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DEFORMATION-BASED SEISMIC DESIGN AND VERIFICATION OF EARTH- AND RETAINING STRUCTURES IN SWITZERLAND

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ABSTRACT

The value of the horizontal ground acceleration for the seismic design of earth- and retaining structures according to the Swiss buildings codes varies between 0.6 and 3.2 m/s^2. This range takes into account the different seismic zones, soil classes and importance factors of constructions, but does not include the reduction factors used for design. On the one hand, the seismic load case can be determinant even at relatively low values of horizontal ground acceleration for a force-based design. On the other hand, observed performances of earth- and retaining structures in earthquakes worldwide and in shake table tests show that such structures are usually not significantly damaged by horizontal ground accelerations in this range, especially for magnitudes that are characteristic for regions with low to moderate seismicity, like Switzerland. Therefore, it can be questioned if the force-based seismic provisions of the buildings codes for earth- and retaining structures are too conservative.

This question has been studied in a joint project of the Swiss federal roads office (FEDRO), the Swiss federal railways (SBB) and the Swiss federal office for the environment (FOEN). In this project, modifications to reduce the conservatism of the force based design for earth- and retaining structures were made and a deformation-based design approach was developed as an alternative to the force-based method. Results of this work were included in the revision of the Swiss building code SIA 267 (Geotechnical design) in 2013, in the new building code SIA 269/8 “Existing structures - earthquakes” (2017) and in a technical documentation of the Swiss federal roads office “Seismic safety of earth- and retaining structures” (FEDRO, 2018). This paper describes the application of the newly developed deformation-based approach.

Keywords: seismic safety; retaining structures; deformation-based approach.

1. FORCE-BASED SEISMIC DESIGN CODE PROVISIONS

1.1 Seismic action - building code SIA 261

The seismic provisions of the Swiss building codes (SIA 261, 2014) for new structures are largely in line with the provisions of the current Eurocode 8, part 1 (EN1998-1, 2004). The seismic action for structural safety design is defined by the design value of the horizontal ground acceleration a_{gd} for ground class A, the type 1 elastic response spectra for a return period of 475 years and the importance factors γ_f of 1.0, 1.2 and 1.4 related to the construction works class. A verification of serviceability is

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only required for the highest construction works class (BWK III) This verification is performed for 50% of the seismic action used for structural safety design. In Switzerland, a_{gd} varies between 0.6 and 1.6 m/s^2. The soil factor S, which takes into account the relative amplification of the seismic action according to the ground class varies between 1.0 and 1.4. Therefore, the range of values for $\gamma_f \cdot a_{gd} \cdot S$ (design value of horizontal ground acceleration at a site) varies between 0.6 and 3.2 m/s^2.

1.2 Force-based design of earth- and retaining structures - building code SIA 267

the design value of the horizontal ground acceleration for the force-based design of earth and retaining structures is obtained from the value of $\gamma_f \cdot a_{gd} \cdot S$ taken from SIA 261 (2013) divided by two correction factors q_a and q_h defined in SIA 267 (2017). The reduction factor q_a varies from 1.0 to 2.0 and takes into account the allowable residual displacements for earth- and retaining structures. The reduction factor q_h varies from 1.0 to 2.5 and takes into account the dimensions of the failure mechanism. For most cases, the vertical seismic action can be ignored.

According to SIA 267, a formal verification of the seismic safety for earth- and retaining structures is not necessary if all the following criteria are met:

- Construction works class I or II
- The structural safety requirements for permanent and temporary design situations are met
- The design value of horizontal ground acceleration at the site $\gamma_f \cdot a_{gd} \cdot S \leq 1.5$ m/s^2 for horizontal terrain and $\gamma_f \cdot a_{gd} \cdot S \leq 1.1$ m/s^2 for other situations
- There is no potential for soil liquefaction, soil compaction and shear strength reduction.

For the design of slopes and embankments, the seismic load case is usually determinant. In the case represented in Figure 1, the factor of safety for slope stability under permanent loads based on the design values of the soil parameters is 1.05 (1.29 for characteristic values). In this case, the seismic load case is determinant for $\gamma_f \cdot a_{gd} \cdot S > 0.5$ m/s^2 with the usual values of $q_a = 2.0$ and $q_h = 1.0$. This value is very low. It is lower than the above-mentioned threshold value of 1.5 m/s^2 in SIA 267 (2013). In contrast, Newmark-based analyses show that even if the force-based seismic slope stability is not met (see also Section 2.5), the resulting permanent slope displacements of typical engineered earth structures is negligible, for a seismic action equivalent to $\gamma_f \cdot a_{gd} \cdot S = 1.5$ m/s^2 or below.

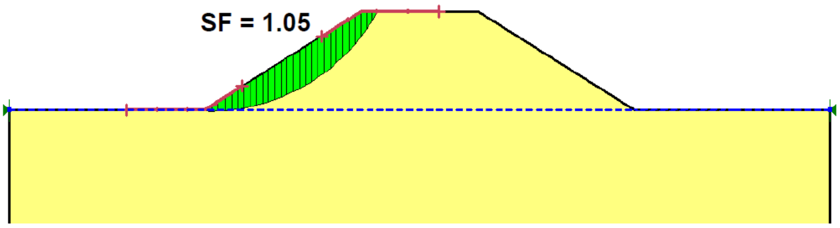


Figure 1: Example embankment dam (FEDRO, 2018). Design values of the soil parameters are $\gamma_d = 18$ kn/m^3, $\phi'_d = 26.6°$, $c'_d = 0.65$ kN/m^2. Characteristic values of the soil parameters are $\gamma_k = 18$ kN/m^3, $\phi'_k = 31$, $c'_k = 1$ kN/m^2. The dam height is 5m and the slope angle is 32°.

