4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1481

Thessaloniki-GREECE 2007

PERFORMANCE-BASED SEISMIC RETROFIT OF RETAINING WALLS

Guillaume VEYLON [1], David CRIADO[2]

ABSTRACT

Initialized in 2002, under the supervision of the Roads' Direction of the French Ministry of Public Works and Transportation, the SISROUTE method was created in order to estimate the vulnerability of existing road sections exposed to earthquakes.
SISROUTE procedure finally locates the zones where the damage can involve a risk of cutting off roads for a given seismic scenario. After a strategic analysis on possible traffic deviation, road managers may start retrofitting programs on essential road sections.
Given that the current seismic code was mostly developed for the design of new structures, the economical cost of seismic retrofitting projects based on these rules is prohibitive in most cases. Designers must formulate effective retrofit approaches that will limit the expected earthquake damage to a specified range for a specified level of ground shaking. These approaches, called performance-based seismic design, are largely used for the seismic rehabilitation of existing buildings, but not for geotechnical structures. This paper presents a methodology for the performance-based retrofitting of retaining walls.
In the first place a literature review of the basis of performance-based seismic design is presented. In the second part of the study, we propose specific performance levels for retaining walls. Then methods of analysis and data needed are described in order to provide designers means to select proper retrofitting objectives for structures evaluated. An example of application of this method in Southern France is given. Characteristic uncertainties of performance-based seismic retrofitting projects are highlighted.

Keywords: performance-based design, seismic, rehabilitation, retrofitting, retaining wall

INTRODUCTION

Most engineering design is performance based. For static loadings, most structures have traditionally been designed for two performance levels : a serviceability level and a failure level. At service level loading, structures are designed to perform without damage and maintain deflections below a level that would be troubling to users. Structures are not specifically designed for failure level loads, however, they are designed such that under expected loading, the structure will provide an acceptable margin against the failure state. This basic approach is not able to take into account the strategic importance of structures and is often inappropriate for retrofitting projects, in terms of costs.

[1] Civil Engineer, Laboratoire d'Aix-en-Provence, CETE Méditerranée, France, Email: guillaume.veylon@equipement.gouv.fr .
[2] Civil Engineer, Laboratoire d'Aix-en-Provence, CETE Méditerranée, France, Email: david.criado@equipement.gouv.fr .

The performance-based design method enables to associate the road administrator during the design phase and to introduce the structural design into the framework of a patrimony management and of a rationalization of the costs. Furthermore, this method is already introduced into the Eurocode 8. The following study presents a new specific methodology helping the engineer for the seismic retrofit of retaining walls based on performance design.

PERFORMANCE-BASED DESIGN BASIS

Structural performance

The fundamental requirements refer to the state of damage in the retaining structure, herein defined through three limit state : Near Collapse (NC), Significant Damage (SD), and Damage Limitation (DL). These limit states shall be characterized as follows :

- Near Collapse (NC). The retaining structure is heavily damaged, with low residual strength and stiffness. Most non-structural components have collapsed. Large permanent drifts are present. The structure is near collapse and would probably not survive another earthquake, even of moderate intensity.
- Significant Damage (SD). The structure is significantly damaged, with some residual strength and stiffness. Non–structural components are damaged. Moderate drifts are present. The structure can sustain after-shocks of moderate intensity. The structure is likely to be uneconomic to repair.
- Damage Limitation (DL). The structure is only lightly damaged, with retained strength and stiffness properties. Non-structural components may show distributed cracking, but could be economically repaired. Permanent drifts are negligible. The structure does not need any repair measures.

The road manager services may decide whether all three limit states shall be checked; or two of them, or just one of them. Of course, this choice must take into consideration the whole section of the road, following the SISROUTE procedure.

