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PROBABILISTIC-BASED STRUCTURAL SAFETY ANALYSIS OF CONCRETE DAMS

PhD thesis work plan of Renato Pereira

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Abstract

The construction and operation of dams, associated with the use of water resources, aim generically at the energy producing, water supplying and, in some cases, flow regulating and flood controlling.

Considering the dam dimensions and the potential risks associated with its collapse, due to the occupation of the downstream valley, and to the costs of the construction, maintenance and rehabilitation, the use of probabilistic principles in its design, as it is already performed for other type of structures, is justified.

With this thesis work plan, it is intended to establish a methodology for the structural safety analysis of concrete dams based on the definition of safety evaluation criteria, considering the partial safety factors obtained through structural reliability analysis. For that purpose, the uncertainties involved in the safety of concrete dams shall be statistically quantified, through the definition of probabilistic distributions for loads and material properties, using, in addition to the elements found in the literature, the information available at LNEC about those features, resulting from the monitoring of the concrete dam behavior during the construction, first filling and operation periods. Later, the partial safety factors shall be calibrated analysing the outcomes of the structural reliability analysis performed to models of concrete dams, representative of the standard solutions for different design situations.

It is expected that this work contributes to the discussion on the design criteria of concrete dams and can be integrated into future revisions of the Portuguese dam safety regulation.

Keywords: Concrete dams / Uncertainty quantification / Probabilistic safety analysis / Partial safety factors

ANÁLISE PROBABILÍSTICA DA SEGURANÇA DE BARRAGENS DE BETÃO

Plano da tese de doutoramento do bolseiro de doutoramento Renato Pereira

Resumo

A construção e exploração de barragens, que está associada ao aproveitamento dos recursos hídricos, visa essencialmente a produção de energia e o abastecimento de água às populações e, em alguns casos, a regularização de caudais e o controlo de cheias.

Por serem obras de engenharia a que estão associados consideráveis riscos potenciais, principalmente relacionados com a segurança das populações no vale de jusante, mas também aos custos de construção, manutenção e reabilitação, justifica-se que as barragens sejam dimensionadas considerando níveis de segurança adequados, sendo que tal pode ser conseguido, com vantagem, usando princípios probabilísticos, à semelhança do que já acontece correntemente com outros tipos de estruturas.

Com este plano pretende-se estabelecer uma metodologia de avaliação da segurança estrutural de barragens de betão, nomeadamente a definição de critérios de verificação da segurança, através da utilização de coeficientes parciais de segurança definidos a partir da análise da fiabilidade estrutural. Começa-se com uma contribuição na caracterização estatística das incertezas envolvidas na segurança de barragens de betão, através da definição de distribuições de probabilidade de ações e resistências, recorrendo-se, para além dos elementos disponíveis na literatura técnica e científica afim, à informação disponível no LNEC resultante do acompanhamento e monitorização do comportamento deste tipo de estruturas, e prossegue-se com a calibração de coeficientes parciais de segurança, aplicando metodologias robustas de análise da fiabilidade estrutural a modelos de barragens de betão representativos de soluções padronizadas para as diferentes situações de projeto. Afigura-se que o conhecimento a criar possa influenciar os critérios de projeto de barragens de betão e ser integrado em futuras revisões da regulamentação portuguesa de segurança de barragens.

Palavras-chave: Barragens de betão / Quantificação das incertezas / Análise probabilística da segurança / Coeficientes parciais de segurança

List of contents

List of figures

List of tables

1 | Introduction

1.1 Overall framework

This document is an updated version of the research plan for the doctoral thesis of the doctoral fellow Renato Miguel Rodrigues Pereira. The initial research plan was submitted to the Science and Technology Foundation (FCT) during the *2012 call for PhD Studentships, PhD Studentships in Industry and Post-Doctoral fellowships*. The work programme started in September 2013. After two years of work, it was considered convenient to present this update version of the research plan.

The fellow concluded his masters in Civil Engineering (structures) in January 2012, at the Faculty of Science and Technology of the New University of Lisbon (FCT-UNL). The master's thesis focused on the probabilistic-based safety assessment of concrete gravity dams sliding (Pereira; 2012).

To better understood the performance of concrete dams, since the beginning of the studentship, in September 2013, the fellow has been involved in the development of studies related to the behaviour analysis and interpretation during the first filling and the first operation phase of the Rebordelo dam (LNEC, 2014). The fellow submitted two papers (Pereira; *et al.*; 2014, 2015) on the probabilistic analysis of concrete gravity dam sliding safety to the *5as Jornadas Portuguesas de Engenharia de Estruturas* (JPEE2014), in 2014, and to the *Second International Dam World Conference* (DW2015), in 2015.

The fellow has also been working on the tasks associated with the uncertainties characterization and modelling. On this subject, two reports about the probabilistic characterization of the uplift pressures in concrete dam foundations and the reservoir water level in normal operation conditions, currently under revision, were produced (LNEC; 2016a, 2016b).