For the force-based seismic design of the retaining stem wall presented in Figure 2, the seismic load case is determinant for $\gamma_f \cdot a_{gd} \cdot S > 2.7$ m/s^2 (Schneider et al., 2015). Bearing capacity failure is the critical failure mode. For a stem wall with a visible height h of 8 m (higher range in practice), the seismic load case becomes determinant for $\gamma_f \cdot a_{gd} \cdot S > 1.7$ m/s^2. This latter value is in good agreement with the threshold value of 1.5 m/s^2 above which an explicit verification of seismic safety is necessary according to SIA 267.

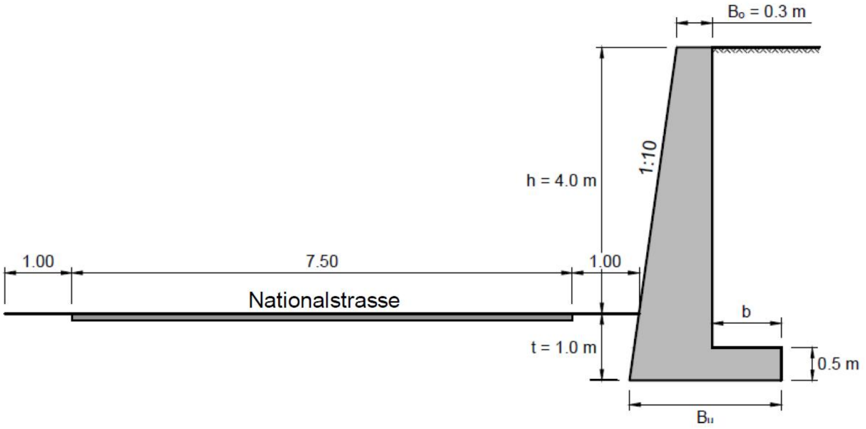
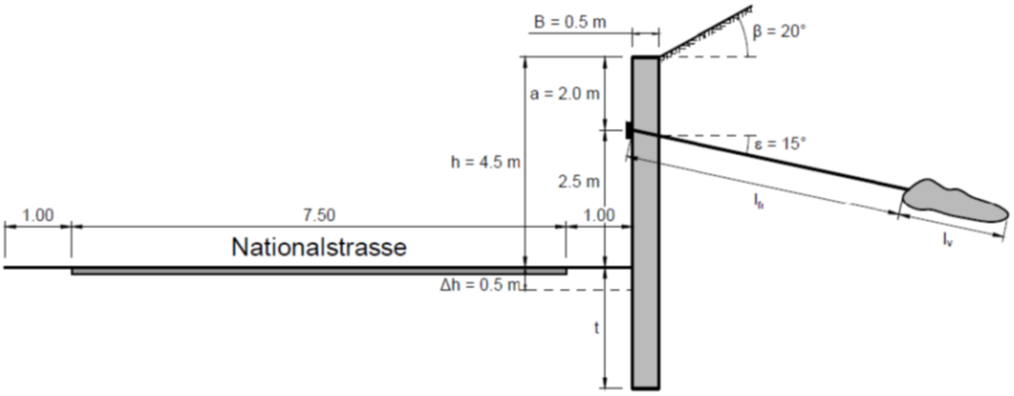


Figure 2: Example stem wall (FEDRO, 2018). Design values of the soil parameters are $\gamma_d = 20$ kN/m^3, $\phi'_d = 25.7°$, $c'_d = 0$ kN/m^2. Characteristic values of the soil parameters are $\gamma_k = 20$ kN/m^3, $\phi'_k = 30°$, $c'_d = 0$ kN/m^2. Reduction factors were selected as $q_a = 2.0$ and $q_h = 1.0$. The required value of B_u is 4.2 m for permanent loads.

For the force-based seismic design of the anchored wall in Figure 3, the seismic load case is determinant for values of $\gamma_f \cdot a_{gd} \cdot S$ above 1.9 m/s^2. Global failure is the critical failure mode.



Characteristics of the anchors for the permanent load case are
Horizontal spacing d = 3.00 m
Required loading $A_d = 427.2$ kN
Characteristic value of external resistance $R_k = 577.0$ kN
Internal resistance $R_{i,k} = 744.0$ kN (4 tendons with 100 mm^2 and $f_{pk} = 1860$ N/mm^2)
Anchoring length $l_v = 5.0$ m
Free anchor length $l_{fr} = 7.00$ m

Figure 3: Example anchored wall (FEDRO, 2018). Design values of the soil parameters are $\gamma_d = 20$ kN/m^3, $\phi'_d = 25.7°$, $c'_d = 0$ kN/m^2. Characteristic values are $\gamma_k = 20$ kn/m^3, $\phi'_k = 30°$, $c'_d = 0$ kN/m^2. Reduction factors were selected as $q_a = 1.0$ and $q_h = 1.5$ to 2.0 (according to the dimensions of the failure mechanism). The soil behind the wall has a slope of 20° up to a horizontal distance of 25 m behind the wall and, then it is horizontal.

