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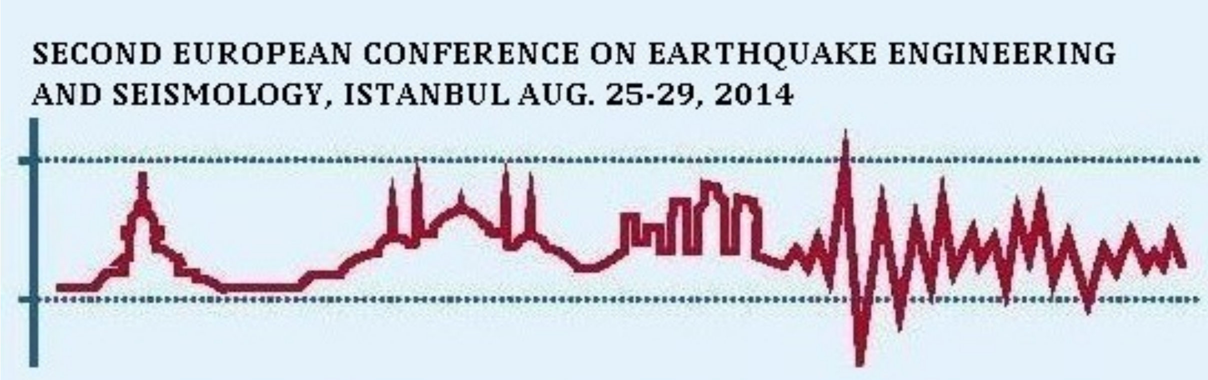

SEISMIC ASSESSMENT BASED ON COST-BENEFIT CONSIDERATIONS

Thomas Wenk[1]

ABSTRACT

Existing structures generally do not meet the seismic criteria introduced in new code generations. Upgrading existing structures to the safety level for new buildings may be very expensive and may lack cost efficiency even in zones of low to medium seismicity. The cost of retrofitting may become disproportionately high in relation to the benefits of risk reduction. To avoid inefficient allocation of resources, cost-benefit considerations are needed in seismic codes for existing structures. The relevant criteria of the risk-based seismic assessment will be presented in detail. Based on case studies of retrofitted buildings in Switzerland, the influence of these criteria on the costs of seismic retrofitting in practical applications is shown.

INTRODUCTION

With every new code generations, requirements for seismic safety are usually increased. Existing structures generally do not meet the new seismic criteria. Upgrading existing structures to the safety level for new buildings may be very expensive and may lack cost efficiency even in zones of low to medium seismicity. The cost of upgrading may become disproportionally high in relation to the benefits of the risk reduction achieved. To avoid inefficient allocation of resources, special rules are needed in seismic codes for existing structures in order to justify a certain relaxation of the requirements in current codes for new buildings. As a response to the seismic code change in 1989, rules for seismic assessment and retrofitting, considering a reduced seismic action in function of the remaining useful life of the existing structure, were presented by Wenk (1997). These rules were based on the principles of Swiss Prestandard SIA 462 (1994) for the assessment of structural safety for any kind of action. The main concept consists of updating all information about the existing structure and its setting.

In 2003, the new generation of structural standards brought an even higher increase of the seismic action than in 1989. Therefore, the question how to deal with the large stock of existing structures which did not meet the new criteria, became more important. There was a consensus of opinion among experts, that the decision on whether or not, and to what extend, an existing structure should be retrofitted has to be based on cost-benefit considerations respecting minimum requirements for individual and collective risks to persons. Comparable requirements have already been used for preventive measures against other natural hazard and against man-made disasters.

In 2004, efficient risk-based rules for the seismic assessment of existing buildings have been introduced in Swiss Prestandard SIA 2018 (2004). They are based on the minimum requirements for personal risks explained by Kölz and Schneider (2005) as well as by Wenk and Beyer (2014). Recently, the risk-based rules in Swiss Prestandard SIA 2018 (2004) have been refined and drafted into Swiss Standard SIA 269/8 (2014) „Existing Structures – Earthquakes “, which has been published

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for public enquiry at the beginning of 2014. The final version of Swiss Standard SIA 269/8 will be published in 2015. This paper explains the risk-based code procedures for the seismic assessment of existing structures and reviews practical experience since the introduction of the Prestandard SIA 2018 in 2004.