Reference seismic action

The French seismic code [NF P06-013] is based since 1991 on a zonation derived from a deterministic approach [Despeyroux, Godefroy, 1986], which is not coherent with the probabilistic format of the European seismic code. A new national zonation will be based on probabilistic hazard assessment. Based on many tectonic, seismic and economic analysis, this zonation (unofficial for instance) will provide for each point of the territory a maximum acceleration of soil for different return period of earthquake. An example is given in **figure 1**.
Given a geographical position of the structure, the appropriate levels of protection are achieved by selecting, for each limit states, a return period for the seismic action. Here, we shall consider the following return periods :

- Frequent earthquakes. Their probability of exceedance in 50 years is 20 %, i.e. a return period of 225 years ;
- Rare earthquakes. Their probability of exceedance in 50 years is 10 %, i.e. a return period of 475 years ;
- Very rare earthquakes. Their probability of exceedance in 50 years is 2 %, i.e. a return period of 2475 years.

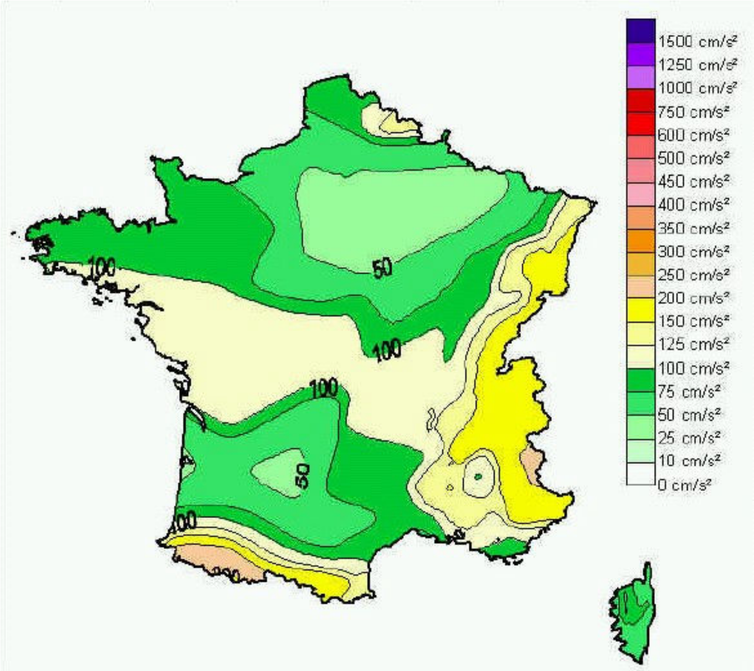

Figure 1. Extract of France probabilistic zonation (unofficial) , PGA for earthquake return period 475 years (GEOTER 2002)

Importance differentiation of structures

The SISROUTE procedure provides local decision-makers a first series of pertinent strategic information that will help them anticipating seismic crisis by reinforcing some elements of the road or by pointing substitution itinerates. The strategic importance of a retaining all may then be highlighted and need to be translated in terms of retrofitting target reliabilities. The target reliability for a given structure is defined by two hypothesis : the strategic importance and the expected lifetime of the structure.

• Reliability differentiation is firstly implemented in the Eurocode 8 by classifying structures into different classes and assigning an importance factor γ_{I0} to each importance class. Wherever feasible, the importance factor should be derived so as to correspond to a higher or lower value of the return period of a seismic event (with regard to the return period) as appropriate for the design for the specific category of structure. If we choose, a rare earthquake (T_{475} = 475 years) as the reference seismic event, we could determine the importance factors as described in the following example. For structures less important than he average, the importance factor is determined as :

$$\gamma_{I0} = \frac{a_{gr}(T_{225})}{a_{gr}(T_{475})} < 1 \tag{1}$$

and for structures more important than the average :

$$\gamma_{I0} = \frac{a_{gr}(T_{2475})}{a_{gr}(T_{475})} > 1 \tag{2}$$

• The specific point concerning seismic retrofit of structures is that the road services may choose the lifetime of the structure after its retrofit. The part 1 of the Eurocode 8 provides a method to calculate the importance factor for a given lifetime of a structure. For a given reference peak ground acceleration, the value of the importance factor multiplying the reference seismic action to achieve the same probability of exceedance in T_L years as in the T_{LR} years for which the reference seismic action is defined, can be calculated with the expression :

$$\gamma_I = \gamma_{I0} \left(\frac{T_{LR}}{T_L} \right)^{-1/k} \quad (3)$$

where k depends on the seismicity but is generally of the order of 3.