These examples show that the value of $\gamma_f \cdot a_{gd} \cdot S$ for which the force-based seismic design becomes determinant is variable depending on the construction type. When it is the case, a deformation-based design would enable the designer to check if the supplementary measures and related costs to comply with the force-based structural safety requirements under seismic loading are justified. The building code SIA 267 mentions this possibility without giving further details. A framework for such a procedure is given in the building code SIA 269/8 “Existing structures - earthquakes” (SIA, 2017).

2. BUILDING CODE SIA 269/8 “EXISTING STRUCTURES - EARTHQUAKES”

2.1 Central concepts

The pre-standard SIA 2018 (SIA, 2004) for the verification of the seismic safety of existing buildings was published in 2004 and replaced in December 2017 by the new building code SIA 269/8 “Existing structures - earthquakes” (SIA, 2017). This new code uses the main principles of the pre-standard SIA 2018 and it is applicable to a wider range of existing structures, like earth- and retaining structures.

The first 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. For construction works class I (common structures) and II (structures with high occupancy, or with high consequences in case of collapse), the minimum compliance factor α_{min} is 0,25. For construction works class III as well as for school buildings and constructions with an important infrastructure function, the minimum compliance factor α_{min} is 0,40.

The second central concept is the **recommendation of measures**. Three cases are distinguished depending on the compliance factor of an existing structure (see also Figure 4):

1. If the compliance factor α_{eff} is under 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}.
2. If the compliance factor α_{eff} is above α_{min} but below the dashed curves in Figure 1, then retrofitting must be implemented as long as the related measures are *commensurate*. The objective is to reach a compliance factor of 1,0. If this is not possible, measures must be implemented up until the limit of commensurability. If no commensurate measures can be found then the existing state can be accepted.
3. If the compliance factor α_{eff} is above the dashed line in Figure 1, the existing state is acceptable as it is probably impossible to find commensurate measures.

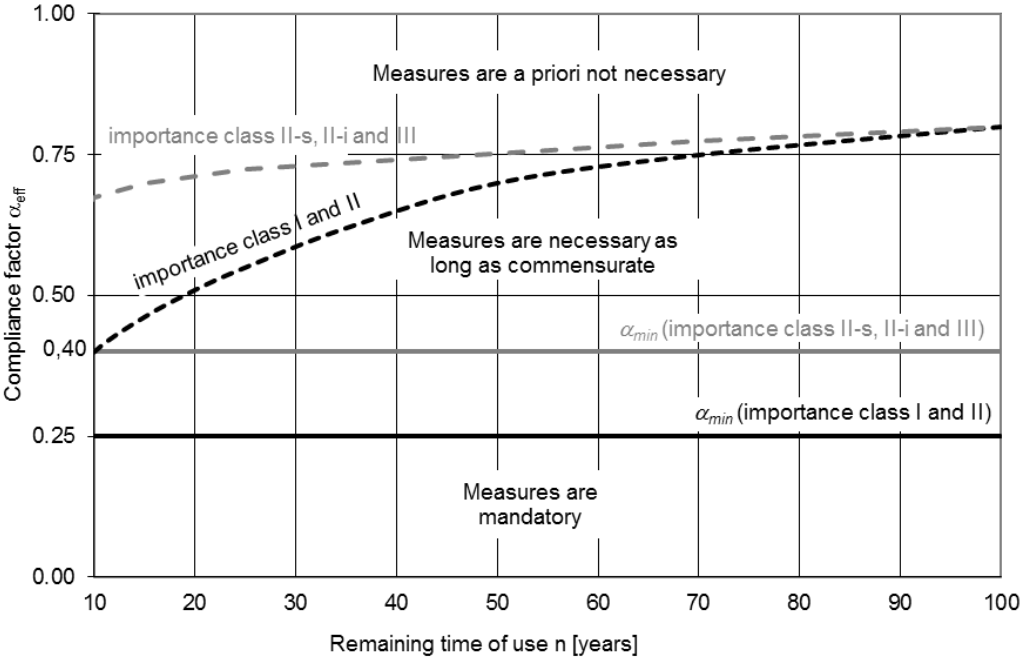


Figure 4: Recommendations of measures according to the new SIA building code 269/8.

The third central concept is the **commensurability of measures**. The criterion used in SIA 269/8 is the efficiency of measures EF_M defined as the ratio between the risk reduction in Swiss francs per year and the annualized cost of measures with a discounting factor of 2% over the remaining time of use of the construction. According to SIA 269/8, the risk reduction can be computed explicitly for casualty risk (Figure 5), risk of direct damage to a construction and its content (Figure 6), business interruption and loss of infrastructure function (Figure 7). Using Figure 5, the casualty risk is computed by multiplying the risk factor for individuals with the average number of people potentially affected by the collapse of a structure and a value of 10 million Swiss francs per life saved. Using Figure 6, the annualized risk from direct damage to the construction is calculated as the multiplication of the risk factor BRF with the replacement value of the construction. The risk reduction for important and vital infrastructure function is computed using the so-called infrastructure rate (Figure 7). The yearly risk reduction is the infrastructure rate IS multiplied with the replacement value of the construction.