PROCEDURE

The seismic assessment procedure according to the Swiss Standard SIA 269/8 (2014) consists of the following three steps:

1. Inspection and data acquisition
2. Seismic assessment
3. Risk-based recommendation for retrofitting measures

In step 1, inspection and data acquisition follow in principle the same methods and procedures as for an examination with regard to other actions such as live load or wind. An important aspect for seismic behaviour is to include all non-structural elements into the examination as they may present a risk to persons in case of failure due to an earthquake.

In step 2, a structural analysis of the existing structure is performed according to the current seismic Standards for new buildings. This analysis may be based on forces or on displacements. In general, the structural modelling of an existing structure becomes more refined or elaborate compared to a new structure. 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. If a displacement-based analysis is performed instead of a force-based analysis, then the compliance factor is defined analogously as ratio of displacement capacity to displacement demand: $\alpha_{eff} = w_R/w_d$.

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 $\geq$ 1,0 then the code requirements for new buildings are fully satisfied. This case does not need any further consideration. However, existing building often present a compliance factor $\alpha_{eff} <$ 1,0 even in zones of low seismicity. In this case, it should be decided based on cost-benefit considerations whether or not, and to what extend, structural interventions should be executed.

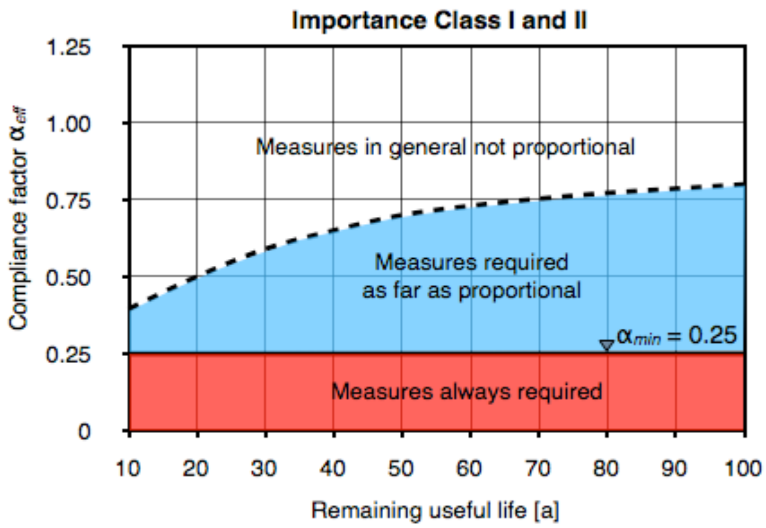

Figure 1. In the risk analysis according to SIA 269/8 (2014) three cases are distinguished in function of the compliance factor α_{eff} and the remaining useful life here shown for buildings in importance category I and II.

In step 3, a simplified risk analysis has to be performed considering the average occupancy, the remaining useful life, and the compliance factor α_{eff} in the existing state calculated in the previous step. Three different cases have to be considered 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. 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.

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. A simplified risk analysis based on the average occupancy 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. 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.

If the compliance factor $\alpha_{eff} < \alpha_{min} = 0{,}25$ measures are always required (red zone in Figure 1). 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. The average occupancy *PB* has to be kept below 0,2 persons and the maximum number of people in the building below 10 persons. The limitation of the number of persons in the building serves as an alternative way to reduce the seismic risk to persons.

The minimum compliance factor $\alpha_{min} = 0{,}25$ in Figure 1 separates the zone where measures are always required from the zone where only proportional measures are required. The factor $\alpha_{min} = 0{,}25$ corresponds to an individual risk of 10^{-5} per person and per year (Figure 3). For essential facilities and for school buildings the minimum compliance factor was raised from $\alpha_{min} = 0{,}25$ to $\alpha_{min} = 0{,}4$ to provide a higher minimum level of protection independent of the individual risk criterion as shown in Figure 2.