This worked is funded by the FCT under grant and is hosted by the Concrete Dams Department (DBB) of the National Laboratory for Civil Engineering (LNEC).

1.2 Theme justification

The use of water resources, including the dam operation, is of great importance for water supply, energy production and flood control.

The dam safety at the design phase is, in Portugal, assessed according to the Portuguese dam design codes (NPB; 1993). Although considering partial safety factors applied to the resistance parameters, these standards, which complement the Portuguese dam safety regulation (RSB; 1990), and later revised in 2007 (RSB; 2007), as well as most of the international codes (Ruggeri; 2004), are based on the global safety factors method. This method, extensively used in the past, is based on expert judgment and historical approach which leads to different safety levels, considering the conditioning actions and the relevant failure modes (Ditlevesen; Madsen; 1996, Melchers; 1999).

However, the probability of failure under extreme events cannot be inferred solely from experience, in particular when the consequences of failure are perceived to be unusually severe. Rather, the structural reliability theory provides a link between the practice of structural engineering and its consequences. In fact, the risks associated with the dam collapse, due to the occupation of the downstream valley and to the loss of operability of this type of structures, justify its design using probabilistic principles.

The probabilistic-based design codes are based on what is referred as the semi-probabilistic format of the structure safety evaluation which is considered as a consistent simplification of fully probabilistic methods (Ditlevesen; Madsen; 1989, Sorensen; *et al.*; 1994, JCSS; 2001, Faber; Sorensen; 2002, Vrouwenvelder; 2008).

The main objective of this thesis is to quantify the uncertainties involved in the dam safety and, performing a probabilistic-based structural safety analysis of concrete dam designed according to the modern practice, draw up a semi-probabilistic format of the dam safety evaluation.

1.3 Integration in the LNEC research thread

The reliability analysis of civil engineering structures gained importance a few decades ago in Portugal as well as over the world. LNEC, as a consequence of the work of its researchers, especially the Engineer Júlio Ferry-Borges (Ferry-Borges; Castanheta; 1968), during its mandate as chairman of the Joint Committee on Structural Safety (JCSS), was a main developer of this approach.

The probabilistic-based design has been, since the creation of JCSS, the main tool to satisfy the societal demand for safety and economy. This approach led to the publication of Eurocodes, based on a semi-probabilistic format of the structure safety evaluation which is considered as a consistent simplification of fully probabilistic methods. However, the concrete dam design is outside the scope of the Eurocodes due to concrete dam scientific community distrust about its applicability.

Partly due to the reference made in the Eurocodes to safety assessment methods of geotechnical structures, the risk analysis in embankment dam design has been increasingly discussed. On this subject, a research programme about the application of concepts associated with the risk analysis to embankment dams was elaborated (Caldeira; 2005). Also Pimenta (2008) address the risk approaches in the field of embankment dams and contributed to develop methodologies for the use of risk assessment, proposing risk evaluation criteria and a new risk analysis method based on risk indexes. This method was applied to 36 Portuguese embankment dams in operation.

In this thread, a general analysis of concrete dam safety based on a probabilistic approach is needed to clarify its potential and suitability. LNEC, as an entity with responsibilities in the safety evaluation, should be pioneer on this matter. Moreover, the dam safety regulation (RSB; 2007) has been periodically revised and it is of LNEC’s interest present a sustained technical point of view.

Aware of the importance of this subject, a research programme (Ramos; 1994) about the reliability and monitoring of concrete dams was done, in order to develop new models to assess their functionality and safety, especially in cases where deterioration phenomena have been recorded.

In fact, the monitoring of dams during its construction, reservoir first filling and operation, one of the activity fields of LNEC in the last decades, has been the main tool to support decisions and to assess the structural safety of concrete dams. Furthermore, the data collected can now be used to quantify the statistical representation of the main features associated with the Portuguese dam operation conditions.

Also the availability of numerical models in LNEC, allowing the safety assessment and the prediction of its future behaviour and providing a powerful tool in regarding preventive and rehabilitation measures, can be used to simulate the dam behaviour up to failure.

The thesis work is integrated in the on-going research project “ReliConDam”, established in DBB/LNEC.

2 | Probabilistic-based safety analysis of concrete dams

2.1 General considerations

The use of probabilistic methods in code development is a consequence of several decades of structural reliability research (Elingwood; 1994). The second half of the last century was a period of theoretical development when the concepts of the classical structural reliability emerged (Elingwood; 1994). In the late 1960's there was a convergence between the theoretical reliability community and the design/standards community, leading to the first use of reliability methods (Cornell; 1969), the notion of reliability index as an alternative quantitative measure of safety and the concept of separating the sources of uncertainty, namely the randomness and the modelling error (Elingwood; 1994).