The final different levels of reliability are obtained by multiplying the reference seismic action by the global importance factor :

$$a_g\,(T) = \gamma_I\, a_{gr}\,(T) \quad (4)$$

where a_{gr} is the reference peak ground acceleration, and T the return period of the considered seismic event.

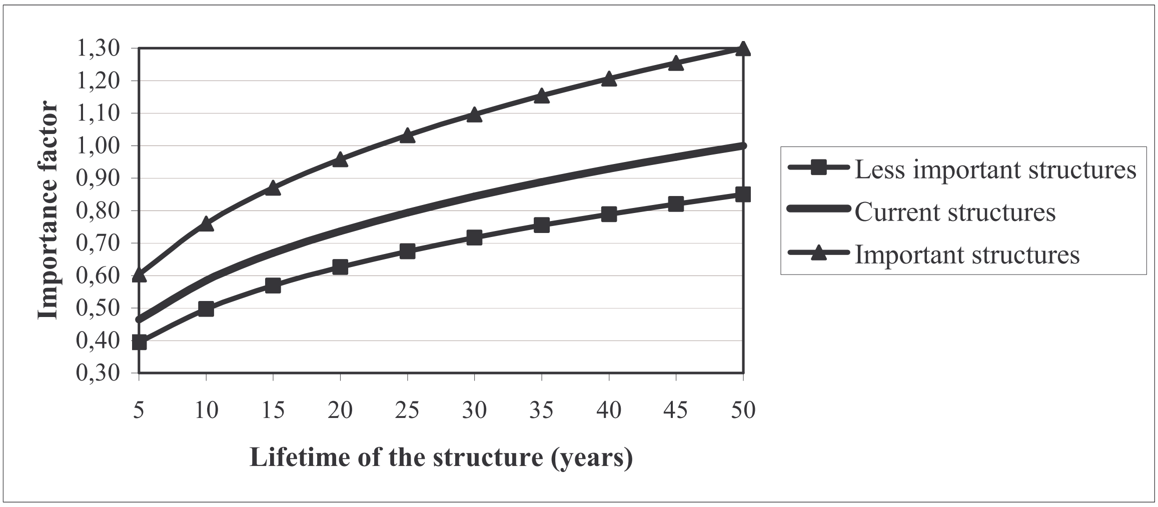

Figure 2. Importance factors

The **figure 2** shows the values of the global importance factors in function of the lifetime and the importance of the structure.

Performance objectives

The appropriate levels of protection are achieved by selecting, for each of the limit states, a design peak ground acceleration. As we already mentioned, the importance factors are generally derived so as to correspond to a higher or lower value of the return period of a seismic event. In this case, each performance objective corresponds to the selection of a return period for the seismic action.

Table 1. Performance objectives

	Performance levels		
Ground motion levels	Damage Limitation (DL)	Significant Damage (SD)	Near Collapse (NC)
Frequent earthquake			Unacceptable
Rare earthquake			
Very rare earthquake	Unrealistic		

Less important structures

Current structures

Important structures

In the **table 1**, for example, a current structure should meet a damage limitation state under a frequent earthquake, whereas an important structure should be able to meet the same damage limitation state under a rare earthquake.

Compliance criteria

Failure modes of retaining walls

The observed damages due to earthquakes are illustrated in the **figure 3** :

- horizontal sliding of the base ;
- tilting of the wall, around the downstream edge of the footing ;
- bearing capacity failure ;
- shear failure of the structure ;
- liquefaction of the foundation soil or the backfill.

The last failure mode is not considered in this study.