Originally, a minimum compliance factor $\alpha_{min} = 0{,}3$ was proposed by the SIA 2018 code committee in the year 2003 to guarantee an individual seismic risk of 10^{-5} per person and per year. Yielding to requests of the public enquiry in the year 2004, the minimum value was lowered to $\alpha_{min} = 0{,}25$ in the final version of Swiss Prestandard SIA 2018 (2004). With the relatively low value of $\alpha_{min} = 0{,}25$ the new code was accepted more easily in practise. A broader discussion of the minimum compliance factor α_{min} was reopened ten years later during the public enquiry of Swiss Standard SIA 269/8. It is expected that $\alpha_{min} = 0{,}25$ will remain unchanged in the final version of SIA 269/8.

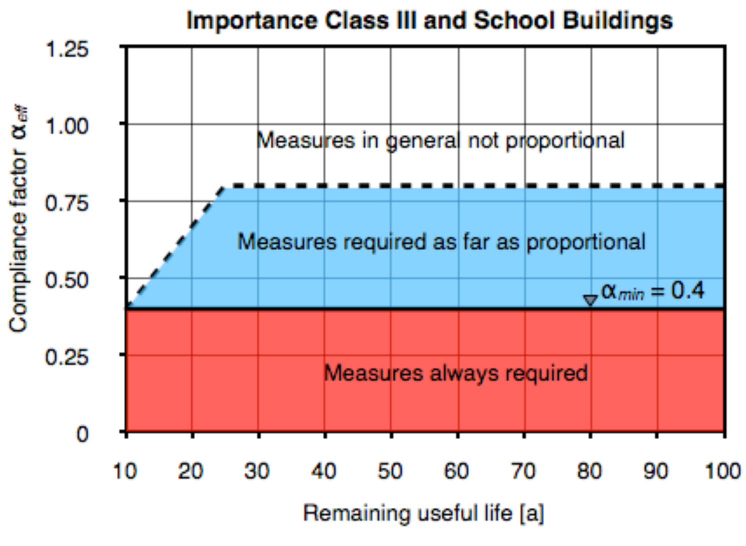

Figure 2. In the risk analysis according to SIA 269/8 (2014) three cases are distinguished in function of the compliance factor α_{eff} and the remaining useful life here shown for essential facilities and school buildings.

The individual risk is the probability that a single person who is staying all the time during a year in a building will be killed by earthquake consequences. An individual risk up to 10^{-5} per person and per year is in general considered acceptable for involuntary exposures without the possibility to influence the risk, such as structural safety of existing buildings (Wenk and Beyer, 2014). The criterion of the individual risk of 10^{-5} was introduced for the first time in Swiss Prestandard SIA 2018 (2004) as minimum requirement for the seismic safety of existing building. Later, it was adopted as a minimum requirement for structural safety in general in Swiss Standard SIA 269 (2011).

LIVE SAVING COSTS

Cost-benefit considerations limited to risks to persons were introduced in Swiss Prestandard SIA 2018 (2004) to decide if an existing structure should be seismically upgraded. In Swiss Standard SIA 269/8 (2014), these cost-benefit considerations have been extended to include material damage of the building structure and of non-structural elements as well as interruption of production. In general, the total risk is dominated by the risk to people and the other factors can be neglected in the cost-benefit considerations.

The analysis of the efficiency of a structural intervention with respect to personal risks comprises following simple steps:

1. 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 $\alpha_{min} = 0{,}25$, 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. $\alpha = 1{,}0$, 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.
2. The safety cost SK_M per year is determined by investment considerations over the remaining useful life of the building. The initial investment cost 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 cost 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 the discount rate DF and the safety cost per year SK_M will be for given initial investment cost SIK_M. The investment cost SIK_M includes all direct and indirect costs involved with the realisation of a structural intervention to increase the seismic safety. In addition to the construction cost, these might include consultant fees and loss of rental income during construction etc.
3. In the final step, the efficiency RK_M of the considered safety measures is determined by the ratio of the safety cost 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 $RK_M \leq 10$ million CHF per live saved.