During the last decades, there has been an increase on society's concern about welfare, safety, sustainability and economy. Engineering structures aims to improve the quality of life, either in terms of financial return or in terms of personal wellbeing (Schneider; 1997). Therefore, the decision making process, prior to design, should be based on the assessment of the benefit during the working life. Although varying from individual to individual, on a societal level, benefit is normally understood as being economically efficient provided that given requirements in regard to the safety and to the effects on the environment are fulfilled (Faber; 2005). Ultimately, during design, what engineers look for is the optimal solution that increases the benefit. Due to the uncertainties related to safety and costs, this optimal solution depends on the probabilities and the consequences that something wrong happen. The product between these two factors is denoted risk.

Risk-based analysis in civil engineering has gained increasingly importance. The public demand for safety and sustainability led to, during the seventies, the creation of the Joint Committee on Structural Safety (JCSS), aiming at improving of the general knowledge about structural safety. The Committee published, a few years later, the probabilistic-based model codes (JCSS; 2001), being the basis for new European Standards, the Eurocodes (EN1990; 2002). In these standards, the reliability theory is considered as the appropriate design tool for structures. However, to keep the design process practicable, the probabilistic methods were translated into a verification process on the basis of partial safety factors (Vrouwenvelder; 2008). Nevertheless, the scope of the Eurocodes is related to other type of structures than concrete dams. Several factors contributed for it, for instance, there have been few dam failures in recent years which does not allow to evaluate directly the probability of failure, as the dam building era was coming to an end (Westberg; 2010), or the determination of the probability of failure for dams is a complex task that is often not readily accomplished in a scientific way with the current state of knowledge (Donnelly; 2006). In practice, the dam safety has been based on the traditional standards-based approach, using qualitative principles relying on the experience and the engineer judgment. The safety is guaranteed by taking conservative values for the loads and the resistances and applying global safety coefficients. Although this strategy has proven to be quite effective, depending on the nature of the problem and the level of experience of those involved in the decision-making process, it is difficult to ensure the same risk levels for different hazards scenarios (Donnelly; 2006).

In the following sections, the scope of risk analysis in concrete dam design, an overview through the safety evaluation methods, the Portuguese dam design codes principles and studies carried out recently about the probabilistic assessment of concrete dams are addressed.

2.2 Risk analysis in concrete dam design

2.2.1 General considerations about risk

Although it is commonly related to probability, risk should be understood as the damage of a certain event (Schneider; 1997). Thus, risk, *R*, is defined by the existence of a hazardous event that has a probability of occurrence, *P*, and the gravity of the consequences of such event, *C* (Schneider; 1997, Melchers; 1999, Faber; 2005, Lemaire; 2009). In civil engineering structures, if the undesirable event is the failure of a structure, the risk is given by,

$$\mathrm{R}=\mathrm{P}(\mathrm{failure})\cdot\mathrm{C}(\mathrm{failure}) \tag{1}$$

According to this definition, risk can be measured by costs, life losses or environmental impact (Ditlevesen; Madsen; 1996, Schneider; 1997, Melchers; 1999, Faber; 2005). In a case which multiple independent failure modes are associated with different potential consequences, the risk is given by the sum of the products between probabilities and consequences (Faber; 2005),

$$\mathrm{R}=\sum_{\mathrm{i}}\mathrm{P}(\mathrm{failure})_{\mathrm{i}}\cdot\mathrm{C}(\mathrm{failure})_{\mathrm{i}} \tag{2}$$

In dams' design, as the risks are normally associated with non-usual scenarios or events, it is important to be able to quantify either the probability or the frequency of occurrence of such scenarios, and this, in general, needs a probabilistic modelling involving conditional probabilities or frequencies respectively (JCSS; 2008). Therefore, if the event is the failure of a dam, the probability of failure depends both on the probability or frequency of the occurrence of an extreme scenario and the probability of failure conditioned to its occurrence (USBR; 2001). The expression (2) can be re-written as,

$$\mathrm{R}=\sum_{\mathrm{j}}\mathrm{P}(\mathrm{event})_{\mathrm{j}}\cdot\sum_{\mathrm{i}}\mathrm{P}\left(\mathrm{failure}|\mathrm{event}_{\mathrm{j}}\right)_{\mathrm{i}}\cdot\mathrm{C}(\mathrm{failure})_{\mathrm{i}} \tag{3}$$

where $P(event)_j$ is the probability or frequency of the occurrence of the loading scenario *j* and $P(failure|event_j)_i$ is the probability of failure, related to the failure mode *i*, conditioned to the occurrence of such event.

The risk analysis procedure for the construction of new dams may be described as the following:

- Selection of the design solution: an initial hypothesis for the dam is tested;
- Assessment and quantification of the hazard scenarios: identification of the loading state corresponding to each hazard scenario;

- Analysis of probabilities: quantification of the probability of the structural failure under a specific loading scenario;
- Analysis of consequences: assessment of the consequences of the dam failure, characterizing it both in probabilities and damage;
- Risk assessment: this step can approve or reject the design solution, leading to the consideration of the selected solution or the selection of other design solution, respectively.

2.2.2 Hazard scenarios identification

The hazard identification should lead to the characterization of a range of possible scenarios as wide as possible. Therefore, the scenarios can be qualitatively ranked, and the quantification of the risk can sometimes be limited to those hazards giving the highest level of risk (Westberg; 2010). According to Faber (2005), this process is called critical risk scenarios identification.