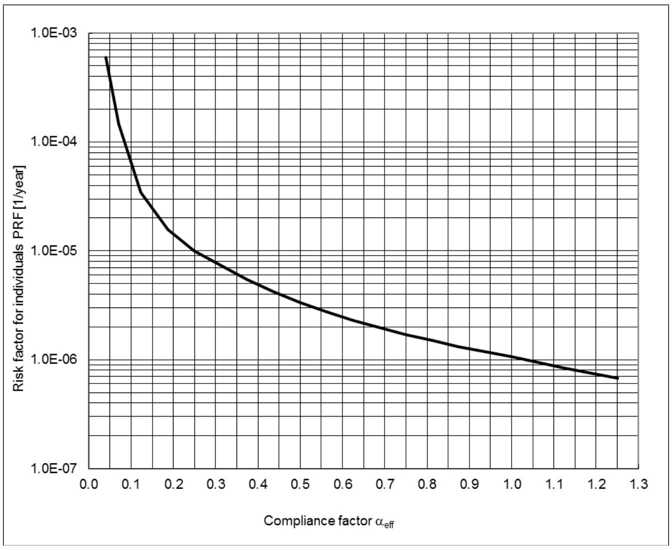


Figure 5: Risk curve in the building code SIA 269/8 (dashed) relating the compliance factor α_{eff} of a construction with the annual risk factor for individuals PRF

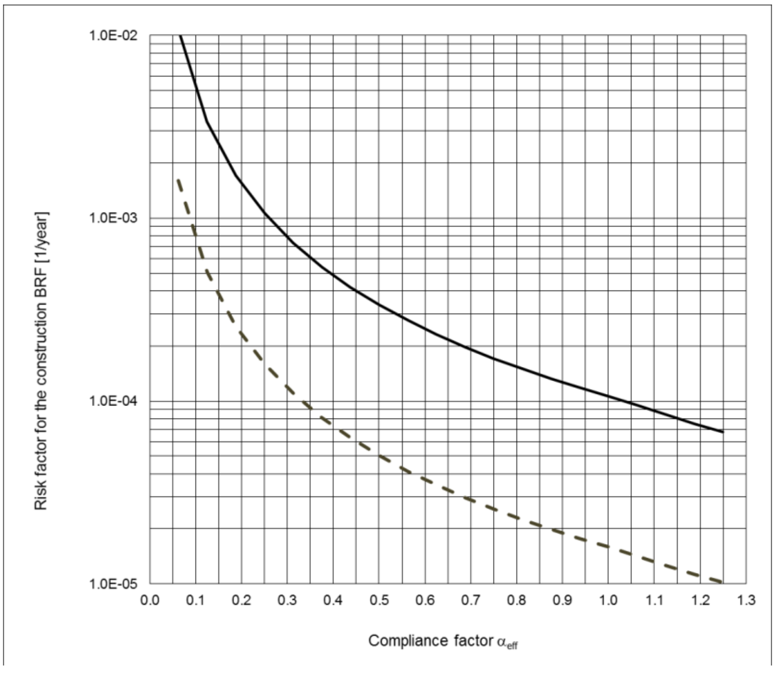


Figure 6: Risk curves in SIA 269/8 relating the compliance factor α_{eff} with the risk factor BRF for direct damage to the construction (and its content). The continuous curve is for constructions with a high proportion of non-structural components and equipments (buildings). The dashed curve is for constructions with a low proportion of non-structural components and equipments (e.g. bridges, retaining walls, etc.).

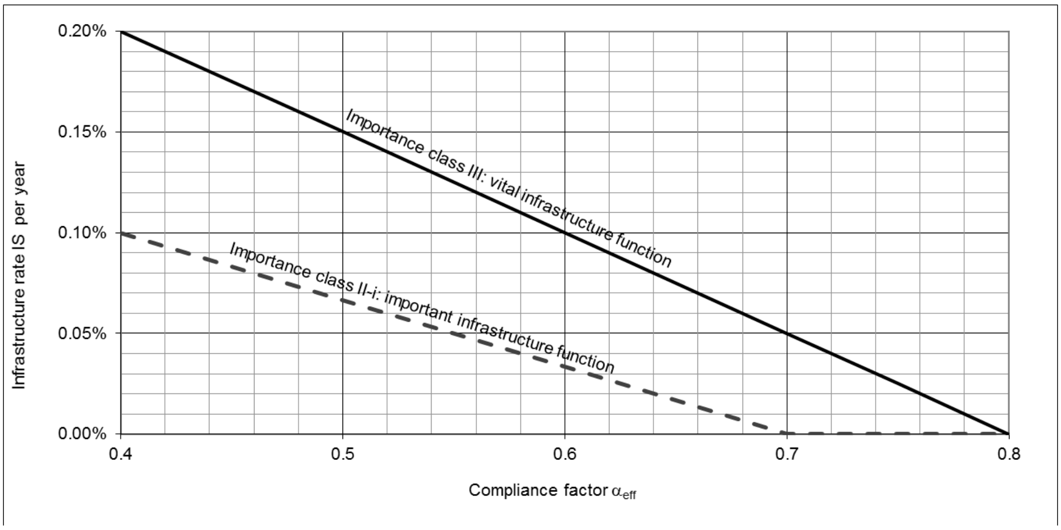


Figure 7: Curves in the building code SIA 269/8 relating the compliance factor α_{eff} with the willingness to pay (infrastructure rate IS given for a period of one year) to reduce the risk for the infrastructure function.