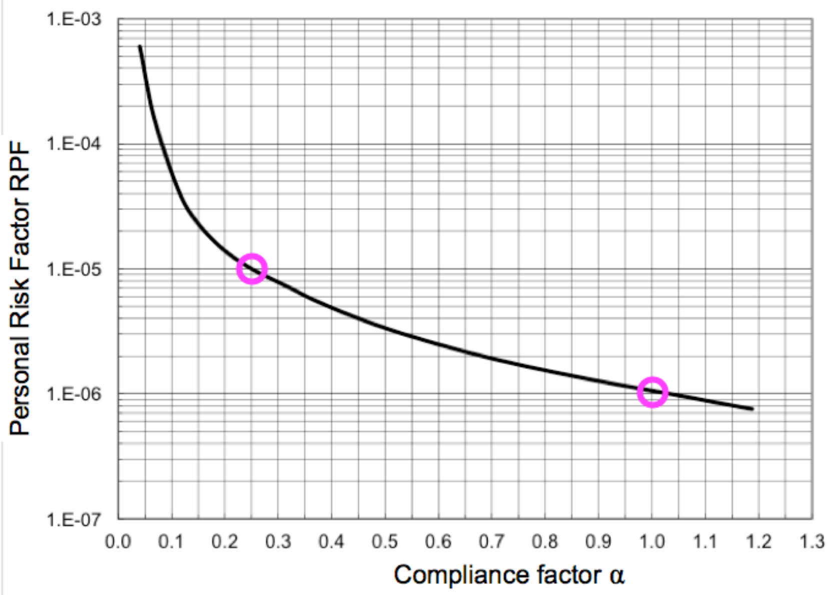

Figure 3. Personal Risk factor *RPF* vs. compliance factor *α* (SIA 269/8, 2014)

Retrofitting measures are only required as long as the cost of the structural intervention is proportional in relation to the achieved seismic risk reduction, i.e. the retrofitting costs do not exceed 10 million CHF per live saved. If the retrofitting 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 or II. If $\alpha_{eff} < \alpha_{min}$ a structural intervention has to be executed independent of cost, i.e. also if its cost is 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.

CASE STUDY FOR 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*.

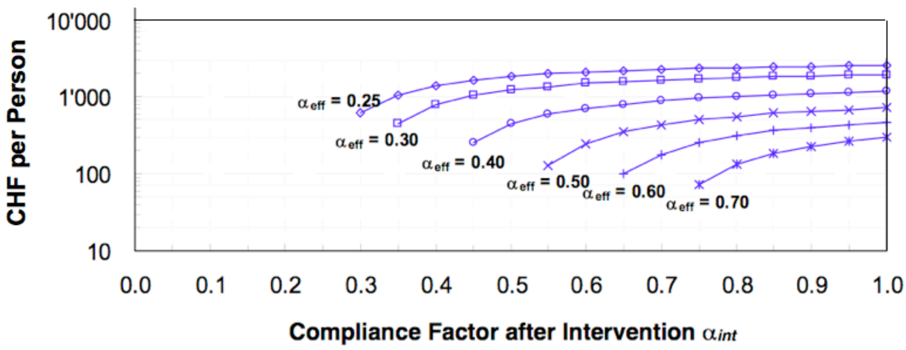

Figure 4. Proportional cost limits per person of the average occupancy *PB* vs. compliance factor for a remaining useful life of 40 years (adopted from BWG, 2005)

The highest blue curve in Figure 3 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 3. 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}: $\alpha_{eff} \geq \alpha_{min}$ = 0,25.

PRACTICAL EXPERIENCE

The key data of 24 seismic retrofitting projects in Switzerland were reported by Wenk (2008). The 21 buildings among them are listed in Table 1 in decreasing order of relative retrofitting cost. The relative costs of retrofitting show a large scatter between 0,5 % and 29 % of building value. The table leads off with three structures in the highest importance category III (essential facilities) in the two highest zones, in other words, structures with the highest demands on seismic safety in Switzerland. These two essential facilities were retrofitted up to the code level for new buildings without considering cost-benefit aspects.