According to Ruggeri (2004), in most of EU countries, reference is made to three levels of loading combinations: usual, unusual and extreme. However, in Portugal, as well as in Spain, reference is made to two levels of loading combinations: usual or normal and exceptional or abnormal (Ruggeri; 2004).

Usually, the three following loading scenarios are generically accepted in the most of the dam design guidelines (Ruggeri; 2004):

- Usual loading scenarios: these involve a range of possible events which may occur during the dam lifetime, for instance, the normal operation hydrostatic pressures, loss of effectiveness of the installed equipment (drainage system, gates, etc), static or dynamic loads generated from the use of external equipment, among others;
- Flood loading scenario: this corresponds to the effects of a flood on the safety of the structure. It is related to the entrance hydrograph in the reservoir and the effectiveness of the discharge equipment. According to that, the reservoir elevation is associated with the flood return period;
- Earthquake loading scenario: this corresponds to the effects of an earthquake on the safety of the structure. It should be based on the information about the frequency of occurrence, the location and the intensity of an earthquake. It is normally taken into account by accelerograms or response spectra associated with the seismic action return period.

For the first loading scenario it is usually required that the structure suffers no damage (identical to the serviceability limit states definition (EN1990; 2002)). For the two last loading scenarios the structure should not fail (identical to the ultimate limit states definition (EN1990; 2002)). These scenarios are generically defined in the dam design guidelines (NPB; 1993, CFBR; 2012, USACE; 1995, USBR; 1976, Ruggeri; 2004).

2.2.3 Quantification of the probability of failure

The structural safety evaluation, i.e. the quantification of the probability of failure, is the main purpose of this study. In order to do that, the hazards scenarios will be considered according to the Portuguese dam design guidelines (NPB; 1993), which follow the recommendations of the ICOLD (2005).

The range of methods available to evaluate the structural safety can generically be divided into (Membrillera; 2007, USBR; 2003, Ditlevsen; Madsen; 1996):

- Probabilistic quantitative analysis: in this method the information about the sources of uncertainty are taken into account. It is usually classified as the most reliable and appropriate method. It incorporates techniques like the event trees and the reliability analysis;
- Expert judgment: the probability of an event is based on specialist opinions;
- Historical approach: the probability of failure is computed using historical information on dam failures. Although each dam is a unique and distinct structure, if the dam population is large enough, this method can be reasonably accurate considering the failure cases and the ageing of dams. This technique is based on the empirical or frequentist definition of probability (Schneider; 1999);
- Classical deterministic approach: considering deterministic values for each variable, the safety is assessed through a safety margin, or a global safety factor, given by the relation between resistance and loads.

The methods of structural reliability analysis are presented in detail in section 2.5.

2.2.4 Analysis of consequences

In a risk analysis context both the direct and indirect consequences should be considered. Generally, concerning to a dam failure, the potential damage in the downstream valley should be probabilistically quantified taking into account the duration and the magnitude of the failure effects (Bowles; 2001, Bowles; *et al.*; 2005).

As mentioned before, the consequence of a hazardous event can be given by costs, loss of lives or environmental impact per year (Ditlevesen; Madsen; 1996, Schneider; 1997, Melchers; 1999, Faber; 2005). If the dam suffers damage during a normal operation scenario, the consequence is usually taken in costs of reparation or rehabilitation. If the dam collapses, the consequence is measured either in costs or number of life losses.

In the design codes, simplifications must be made allowing easier but substantiated safety verification. In that sense, the structures, including the dams, are usually grouped into consequence classes, ensuring that the potential risks of a failure fulfil the acceptance criteria (NPB; 1993, CFBR; 2012).

2.2.5 Risk assessment

The risk assessment is merely a comparison of the estimated risks given by the expression (3) with the accepted risks initially stated in the risk acceptance criteria (Faber; 2005).

As stated by Faber (2005), the acceptance limits for a given disaster are usually originate from three different angles:

- Individual acceptable level of risk;
- Societal acceptable level of risk;
- Economic criteria.

According to that, these criteria may vary from culture to culture as the understanding of risk and the acceptable risk values depend on the affected population and country (Bowles; 2001). This is the reason why the safety criteria in international guidelines should not be used in other countries practice as the acceptance of risk may vary (Westberg; 2010).

For instance, in Figure 2.1, the ANCOLD recommendations (ANCOLD, 2003), which have been extensively referred (Membrillera; 2007, Altarejos; 2009), for the societal acceptable risks, are presented.