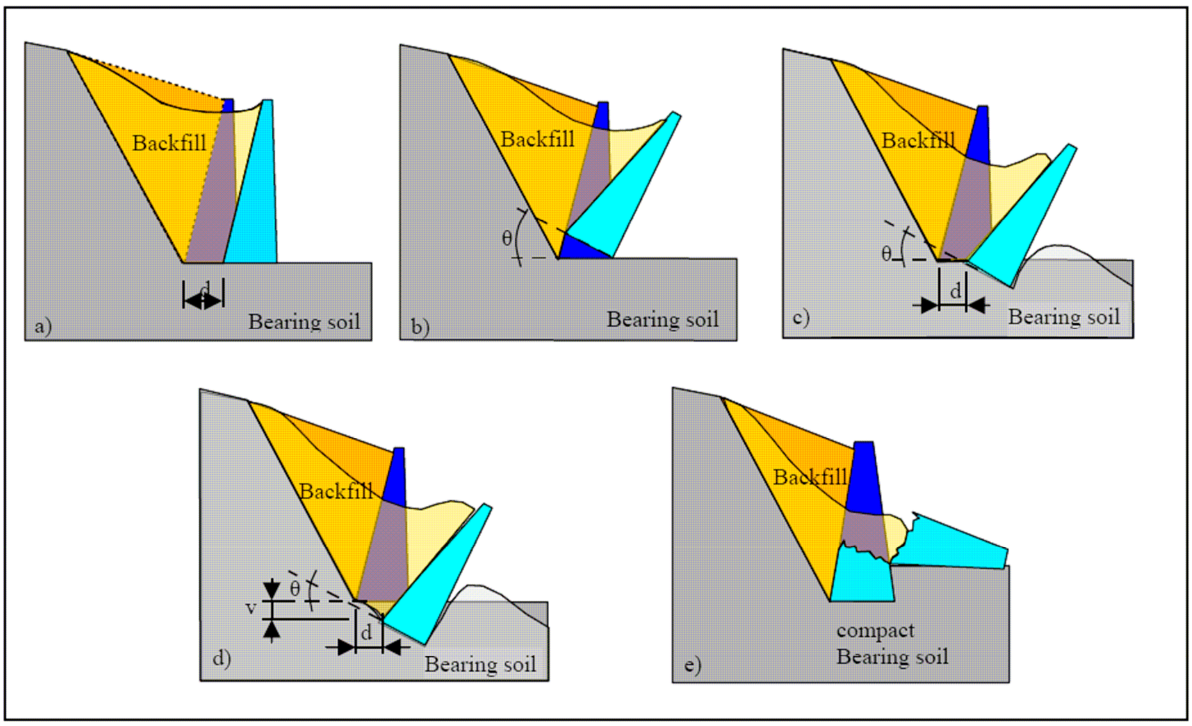

Figure 3. Failure modes of retaining walls

Compliance criteria

For current structures, simplified approaches such as pseudo-static analysis will be used. Generally, according to this analysis, the intensity of equivalent seismic pseudo-static actions depends, on the amount of permanent displacement which is both acceptable for the road serviceability or use and actually permitted by the structure. Under this assumption, every compliance criteria can be expressed as :

$$H(E_d,R_d) \leq 0 \tag{5}$$

and/or as

$$E_d \leq C_d \tag{6}$$

where E_d represents the design value of the effect of seismic action, R_d represents the design value of the resistance to the seismic action and C_d represents the limiting design value of the effect of seismic action.

MODEL UNCERTAINTIES AND BACK ANALYSIS

Back analysis procedure

Let us note on the other hand F the combination of actions applied to the structure, X the vector of materials properties of the model and a the vector of geometrical data of this model. The first step of a retrofitting project consists in making a relevant diagnosis and to elaborate a model allowing to correctly represent the phenomena observed on the site. This model must be then adjusted from the observations raised. In a formal way, the back analysis consists in determining the parameters F^*, X^* and a^* such as :

$$f(F^*; X^*; a^*) = \max_{Df}\{f\} \tag{7}$$

where f is a function representing the reliability of the model towards the observations made on the site and the uncertainties attached to the interpretation of these observations, to the model chosen to reproduce them.

Obviously, there are still degrees of uncertainty on the parameters, which must be taken into account. The **figure 4** illustrates this back analysis procedure.

Uncertainties assessment

Knowledge level on the existing structure

This analysis is adapted from the Eurocode 8 part 3. For the purpose of choosing the admissible type of analysis and the appropriate confidence factor values, three knowledge levels are defined in the Eurocode 8 :

- KL1 : limited knowledge. No detailed construction drawings or geotechnical report are available and limited visual in-situ inspection as been performed. The design of the wall is assumed based on simulated design in accordance with the usual practice at the time of construction.
- KL2 : normal knowledge. Incomplete construction drawings or geotechnical report are available and limited in-situ investigations as been performed or extended in-situ investigation have been performed.
- KL3 : full knowledge . Complete construction drawings and geotechnical report are available and extended in-situ investigation have been performed.