2.2 Conditions not requiring a seismic verification for earth-and retaining structures

In SIA 269/8 (2017), if all the following conditions are met, a seismic verification of the seismic safety of earth- and retaining structures is not required.

- The construction works class is I or II
- The requirements for structural safety for permanent and temporary design situations are met
- The design value of horizontal ground acceleration at the site $\gamma_f \cdot a_{gd} \cdot S \leq 2.0$ m/s^2 for horizontal terrain and $\gamma_f \cdot a_{gd} \cdot S \leq 1.4$ m/s^2 in other situations
- There is no potential for soil liquefaction, soil compaction and shear strength reduction.

These conditions are similar to the ones found in SIA 267 (2013), but with slightly higher threshold values for $\gamma_f \cdot a_{gd} \cdot S$, taking into account that no commensurate retrofit measures can usually be found for compliance factors above 0.75 (see Figure 4).

2.3 Force-based verification method for earth- and retaining structures

The force-based verification of earth- and retaining structures is analogous to the usual verification formats for design. The compliance factor is computed as the ratio between the critical value of horizontal acceleration a_{crit} for which the structural safety or serviceability requirement is just met and the design value of $\gamma_f \cdot a_{gd} \cdot S$. An alternative definition of the compliance factor for slopes is proposed in Equation 1 based on Newmark-analyses. In Equation 1 a_{crit} is the horizontal acceleration for which slope stability is just met with characteristic values of the soil parameters and a value of $q_a = 1.0$ for.

$$\alpha_{eff} = [(a_{crit} / (\gamma_f \cdot a_{gd} \cdot S)) - 0.1]\, q_a \qquad \text{(valid for values of } a_{crit} / (\gamma_f \cdot a_{gd} \cdot S) > 0.1) \qquad (1)$$

2.4 Deformation-based verification method

A framework for a deformation-based verification of earth- and retaining structures is given in the Geotechnics section of SIA 269/8 (2017). It enables the engineer to critically evaluate the outcome of a force-based verification, especially if a retrofit is required according to the force-based compliance factor. The principles are the following:

- The examination of the seismic safety consists in a comparison of the permanent displacements w_{bd} induced by the design (formally verification) value of the seismic action against permanent displacement limits w_{Rk} (deformation capacity).

- The deformation-based method can only be used if brittle failure mechanisms (e.g. shear failure, pulling out of the anchor zone and failure of anchor heads) can be excluded.
- For anchored constructions, it must be verified that the anchor deformation can be accommodated. This is verified if the estimated anchor deformation is smaller than $\varepsilon_{uk} / \gamma_D$, with ε_{uk} as the characteristic value of elongation at rupture and $\gamma_D = 2.5$.
- The permanent displacements of earth- and retaining structures w_{bd} induced by the design (verification) value of the seismic action are determined using characteristic values of the soil parameters. If relevant, the sensitivity to soil liquefaction, compaction and shear strength degradation must be considered.
- The characteristic values of the permanent displacement limits w_{Rk} must be determined individually.
- The deformation-based verification is fulfilled when $w_{bd} \leq w_{Rk} / \gamma_D$, using the partial factor $\gamma_D = 2.5$ when no further investigations are performed.

The deformation-based compliance factor α_{eff} is defined as the ratio between the seismic action for which $w_{bd} = w_{Rk} / \gamma_D$ and the design value of the seismic action. Computing the value of this compliance factor usually requires an iterative process. A conservative approximation of the deformation-based compliance factor can be computed as $\alpha_{eff} = (w_{Rk} / \gamma_D) / w_{bd}$.

This deformation-based framework can be used for the design of new earth- and retaining structures, although it was initially developed for existing structures.

2.5 Determining the permanent displacement w_{bd} due to the design value of the seismic action

Annex D of SIA 269/8 proposes a method to determine the design values of permanent displacement w_{bd} (Figure 8) for sliding failure mechanisms such as slope instability. The permanent displacement of earth- and retaining structures w_{bd} is computed as a function of the critical acceleration a_{crit} of the sliding failure mechanism obtained with characteristic soil parameters and a value of $q_a = 1.0$. The curves in Figure 8 were developed based on Newmark analyses with time histories that are representative of the seismicity in Switzerland (Laue et al., 2014). These curves are valid only for cases where the soil mass included in the failure zone can be approximated as a rigid body.