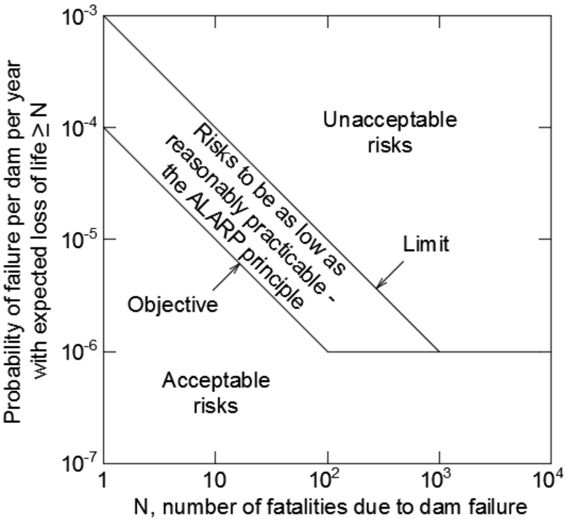


Figure 2.1 – ANCOLD societal risk criteria for dams (ANCOLD; 2003)

In the design codes, the safety evaluation criteria should incorporate both the hazard scenarios and the consequences of failure. Thus, the failure can be assessed using the definition of reliability index. In this study, the risk at the design stage is addressed. Furthermore, the target safety index, which fulfils the risk acceptance requirements, can be calibrated to existing practice, assuming that the existing practice is optimal (Westberg; 2010). This can be accepted considering that if structures designed according to the existing practice failed too often, the design criteria would have been changed quickly (Westberg; 2010).

2.2.6 Framework of the dam design codes

The dam design codes (USBR; 1976, USACE; 1995, NPB; 1993, CFBR; 2012, Ruggeri; 2004) establish that the safety evaluation should be performed concerning to two major hazard events: flood and earthquake.

The possible loading combinations are then considered according to the hazard events. Usually, the most critical loading combinations are (CFBR; 2012):

- Extreme hydrostatic combination: the dam must not fail under the loads caused by a flood associated with a specific return period;
- Accidental seismic combination: the dam must not fail if the maximum design earthquake (MDE) occurs during its normal operation. The seismic action is considered an accidental action whose magnitude varies according to the return period and the dam location.

In the design codes, it is also required that during the dam normal operation period the service loads must not cause important structural damage.

As mentioned before, the design guidelines are based on simplifications of the risk analysis procedure. Consequently, the dams are divided into classes of consequences, according to the potential risks downstream. Also the return period of either the flood or the earthquake is set according to the importance of the structure. Thus, the verification of explicit criteria, such as, e.g., allowable stresses or sliding stability criteria, ensures an acceptable design.

The main question that arises is how such criteria are formulated. A deterministic safety criterion, based on experience and experts' judgement, may not guarantee the risk acceptance criteria, in contrast to a probabilistic-based approach.

According to Altarejos (2009) and Membrillera (2007), the Spanish guidelines state that the risk analysis should be taken explicitly. In this case, the simplifications made in the design codes lose its meaning and two different dams will have, certainly, different characteristics to fulfil the risk acceptance criteria. This is the ideal approach, however, the design process becomes too complex.

Ruggeri (2004) refers that the Chinese standards apply a semi-probabilistic approach, distributing the uncertainties among various partial safety factors applied to the loads, material properties, etc. Also the new French guidelines (CFBR; 2012) uses concepts issued from the semi-probabilistic approach.

Although indicates partial safety factors applied to the material properties, the Portuguese dam design codes (NPB; 1993), as well as most of the international codes (Ruggeri; 2004), still used the global safety factor method. This method was extensively used in the past and is based mainly on the expert judgment and the historical knowledge (Elingwood; 1994, Schneider; 1997).

2.3 Safety evaluation methods

2.3.1 Concepts of safety and reliability

The society expects that the users of the structures and people in their vicinity be safe. In this sense, safety is a qualitative term and is not related to the safety of the structure but rather to safety of the people in its area of influence, as opposed to the term risk (Schneider; 1997).

When related to a structure, the correct term is reliability. Reliability is defined as the probability that a structure will perform its function for a specific period of time (Schneider; 1997). Thus, regarding the failure, a structure should be considered reliable if the probability of failure is smaller than a maximum allowed value, which depends on the acceptable risks. The maximum allowed probability of failure is actually the target value of the design codes. According to this definition, the reliability, r, is defined at the complement of the probability of failure (Schneider; 1997), p_f,

$$r=1-p_f \tag{4}$$

The main difference between these two terms is that safety is a qualitative term and reliability is a quantitative term that can be measurable (Schneider; 1997). However, structural reliability and structural safety are terms commonly used in practice with the same meaning.

2.3.2 Uncertainties in reliability analysis

The engineering problems are intrinsically uncertain. The variables involved in the concrete dam structural analysis, representing physical features, are naturally uncertain. Other sources of uncertainty can be pointed out in typical structural analysis: the methods used, the models admitted, the simplifying assumptions taken, etc. are approximations of the reality and also introduce uncertain into structural problems (JCSS; 2001).

The uncertainties from all essential sources must be considered as basic variables. The basic variables may be random variables, stochastic processes or random fields (JCSS; 2001). Usually, the types of uncertainty considered are (Thoft-Christensen; Baker; 1982, Faber; 2005):

- Inherent or natural random uncertainty;
- Statistical uncertainty due to sparse information;
- Uncertainty due to inadequate knowledge or simplifications (model uncertainties).