Table 1. Key data of 21 seismically retrofitted buildings in Switzerland

Building Type and Location	Importance Category	Seismic Zone	α_{eff}	αi_{nt}	Cost in % of Bdg. Value
Fire station in Basel	III	Z3a	0,2	1,0	23 %
Police station in Sion	III	Z3b	0,2	1,0	29 %
School ESC in Monthey	II	Z3a	0,15	0,8	11 %
School in Gossau	II	Z1	0,3	1,0	10 %
School CO in Monthey	II	Z3a	0,16	1,0	7,7 %
Shopping center in Fribourg	II	Z1	0,5	1,0	7,4 %
Substation in Basel	III	Z3a	0,3	1,0	5 %
Hospital in Aarau	II	Z1	0,1	1,0	4 %
Residential bdg. Crans-Montana	I	Z3a	0,2	1,0	4 %
Office building in St. Maurice	II	Z3a	0,17	0,7	3,5 %
Office building in Sion	II	Z3b	0,2	1,0	3 %
School in Zurich	II	Z1	0,2	1,1	3 %
Radio studio in Zurich	II	Z1	0,3	1,0	2,3 %
Shopping center in Winterthur	II	Z1	0,2	1,0	2,2 %
Fire station in Visp	III	Z3b	0,4	1,0	1,8 %
Office building in Dübendorf	II	Z1	0,25	1,0	1,5 %
Hotel in Bussigny	I	Z1	0,12	1,0	0,7 %
School in Ostermundigen	II	Z1	0,1	0,5	0,7 %
School in Bern	II	Z1	0,24	0,6	0,7 %
Auditorium ETH Zurich	II	Z1	0,25	1,0	0,7 %
Sports center in Oberdorf	II	Z2	0,1	1,0	0,5 %

If the structures of Table 1 are grouped by importance category and seismic zone, the bandwidth of relative costs of the seismic retrofit is somewhat reduced as can be seen in Table 2. These wide ranges indicate that the costs depend strongly on construction constraints of the seismic retrofit in the particular case and less on the intensity of the seismic action. The structures with the favourable costs distinguish themselves through locally narrow, limited structural intervention, for example, only closing an expansion joint or adding bracing in only one storey. When new structural elements over the whole building height were necessary, the costs quickly rise even in the lowest seismic zone Z1, especially when additional strengthening of the foundation is required.

Table 2. Seismically retrofitted buildings in Switzerland of Table 1 grouped by importance category and seismic zone

Importance Category	Seismic Zone	Cost in % of Building Value
III	Z3b	2 - 29 %
III	Z3a	5 - 23 %
II	Z3b	3 %
II	Z3a	3,5 - 11 %
II	Z2	0,5 %
II	Z1	0,4 - 10 %
I	Z3b	4 %
I	Z1	0,7 %

In Table 3, the cost of retrofitting is determined in function of the occupancy *PB* for 12 selected buildings from the full set of 21 buildings in Table 1, four buildings of importance category III as well as five buildings of importance category II, which have been retrofitted before the Swiss Prestandard SIA 2018 (2004) was published, were eliminated because the risk-based criteria were not applied. The remaining 12 buildings in Table 3 can be divided into two groups: For four buildings, *marked in italic* in Table 3, the proportional limit to retrofitting costs, i.e. cost-benefit considerations, was applied because their compliance factor α_{eff} reached about the lower limit α_{min} = 0,25 or was above it. The other eight buildings had compliance factors α_{eff} clearly below 0,25 and, as a consequence, were retrofitted without considering the proportional cost limit. The eight buildings retrofitted without cost-benefit considerations had relatively high average cost of CHF 13'000 per person and maximum cost of CHF 25'000 per person. The four buildings retrofitted with cost-benefit considerations present much lower costs between CHF 1'500 and 2'700 per person with an average of CHF 1'800 per person. The range of proportional costs between CHF 1'500 and 2'700 is in line with the values shown in Figure 4 for a remaining useful live of 40 years. The upper bound of CHF 2'700 for the proportional cost per person in the case of the school in Zurich was probably reached by assuming a remaining useful life of more than 40 years.

Table 3. Cost of retrofitting vs. occupancy *PB* for selected buildings. Four buildings retrofitted with cost-benefit considerations are shown in *italic*.