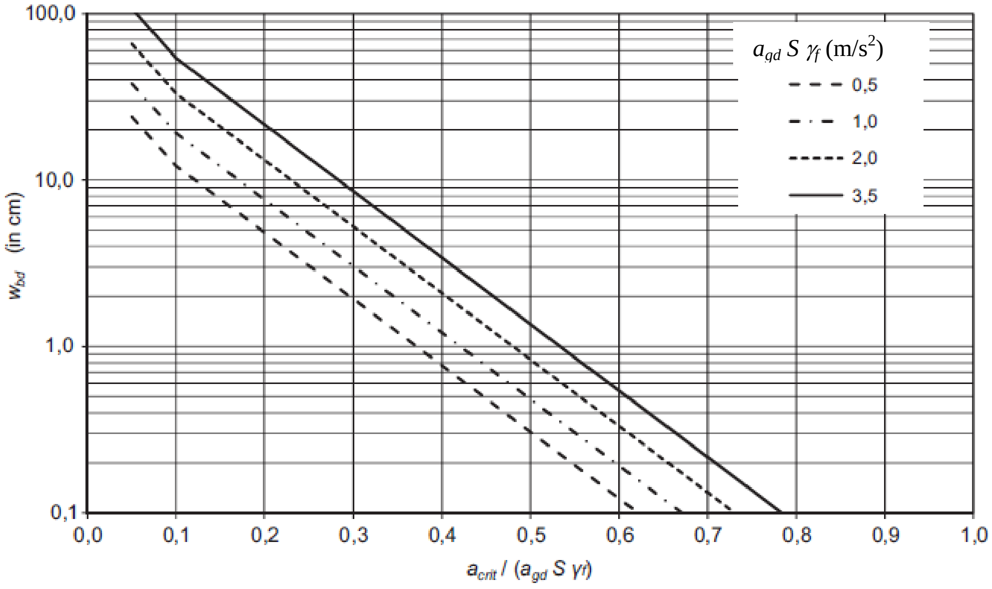


Figure 8: Permanent displacement w_{bd} as a function of the critical acceleration a_{crit} of the sliding failure mechanism obtained with characteristic soil parameters and a value of $q_a = 1.0$

For all other cases, the design value of the permanent displacements w_{bd} needs to be defined based on the more complex approach with dynamic finite element analyses. The documentation “Seismic safety of earth- and retaining structures” of the federal roads office (FEDRO, 2018) is proposing guidelines regarding good practice for such analyses.

3. PERMANENT DISPLACEMENTS LIMITS

3.1 Permanent displacements limits for earth- and retaining structures

The documentation “Seismic safety of earth- and retaining structures” of the federal roads office (FEDRO 2018, in german) proposes characteristic values of permanent displacement limits w_{rk} for the structural safety verification of earth- and retaining structures under seismic loading (Table 1).

Table 1. Characteristic values of permanent displacement limits w_{Rk} for the structural safety verification of earth- and retaining structures under seismic loading (H: visible height of the wall).

Construction type	**Displacement type**	**Permanent displacement limit w_{Rk}**
Gravity wall and stem walls	Rotation Horizontal displacement Settlement	0.10 H (5.7°) 0.05 H 0.025 H
Wall with pre-tensioned anchors	Horizontal shift Settlement	Anchors are not crossing the failure surface: Like gravity walls Anchors are crossing the failure surface: Like gravity walls but under consideration of the deformation capacity of the anchors between the bond zone and the anchor head.
Nailed walls	Horizontal displacement, Settlement	Like gravity walls
Embankment, fill,	Differential Settlement	75 cm
Slope, cut	Settlement, horizontal shift, bulging	75 cm

These values were defined based on expert opinion and can be used in conjunction with the building code SIA 269/8 to perform a deformation-based verification of the seismic safety of earth- and retaining structures. They can be also used analogously for the design of new earth- and retaining structures. The performance objective of these permanent deformations is that the geotechnical structure can still fulfill its function and can be repaired with such permanent deformations. It should also be able to sustain the design value of the seismic action a second time without collapsing.

3.2 Permanent settlement limits for roadways and rail tracks.

For cases where the permanent displacements of earth- and retaining structures can cause permanent settlements of roads or train tracks, the documentation “Seismic safety of earth and retaining structures” of the federal roads office (FEDRO 2018) proposes characteristic values of permanent settlement limits for traffic lanes and railway tracks. In such cases, the two deformation-based verifications in Equations 2 and 3 must be satisfied:

$$w_{bd} \leq w_{Rk} / 2.5 \text{ for the structures} \tag{2}$$

$$v_d \leq v_{Rk} / 2.5 \text{ for the traffic lanes or train tracks} \tag{3}$$

with v_d: estimated permanent settlement of traffic lanes or railway tracks under seismic action.

The values of the permanent settlement limits for traffic lanes or railway tracks v_{Rk} are defined in function of a so-called “seismic class” of the road or railway section such as presented for roads in Tables 2 and 3. These permanent displacement limits are valid for the design value of the seismic action used for the structural safety check. The design or verification requirements for permanent settlements of traffic lanes or railway tracks are considered to be implicitly fulfilled if the force-based structural safety of the earth- or retaining structure is verified.

Table 2. Definition of the seismic classes for road segments.

Seismic class	**Definition of infrastructure function**	**Minimum requirements for earth- / retaining structures**
ESK 0	Minor. Disruptions have negligible consequences.	Construction works class I
ESK I	Normal. Eventual traffic disruptions have limited and local societal and economic consequences. Redundancy and compensation possibilities are sufficient.	Construction works class I
ESK II	Important. The road segment has an important but not critical/vital function after an earthquake. Eventual traffic disruptions have significant societal and economic consequences. Redundancy and compensation possibilities are not sufficient.	Construction works class II if failure of structure potentially impacts traffic, otherwise construction works class I.
ESK III	Critical/vital. The road segment has a vital function in the disaster response phase (very important for the access to selected constructions or zones after an earthquake). There is no redundancy and compensation possibility. Eventual traffic disruptions have severe societal and economic consequences.	Construction works class III, if failure of structure potentially impacts traffic, otherwise construction works class I.

Table 3. Characteristic values of permanent settlement limits v_{Rk} and associated descriptions of maximum tolerable damage and loss of use for roads for a seismic action corresponding to the structural safety check.