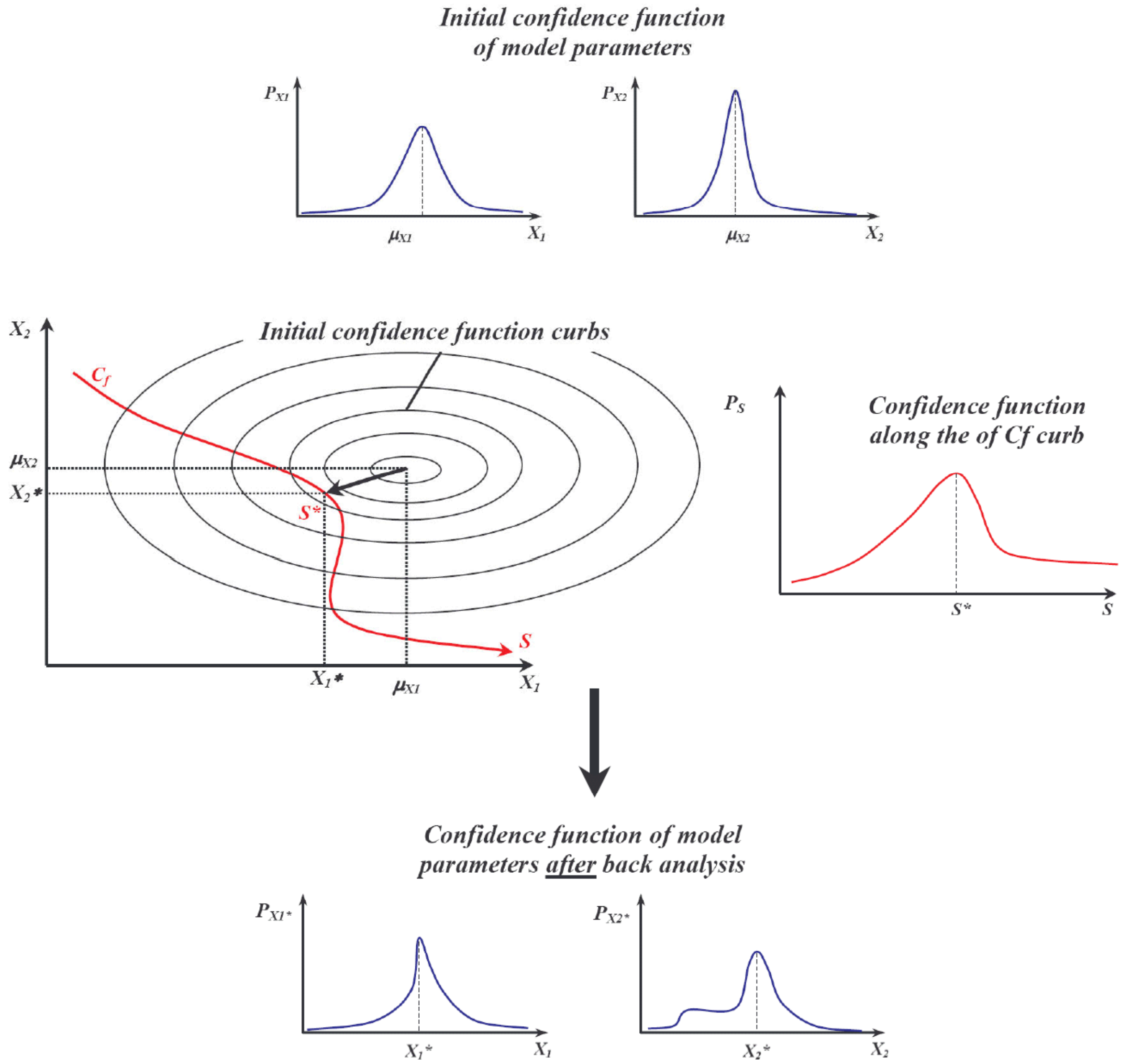

Figure 4. Illustration of back analysis procedure

The engineer regarding a variety of information sources determines these knowledge levels. For example :

- available documentation specific to the structure;
- relevant seismic design (codes, standards, etc.)
- data from field investigations ;
- in-situ and laboratory measurements and tests on the bearing soil or backfill.