Building Type and Location	Cost in CHF	Occupancy *PB*	Cost in CHF per *PB*	Cost in % of Bdg Value
School ESC in Monthey	540’000	32	17’000	11 %
School CO in Monthey	1’850000	76	24’000	7,7 %
Residential bdg Crans-Montana	150’000	6	25’000	4 %
Office building in St. Maurice	50’000	2.2	23’000	3,5 %
Office building in Sion	*130’000*	*85*	*1’500*	*3 %*
School in Zurich	130’000	48	2’700	3 %
Radio station in Zurich	*340’000*	*150*	*2’300*	*2,3 %*
Shopping center in Winterthur	*120’000*	*71*	*1’700*	*2,2 %*
Office building in Dübendorf	*150’000*	*80*	*1’900*	*1,5 %*
Hotel in Bussigny	180’000	60	3’000	0,7 %
School in Ostermundigen	140’000	38	3’700	0,7 %
Sports center in Oberdorf	25’000	5	5’000	0,5 %

With the average costs determined in Table 3, the cost of seismic retrofitting for a larger stock of existing ordinary buildings in importance category I or II can be roughly estimated based on occupancy *PB* and compliance factor α_{eff}. For buildings with compliance factors $\alpha_{eff} < 0,25$ the average cost could reach about CHF 13'000 per *PB* person. For buildings with compliance factors in the range of 0,25 ≤ α_{eff} ≤ 0,5 the average cost is about CHF 1'800 per *PB* person. Buildings with compliance factors α_{eff} > 0,5 can be neglected for a first retrofitting cost estimate of a larger building stock.

CONCLUSIONS

Retrofitting existing structures to the safety level for new buildings may become very expensive even in zones of low to medium seismicity. Cost-benefit considerations allow avoiding disproportionally high costs of seismic retrofitting. In any case, minimum requirements of personal risks have to be respected. Proportional cost limits for retrofitting can be efficiently determined by the risk-based rules introduced 10 years ago in Swiss Prestandard SIA 2018 (2004). The main parameters of the risk-based assessment are the compliance factor, the occupancy, and the remaining useful life of the existing structure.

The proportional cost limit can serve as filter to focus seismic retrofitting on structures with high personal risks. The other structures can be accepted as sufficiently safe in the existing state if the assessment results in a compliance factor above the minimum value. Case studies of completed projects in Switzerland showed that proportional retrofitting costs reach only about 1 % to 3 % of building value.

REFERENCES

BWG (2005) Beurteilung der Erdbebensicherheit bestehender Gebäude, Konzept und Richtlinien für die Stufe 3, Guidelines of the Federal Office for Water and Geology, Biel, Switzerland

Eurocode 8-1 (2004) Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings, EN 1998-1, European Committee for Standardization, Brussels

Eurocode 8-3 (2005) Design of Structures for Earthquake Resistance - Part 3: Assessment and Retrofitting of Buildings, EN 1998-3, European Committee for Standardization, Brussels

Kölz E. and Schneider J. (2005) Beurteilung der Erdbebensicherheit bestehender Gebäude – der risikobasierte Ansatz des Schweizer Merkblatts SIA 2018, *Bautechnik* 82 (2005) Heft 8

SIA 269 (2011) Swiss Standard SIA 269: Existing Structures – Basis for Examination and Interventions, Swiss Society of Engineers and Architects, Zurich, Switzerland

SIA 269/8 (2014) Swiss Standard SIA 269/8: Existing Structures – Earthquakes, Enquiry version, Swiss Society of Engineers and Architects, Zurich, Switzerland

SIA 462 (1994) Pre-Standard SIA 462: Assessment of the Structural Safety of Existing Structues, Swiss Society of Engineers and Architects, Zurich, Switzerland

SIA 2018 (2004) Pre-Standard SIA 2018: Examination of Existing Buildings with Regards to Earthquakes. Swiss Society of Engineers and Architects, Zurich, Switzerland

Wenk T. (1997) Erdbebensicherung bestehender Bauwerke nach verschiedenen Normen, SIA-Documentation D0145, Swiss Society of Engineers and Architects, Zurich, Switzerland

Wenk T. (2008) Seismic Retrofitting of Structures, Strategies and Collection of Examples in Switzerland, Environmental studies No. 0832, Federal Office for the Environment, Bern, Switzerland

Wenk T. (2014) Die neue Norm SIA 269/8 Erhaltung von Tragwerken – Erdbeben, DACH-Mitteilungsblatt, *Bauingenieur 89* April 2014

Wenk T., Beyer K. (2014) Seismic Conservation Strategies for Cultural Heritage Buildings, Second European Conference on Earthquake Engineering and Seismology, Istanbul, Aug. 25-29, 2014