Paté-Cornell (1996) and Kiureghan and Ditlevesen (2008) also distinguish between aleatory and epistemic uncertainty. Aleatory uncertainty is the intrinsic randomness of a phenomenon, while epistemic uncertainty is caused by lack of knowledge. Meaning that, aleatory uncertainty cannot be reduced.

When applied to the engineering problems, the statement "*All in the future is uncertain*" (Lindley; 2006) is quite appropriate. In the design of new structures, the knowledge, and consequently the uncertainty, is based on statistical information and probabilistic modelling available prior to the operation of the structure (Faber; Stewart; 2003). In this phase, the variable uncertainties are modelled with the so-called *a priori* distributions. Later, the monitoring, testing and observation of a structure during its construction and normal operation may reduce the uncertainties, adjusting each uncertainty representative distributions to the real information, i.e, *a posteriori* distribution.

2.3.3 Classical deterministic-based approach

The classical deterministic approach was extensively used in the design of civil engineering structures during the previous century (Elingwood; 1994, Schneider; 1997, Faber; 2005).

Taking the simplest example, the structural safety criterion is verified if the resistance, *R*, is greater than the loads, *S*,

$$\mathrm{R} \geq S \tag{5}$$

In this case, the structure might fail if the resistance is lower than anticipated or if the loads are greater than predicted. Although engineering science is not able to predict the loads and resistance with certainty (Elingwood; 1994), in this approach both resistance and loads are considered as deterministic values. In view of the uncertainties, the design codes needed a tool to minimize the risk of failure (Ponslet; 1994). This led to the use of the factors of safety, or safety margins, given by,

$$\mathrm{FS} = \mathrm{R}/\mathrm{S} \tag{6}$$

The factor of safety (*FS*) was scaled to given values which were expected to absorb the scatter of the random parameters and guaranteed adequate performance or safety of the system (Ponslet; 1994). Other approach is to estimate the loads conservatively, calculate the stresses from these loads and then design the structure so that the stress is less than a fraction of the stress at which a failure occurs (Elingwood; 1994). In this case, the factor of safety is given by,

$$\mathrm{FS} = \mathrm{f_k}/\mathrm{F_k} \tag{7}$$

where f_k is the stress due to applied loads and F_k is the limit stress. This is the basis of the widely-applied allowable stress design.

Hoek (2007) refers that a technique which is frequently taken to give a more rational assessment is a sensitivity study based on the factor of safety. This involves a range of calculations in which each significant parameter is varied systematically in order to determine its influence upon the factor of safety. Unless the variation of each significant parameter follows a probability distribution truly representative of its uncertainty, this technique cannot be considered as based on probabilistic principles. Moreover, it does not allow the computation of the probability of failure.

2.3.4 Probabilistic-based approach

Although some standards explicitly establish the risk analysis to prevent and limit the potential risk – for instance, as far as dam design is concerned, the Spanish guidelines (Ruggeri; 2004, Altarejos; 2009) – the authorities usually prefer a design based on specific conditions and a standardized code. The probabilistic-based design codes are based on what is referred as the semi-probabilistic format of the structure safety evaluation which is considered as a consistent simplification of fully probabilistic methods (Ditlevesen; Madsen; 1989, JCSS; 2001, Faber; Sorensen; 2002, Vrouwenvelder; 2008).

The first clause of the Eurocodes (EN1990; 2002), the main references as semi-probabilistic design codes, clearly state that the objective of the probabilistic-based design is to design and execute a structure in such a way that it will, during its intended life, with appropriate degrees of reliability and in an economical way, sustain all actions and influences likely to occur during execution and use, and remain fit for the use for which it is required.

The Eurocodes are based on the concepts of limit states and partial safety factors. Unlike the allowable stress design concept, the limit state is the demarcation between desired and adverse states of the structure (Vrouwenvelder; 2008) regarding to different failure modes (Faber; Sorensen; 2002). Two main groups of limit states are currently used: ultimate and serviceability limit states are associated with the collapse and the usefulness of a structure, respectively.

The process of calibrating the semi-probabilistic design codes begins with reliability analysis, regarding a limit state function, replacing the characteristic values (previously established) of the resistance and loads by basic random variables (Faber; Sorensen; 2002). Later, the partial safety factor may be derived from the design values of the basic random variables.

In this approach, the loads are accounted for by its effects, *E*, rather than the loads value. Therefore, the general formulation of the Eurocodes (EN1990; 2002) for the partial factor limit state requirement (Vrouwenvelder; 2008) is given by,

$$\mathrm{R}(\sum \mathrm{X_k}/\mathrm{Y_k})=\mathrm{E}\left(\sum \mathrm{G_k}\cdot\gamma_\mathrm{G}+\sum \mathrm{Q_k}\cdot\gamma_\mathrm{Q}\cdot\varphi\right) \tag{8}$$

where X_k, G_k, Q_k and γ_X, γ_G, γ_Q are the characteristic values and the partial safety factors of the material properties, permanent and variable loads, respectively, and φ are the combination factors.