Seismic class	**Importance factor γ_f**	**Maximum tolerable damage**	**Maxixum tolerable limitation of use**	**v_{Rk} (cm)**
ESK 0	1.0	Very large settlements or offsets of traffic lanes. Failure of road dams and underlying slopes.	Lanes closed during several months for repairing / replacement works.	-
ESK I	1.0	Large differential settlements, offsets of traffic lanes. Sliding and settlement of dams or cuts and underlying slopes.	Lanes closed during a few days for temporary repairing works, partly closed for further repairing works during weeks / a few months.	30-50 cm
ESK II	1.2	Significant differential settlement of traffic lanes or offset of dam shoulders or slope faces with significant deformations of the traffic lanes. Soil material on traffic lanes from slope sliding above the road.	Lanes closed during a few days for temporary repairing works, partly closed for further r repairing works during a few weeks.	10-25 cm
ESK III	1.4	Small settlement of traffic lanes, small offsets of dam shoulders. Limited bulging at the base of slopes.	Lanes open with reduced speed during repairing works or fully operational.	5–15 cm

4. APPLICATION EXAMPLES AND ISSUES

4.1 Application examples

In the technical documentation of the Swiss federal roads office “Seismic safety of earth- and retaining structures” (FEDRO, 2018), five examples of engineered earth- and retaining structures are presented with the following principles.

- The earth or retaining structure was not designed for earthquake loading and it complies with the structural safety requirement for permanent loads.
- The earth- or retaining structure must be verified for seismic safety in the highest seismic zone of Switzerland
- Compliance factors are computed for the earth- or retaining structure and the adjacent road for a force-based and a deformation-based approach.
- Recommendations of measures according to SIA 269/8 are formulated depending on the computed compliance factor.
- Sensitivity analyses are performed for relevant parameters.

These examples (three of which are shown in Figures 1 to 3) show force-based compliance factors below 1.0, but not in the critical range where measures would be mandatory according to SIA 269/8 (Figure 4). Potential commensurate retrofit measures are required considering the force-based verification alone. However, deformation-based verifications provide compliance factors above 1.0, leading to the conclusion that the current situation can be considered as code-compliant.

Figure 9 presents the case of a natural slope with a marginal factor of safety for slope stability under permanent loads. In this case, the global factor of safety for permanent loads is 1.07 using characteristic values of the soil parameters. The force-based compliance factor for slope stability under seismic loading using equation (1) is 0.02 with $\gamma_f \cdot a_{gd} \cdot S = 2.7$ m/s^2, as well as q_a and $q_h = 2.0$. Such a situation would require mandatory retrofit measures according to the principles of SIA 269/8 (Figure 4). A deformation-based verification of slope stability with a Newmark-based method (see Section 2.5) leads to an estimation of the design value of permanent slope displacements w_{bd} of 40 cm. Further dynamic FEM analysis shows permanent slope displacement w_{bd} of 25 cm and permanent settlements of the traffic lanes v_d of 15 cm. These values must be compared with the permanent displacement limits for slopes w_{Rk} (Table 1) and for traffic lanes v_{Rk} (Table 3) using Equations 2 and 3 respectively.

Verification of limit displacements for the slope:

The verification leads to the following results for a value of the permanent slope displacement limit of w_{Rk} = 75 cm:

> Newmark-based:
> w_{bd} = 40 cm $\leq w_{Rk}$ / 2.5 = 75 cm / 2.5 = 30 cm is not fulfilled. A conservative compliance factor α_{eff} = 0.75 (30 cm/40 cm) is estimated. According to Figure 4, the present situation is acceptable.
>
> FEM-based:
> w_{bd} = 25 cm $\leq w_{Rk}$ / 2.5 = 75 cm / 2.5 = 30 cm is fulfilled. The compliance factor α_{eff} is above 1.0. The present situation is code-compliant.

Verification of limit permanent settlements for the road:

The verification leads to the following results for a value of the permanent settlement limit of the traffic lanes (road section with seismic class ESKII) v_{Rk} = 25 cm:

> Newmark-based:
> v_{bd} = 40 cm $\leq v_{Rk}$ / 2.5 = 25 cm / 2.5 = 10 cm is not fulfilled. A conservative compliance factor α_{eff} = 0.25 (10cm / 25 cm) is estimated. According to figure 4, retrofit measures are required to limit the differential settlements of the traffic lanes.
>
> FEM-based:
> v_{bd} = 15 cm $\leq w_{Rk}$ / 2.5 = 25 cm / 2.5 = 20 cm is not fulfilled. A conservative compliance factor α_{eff} = 0.75 (15cm / 20 cm) is estimated. According to figure 4, the present situation is acceptable.