Cross-checks should be made between the data collected from different sources to minimise uncertainties. At each knowledge level corresponds a confidence factor CF supposed to quantify the general reliability we have in the model of the structure. In this paper we propose the values CF_{KL1}=1.20, CF_{KL2}=1.10 and CF_{KL3}=1.00.

Confidence factors of geotechnical parameters

After the back analysis, it still exists uncertainties on geotechnical parameters. The optimisation function being non linear, it would be interesting to introduce different confidence factors for each geotechnical parameters. The main idea is to note that if a parameter has a great influence on the optimisation function *f*, we have a good estimation of this parameter after the back analysis. On the contrary, if a parameter has a low influence on the optimisation function, we may still have a great uncertainty on the value of this parameter, even after the back analysis. The mathematical translation of this idea is :

$$\gamma_{M,Xi^*} = 1 + \left(CF_{KL} - 1\right) \frac{\overline{\left| \partial f / \partial X (F^*; X^*; a^*) \right|}}{\left| \partial f / \partial X_i \, (F^*; X^*; a^*) \right|} \tag{8}$$

where $\partial f/\partial X_i$ is the average partial derivative of f in the vicinity of (F^*,X^*,a^*). Of course, if the f function is linear and the influence parameter of each parameter is the same, then the global confidence factor on f is CF_{KL} .In practice, this confidence factor shall be estimated as follows :

$$\left| \frac{\partial f}{\partial X_i} \right| \approx df_{Xi} \equiv \frac{1}{2} \left[\left| \frac{f\left((1+\varepsilon) X_i^*\right)}{f\left(X_i^*\right)} - 1 \right| + \left| \frac{f\left((1-\varepsilon) X_i^*\right)}{f\left(X_i^*\right)} - 1 \right| \right] \tag{9}$$

$$\overline{\left| \frac{\partial f}{\partial X} \right|} \approx \overline{df_X} \equiv \frac{1}{n} \sum_{i=1}^{n} df_{Xi} \tag{10}$$

$$\gamma_{M,Xi^*} = 1 + \left(CF_{KL} - 1\right) \frac{\overline{df_X}}{df_{Xi^*}} \tag{11}$$

where ε is small regarding 1.00 (it shall be chosen from 0.01 to 0.10 for example).

QUANTIFICATION OF STRENGTHENING NEED

The particular difficulty related to the retrofit projects notably lies in the modelling of the interaction between the existing structure and its reinforcement. This interaction depends on:

- the sequences of loadings applied to the structure,
- the different building stages,
- the constitutive laws of behaviour of the material;
- the associated parameters,
- etc.

The modelling of the strengthened structure may sometimes introduce some others parameters, which we shall note *X'* and *a'*. The additional material properties can correspond to new geotechnical parameters, or report the differential behaviour of the same material according to its previous solicitations (during the life of the existing structure for example).

Let us call M1 the model of the existing structure and M the model of the retrofitted structure. The semi-probabilistic format of the Eurocodes is used in the design checking. The compliance criteria for the considered limit state can be expressed as :

$$\gamma_R \, E_M (F_d \,; X^*/\gamma_M^* \,, X'_d \,; a^*, a'_d) \le R_M (F_d \,; X^*/\gamma_M^*, X'_d \,; a^*, a'_d) \tag{12}$$

and/or

$$\gamma_R\, E_M\, (F_d\, ;X^*/\gamma_M^*\, ,\, X'_d\, ;a^*,\, a'_d) \;\leq\; C_M\, (F_d\, ;X^*/\gamma_M^*,\, X'_d\, ;a^*,\, a'_d) \qquad (13)$$

where the d index refers to the design values of the parameters and γ_R corresponds to the model factor of the retrofitted structure. In this model, the γ_M^* parameter enable to take into account the importance factor, but also the evolution of material properties during the lifetime of the structure. Hence, the strengthening need of the structure $N_{strength}$ for the considered limit state shall be defined as follows :

$$N_{strength} = \gamma_R\, E_M\, (F_d\, ;X^*/\gamma_M^*\, ,\, X'_d\, ;a^*,\, a'_d) \;-\; R_{M1}\, (F_d\, ;\, X^*/\gamma_M^*\, ;\, a^*)\, /\, \gamma^*_{R1} \qquad (14)$$