The partial safety factor method takes the substantial uncertainties into account by applying partial safety factors to the respective parameter. Performing a probabilistic-based evaluation, the partial safety factors are determined such that the difference between the reliability for the different structures of the same consequence class and the target reliability level is minimized (Sorensen; *et al.*; 1994).

2.4 Portuguese dam design codes

2.4.1 Scope of application

The Portuguese dam design codes (NPB; 1993) establishes the principles of dam design, aiming at the proper implementation of the Portuguese dam safety regulation (RSB; 1990) which was later revised (RSB; 2007). The scope of application of the RSB is limited to dams with:

- height greater than 15 m;
- height greater than 10 m and the reservoir capacity greater than 1 hm^3;
- height smaller than 15 m and the reservoir capacity greater than 0.1 hm^3.

2.4.2 Loading scenarios

Following the recommendations of ICOLD, the Portuguese dam design codes (NPB; 1993, RSB; 2007) state that in the dam safety evaluation, scenarios must be considered, rather than limit states.

Regarding the design of a dam, the design codes point out that, through the appropriate specification of the intensity and frequency of the loads, the properties of the structural and foundation materials and the techniques of the construction and operation, the current (associated with normal operation conditions) and failure (associated with the occurrence of low probability events) scenarios should cover all loading situations (NPB; 1993).

In the design, apart from other occasional combinations of loads, the following loads should be considered:

- During the construction:
    - gravity loads due to the concreting and placing of the equipment;
    - overlap the previous gravity loads to the thermal loads due to the concrete setting (hygrometric and autogenous expansions) and the air temperature variations, the actions resulting from the concrete joints sealing, the foundation treatment and, eventually, the pre-stressing.
- During the first filling of the reservoir:
    - overlap gravity loads corresponding to the end of the construction, to water and thermal actions resulting from the reservoir filling.
- During the operation period:
    - overlap the conditions observed at the end of the first filling to the reservoir elevation and temperature variations, the silt loads and the ice loads;
    - overlap the previous conditions to the operating basis earthquake (OBE) which has an expected probability of occurrence of 50% during the lifetime of the dam.
- During accidental situations:
    - overlap the operation conditions to the water loads corresponding to a flood with return period greater than the one of the design flood;
    - overlap the operation conditions to the maximum design earthquake (MDE);
    - overlap the operation conditions to large displacements imposed on the foundation;
    - overlap the operation conditions to extreme values of the shear resistance of the rock mass discontinuities or the concrete resistance.

These combinations of loads usually lead to the following conditioning design scenarios:

- Current scenarios:
    - considering the normal operation conditions;
    - considering the occurrence of the OBE during the normal operation period.
- Failure scenarios:

considering the occurrence of the design flood (whose return period depends on the dam height and the potential risks in the downstream valley, as shown in

-
    - Table 2.1) during the normal operation period;
    - considering the occurrence of the MDE during the normal operation period.

Table 2.1 – Return period of the design flood (NPB; 1993)

Height (m)	Return period (years)	
	High potential risk	Moderate potential risks
≥100	5000 up to 10000	1000 up to 5000
≥50 and <100	1000 up to 5000	1000
≥15 and <50	1000	1000
< 15	1000	500

2.4.3 Consequences of failure

The consequences of a structural failure are considered grouping the dams into classes according to the potential damage caused downstream by the flood wave: Class I, Class II and Class III. According to Table 2.2, the number of human lives, facilities and the environmental impact are taken into account in this classification.

Table 2.2 – Dam classes according to the Portuguese dam safety regulation (RSB; 2007)

Class	Human occupation, facilities and environment
I	Number of inhabitants greater or equal to 25
II	Number of inhabitants smaller than 25; or Important infrastructures and facilities or environmental assets of great value and hardly recoverable or existence of facilities of production or storage of dangerous materials
III	Remaining dams

Also, the consequences of a failure are quantified, considering a total or partial and sudden or progressive failure, by an evaluation of both the material and human losses.

The on-going revision proposal of the dam safety regulation includes a more sustained definition of the consequences classes. According to that, the hazard associated with a dam operation should be characterize by the factor X,

$$X=H^2\cdot\sqrt{V} \tag{9}$$

where H is the dam height (m) and V is reservoir capacity (hm^3).

In addition, the population affected by the eventual dam collapse is quantified according to the number of permanent edifications (Y) and the potential risks are evaluated taken into account the existence of infrastructures, facilities and important environmental assets, according to the Table 2.3.

Table 2.3 – Dam class in the revision proposal of the Portuguese dam safety regulation

Class	Dam operation hazard and potential risks
I	Y≥10 and X≥1000
II	Y≥10 and X<1000; or 0<Y<10; or Existence of infrastructures, facilities and important environmental assets
III	Remaining cases

2.4.4 Safety evaluation framework

Initially, the design solution (buttress, gravity, hollow gravity, arch-gravity, arch or multiple-arch) should be adopted according to the valley's shape, the type of foundation, the available materials, the available construction equipment and the flood flow. Then, the foundation treatment is designed based on the rock mass characterization (state of weathering, permeability, deformability, strength and initial stress state).

