancy of about *PB* = 1 person. Every blue curve in Figure 4 corresponds to a certain compliance factor α_{eff} in the range between 0.25 and 0.70 for the existing state of the considered building. Depending on the compliance factor α_{int} reached by the retrofitting intervention, the blue curves in Figure 3 indicate the maximum of proportional costs in CHF per person of the average occupancy *PB*.

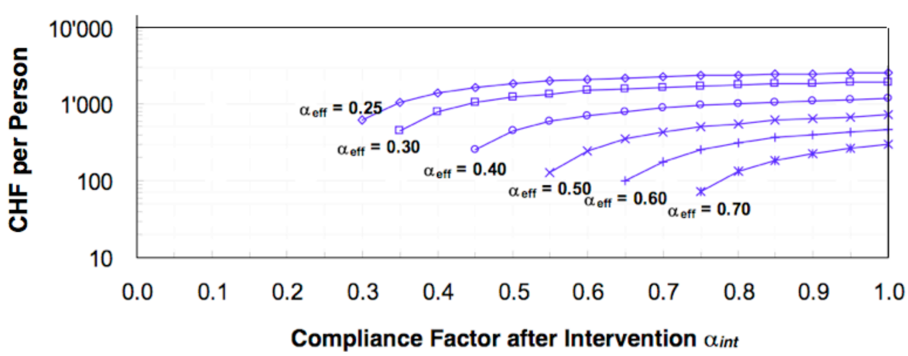

Figure 4 – Proportional cost limits per person of the average occupancy *PB* vs. compliance factor for a remaining useful life of 40 years (adopted from BWG, 2005)

The highest blue curve in Figure 4 shows as an example that starting from a compliance factor α_{eff} = 0.25 intervention cost up to CHF 2‘600 per *PB* person are proportional if α_{int} = 1.0 is reached. If starting from α_{eff} = 0.25 only α_{int} = 0.5 can be reached, then intervention cost up to CHF 1‘900 per *PB* person are proportional. For higher starting values of α_{eff}, the proportional cost limits are even lower as can be read from the other five blue curves in Figure 4. In general, these low proportional cost limits do not give sufficient funds for retrofitting measures for buildings with modest occupancy. Practically, retrofitting measures below the proportional cost limit can only be found for buildings with relatively high occupancy

($PB \geq 50$ persons). As a consequence, the proportional cost limit serves as efficient filter to sort out buildings with high personal risk. These buildings should then be retrofitted by constructional measures to reduce the personal risk whereas buildings with low occupancy can often be accepted as sufficiently safe in the existing state even when the requirements for new buildings are not fully satisfied as long as the compliance factor α_{eff} lies above the minimum compliance factor α_{min}, i.e. $\alpha_{eff} \geq \alpha_{min} = 0.25$.

6. Conclusions

The new Swiss Standard for the seismic assessment of existing buildings SIA 269/8 (2014) introduces new concepts on the proportionality of retrofitting costs and minimum life safety standards. The main parameters of the risk-based assessment are the compliance factor, the occupancy, and the remaining useful life of the existing structure. Proportional cost limits for retrofitting can be efficiently determined by criteria based on collective risks to persons. With cost-benefit considerations disproportionally high costs of seismic retrofitting can be avoided. The proportional cost limits serve as filter to focus seismic retrofitting on structures with high personal risks. Structures with low personal risks can be accepted as sufficiently safe in the existing state if the assessment results in a compliance factor above the minimum value. In any case, minimum requirements of individual risks to persons have to be respected.

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