EXAMPLE OF SEISMIC RETROFIT OF A GRAVITY WALL

Presentation

The procedure is detailed in this example. We consider a concrete rigid gravity wall (B=3m, b=1m, h=6m, γ_m=24 kN/m3) , supporting dry cohesionless backfill (β=10°) as shown in **figure 5**. The geotechnical properties of the backfill are φ_r'=30°, c_r'=0 kPa, δ_r=20° and γ_r=18 kN/m3. The geotechnical properties of the bearing soil are unknown. The geological investigations give an important thickness of loose to medium sand so that the category of the foundation soil according to Eurocode 8 is D. In a simplicity concern, only the results concerning the sliding limit state are developed.

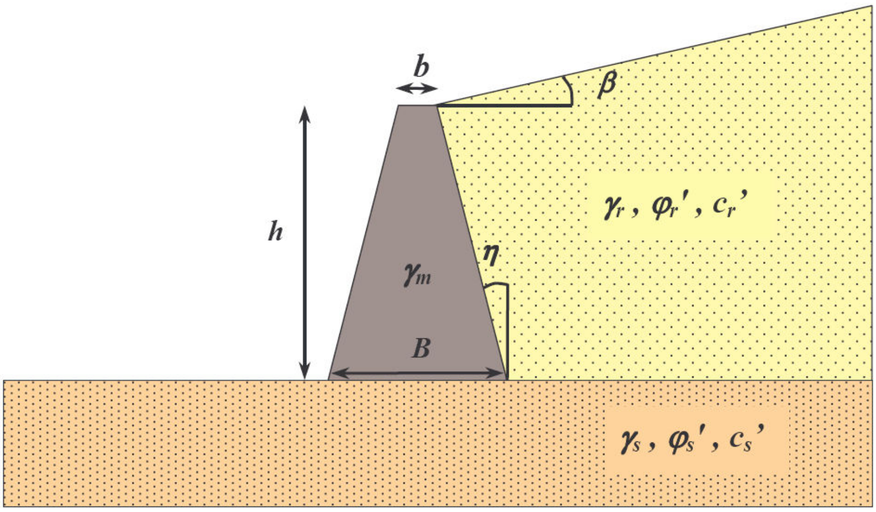

Figure 5. Gravity wall model

The seismic design hypothesis of the retrofitting project is based on a SISROUTE procedure, which lead the administrators to consider that the retaining wall had a current importance for the road section. The design peak ground accelerations, including the importance factors and a 20 years lifetime for the retrofitted structure are given in **table 2**.

Table 2. Design peak ground acceleration

Ground motion levels	a_g (m/s^2)
Frequent earthquake	1.25
Rare earthquake	1.50
Very rare earthquake	2.00

Passive (α=10°) are considered in this example for the retrofitting project. The performance objectives of the retrofitted structures are detailed in the **table 3**.

Table 3. Performance objectives

Ground motion levels	Horizontal displacement *(mm)*	Strain in the anchor (Mpa)
Frequent earthquake	10.0	2/3 σ_{el}
Rare earthquake	20.0	σ_{el}
Very rare earthquake	30.0	1.05 σ_{el}

As we can see, we admit some limited damage, i.e. an incursion in the plastic area, of the passive anchor for very rare earthquake levels.

Back analysis and uncertainty assessment

The back analysis is based on the assumption that the static sliding safety factor of the wall calculated from the Coulomb theory is 1.50. The friction angle between the wall's footing and the foundation soil getting from a back analysis is δ_r = 27.1°. We shall now develop the procedure used to calculate the confidence factors. If we assume that the global confidence factor of the model is taken as CF=1.10, then, we can evaluated a set of confidence factors for each material parameters. The following table gives the results of this calculation.