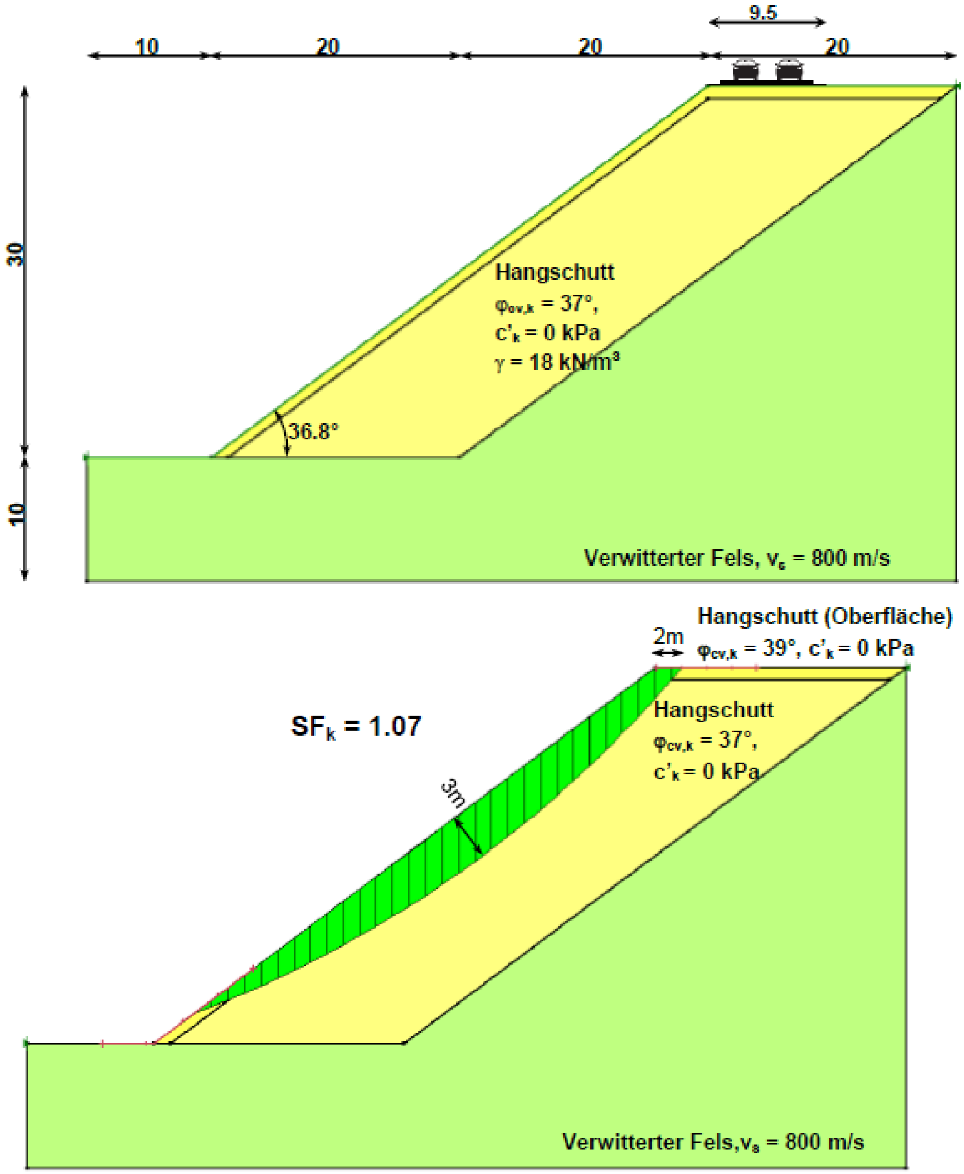


Figure 9: Case of a road passing on top of a natural slope with marginal safety for slope stability under permanent loads (FEDRO, 2018). The model has a superficial layer of 1.5 m of soil with characteristic soil parameters of $\gamma_k = 18$ kN/m^3, $\phi'_k = 39°$, $c'_k = 0$ kN/m^2. The rest of the soil mass has characteristic parameters of $\gamma_k = 18$ kN/m^3, $\phi'_k = 37°$, $c'_k = 0$ kN/m^2. The slope angle is 36.8°. “Hangschutt” means “colluvium” and “verwitterter Fels” means “weathered rock”.

This example is clearly shows the advantages of more elaborate analysis methods in the decisional process related to the seismic safety and retrofit measures of existing geotechnical structures.

4.2 Issues

One serious difficulty with deformation-based methods for geotechnical structures is to guarantee that the time histories selected for the FEM-analyses are consistent with the design elastic response spectra from the building codes. Eurocode 8 requires that the average response spectrum at the surface of the soil model for a dynamic analysis with multiple time histories (more than seven) should not lie below 90% of the relevant design elastic response spectrum, for a period range between 0.2 T_1 and 2 T_1 (where T_1 is the fundamental period of the analyzed structure). In FEDRO (2018) this requirement was fulfilled for the period range between 0 and 2 s, since the exact fundamental period of the failure mechanisms of earth- and retaining structures is difficult to evaluate. Meeting this requirement implied an iterative and time-consuming procedure, since the time histories were applied at the base of the FEM-models.

Furthermore, permanent displacement limits proposed in the FEDRO documentation were set by geotechnical engineering professionals on the basis of expert judgment. Future validation work is needed for confirming or adjusting these limits.

5. CONCLUSIONS

The new building code SIA 269/8 “Existing structures - earthquakes” (2017) and the technical documentation of the Swiss federal roads office “Seismic safety of earth- and retaining structures” (FEDRO, 2018) together with the actual Swiss building code SIA 267 “Geotechnical design” represent a consistent and practical framework for deformation-based seismic verifications and design of geotechnical structures. This framework enables the engineers to critically evaluate the results of force-based design or verification methods, and potentially to avoid the implementation of unnecessary retrofit measures. Further developments of the deformation-based procedures for geotechnical structures are necessary to consolidate the performance requirements and to simplify the computations for practice.

6. REFERENCES

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