Table 4. Confidence factor for each parameter

Parameter	df_X	γ_X
tan φ_r'	1.27	1.08
tan φ_s'	1.26	1.08
γ_r	0.81	1.13
γ_m	0.81	1.13

Seismic retrofit design of the retaining wall

The retaining walls can't sustain performance levels required under seismic loadings. Inclined passive anchors (α=10°) with a L=10 m free length are considered in this example for the reinforcement of the structure against sliding on his base. The Mononobe-Okabe method is used to evaluate the dynamic earth pressure on the wall. The horizontal strengthening need of the gravity wall can be deduced from equation 12 and with a calculation of the displacement of the anchors compared to the performance objectives (table 4). Considering a model factor of 1.125 for the pseudo-static analysis, we have :

Table 5. Design horizontal strengthening need

Ground motion levels	Horizontal strengthening need *(kN/ml)*
Frequent earthquake	37.7
Rare earthquake	52.9
Very rare earthquake	102.3

We consider a thickness loss of steel (500 S) from corrosion of 2 mm during the lifetime of the retrofitted retaining wall, a ϕ=40 mm diameter positioned every 2.25 m. The maximum displacement δ_{max} are calculated as follows :

$$\delta_{max} = \frac{H}{k_H} \tag{15}$$

where H is the horizontal force applied to the anchor and k_H the horizontal stiffness of this anchor.

$$k_h = E\frac{S}{L}cos\,\alpha \ . \tag{16}$$

As we can see in the **table 6**, the performance levels defined by the road manager are met for this seismic retrofitting solution.

Table 6. Design effective performance

Ground motion levels	Horizontal displacement *(mm)*	Strain in the anchor (Mpa)
Frequent earthquake	9.5	190
Rare earthquake	13.4	267
Very rare earthquake	25.8	517

CONCLUSION

This paper presents a simplified procedure for the seismic engineering retrofitting of retaining walls based on performance-based design. Uncertainties assessment is included in the first step of the method corresponding to back analysis of the structure. This method enables to calculate the strengthening need of retaining walls according to the remaining lifetime of the structure and the importance of the structure determined according to a strategic analysis on the whole road section (SISROUTE). After a theoretical and methodological presentation, this method is illustrated by a numerical example.
The procedure will be applied on an experimental basis in 2007 on a road located in the Maritime Alps. This test will be a first opportunity to calibrate the confidence factors. Furthermore, this general procedure shall be extended to dynamic analysis methods.

AKNOWLEDGEMENTS

We gratefully acknowledge the Laboratoire Central des Ponts et Chaussées and the Service d'Etudes Technique des Routes et Autoroutes for their financial support.

REFERENCES

Okabe S. "General theory of earth pressure and seismic stability of retaining walls", J. Japan Civ. Engrg. Soc., 10(6), 1924

Mononobe N. and Matsuo H. "On the determination of earth pressure during earthquakes", Proc., World Engineering Congress, Vol 9, 177-185, 1929

Franklin A. G. and Chang, F. K., "Permanent displacements of earth embankments by Newmark sliding block analysis", Rep. 5, Misc. Paper S-71-17, U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Miss., 1977

Despeyroux J., Godefroy P., "Nouveau zonage sismique de la France en vue de l'application des règles parasismiques de construction et de la mise en oeuvre des plans d'exposition aux risques", La documentation française, Paris, 1986.

Eurocode 8 – Design of structures for earthquake resistance, 2005

Criado D., Thibault Ch. "SISMUR, a tool for the evaluation of the seismic risks on existing retaining walls", First European Conference on Earthquake Engineering and Seismology, Geneva, 2006

Duval A. M., Bertrand E., Renou C., Marchand P., Davi D., Criado D., "SISROUTE, earthquake scenario generation system along roads – global concepts and hazard assessment", First European Conference on Earthquake Engineering and Seismology, Geneva, 2006

Veylon G., "Quantify the strengthening need of geotechnical structures", Ultimate Limite State Symposium, France, 2006