The dam structural analysis for the normal operation period is performed considering the following loads:

- Gravity loads: due to the weight of the materials used;
- Water loads:
  - Hydrostatic pressure: due to the storage of water in the reservoir. Mean values for the reservoir and tailwater elevations and variations around these mean values may be considered;
  - Uplift pressure: due to the seepage through the materials' pores and joints which generate velocity and stress fields.
- Thermal loads: due to the variations in the temperature of the air and the water;
- Seismic loads: due to earthquake actions;
- Ice loads: due to the formation of a layer of ice on the reservoir which causes pressures on the upstream face and due to the cycle of freezing-thawing of the water in the concrete pores which causes volume variations;
- Silt loads: due to the accumulation of transported sediments.

Considering the operation period, the following models should be used in the dam structural analysis:

- For normal operation conditions:
  - Linear elastic models considering a monolithic structure;
  - Linear elastic models considering independent blocks;
  - Linear elastic or elasto-viscoplastic models considering successive geometries, with contraction joints, at different ages.
- For extreme situations: Non-linear models.

In the Portuguese design codes (NPB; 1993), it is also pointed out that the safety, in terms of probability of failure, cannot be quantified and therefore should be guaranteed using extreme coefficients affecting the significant parameters associated with both the loads and the structural properties, until the occurrence of the incident or accident. This procedure is actually the sensitivity approach, pointed out by Hoek (2007), which should not be understood as a probabilistic-based procedure.

The structural safety is verified and the design solution accepted if the dam is able to fulfil its functions:

- not having excessive deterioration during normal operation conditions (current scenarios), i.e.:
    - the structural response is mainly elastic, the correct operation of the dam is guaranteed, the quality of the rock mass in the vicinity of the foundation remains unaffected and the drainage efficiency is maintained;
    - although localized cracking is allowed, the stresses in the dam, either in the volumetric elements or in joints, meet the Mohr-Coulomb criteria, considering the peak resistance, either in tension or compression, affected by a safety coefficient between 2.5 and 4;
    - although localized cracking is allowed, the stresses in the foundation, either in the volumetric elements or in joints and low-resistance surfaces, meet the Mohr-Coulomb criteria, considering the peak values of the cohesion, affected by a safety coefficient between 3 and 5, and the coefficient of friction, affected by a safety coefficient between 1.5 and 2;
    - although higher localized values are allowed, the drained flow of the foundation corresponds to average values at the waterproof curtain not greater than 1 Lugeon;
    - the uplift pressures at the drainage line are one third of the reservoir pressure.
- not suffering failure even when exposed to extreme low likelihood events (failure scenarios), i.e.:
    - the movement of the fractured blocks does not lead neither to its overturning nor to the percolation of large amounts of water under great velocities through the foundation;
    - the stresses on the failure surfaces, taking into account the uplift pressures, meet the Mohr-Coulomb criteria, considering null cohesion and the residual values of the coefficient of friction, affected by a safety coefficient between 1.2 and 1.5;
    - in the case of thin dams, the stresses in the concrete is less than 25% of its compressive strength (allowable stress design approach);
    - the drained flow of the foundation corresponds to average values at the waterproof curtain not greater than 5 Lugeon.

2.4.5 Final considerations

The Portuguese dam design codes (NPB; 1993) are based on the global safety factor method. In fact, the variables uncertainties are taken into account considering the loads' intensity with low probability of occurrence and safety coefficients affecting the material properties. However, this method, extensively used in the past, is based on the expert judgment and the historical approach (Elingwood; 1994, Schneider; 1997).

The increasing of the concern about welfare, safety, sustainability and economy requires a risk-based analysis concerning the construction of engineering structures. As the probability of failure is not explicitly computed and the design criteria of the dam design codes are not based on probabilistic principles, the risk analysis is not feasible. Thus, a probabilistic-based approach should be performed and semi-probabilistic guidelines should be drawn up, such as that currently used for other types of structures (EN1990; 2002), providing similar safety levels both for multiple hazard events and for dams with identical potential risks.

2.5 Structural reliability analysis methods

2.5.1 General considerations

The reliability analysis allows the quantification of the probability of failure of a structural system. In order to do that, uncertainties must be taken into account in the form of probabilistic distributions associated with the basic random variables, $X_1, X_2, \ldots, X_n$ or merely X.

Amongst other requirements, the structures should be design guarantying its safety and serviceability, with a specific degree of confidence, for some period of time (durability) and achieved by minimum costs (economy) (Schneider; 1997). As a rule, each requirement can be expressed in a form of the so-called limit state function (Thoft-Christensen; Baker; 1982, Schneider; 1997, Melchers; 1999, Haldar; Mahadevan; 2000, Faber; 2005, Lemaire; 2009),

$$g(X)=0 \tag{10}$$

where $g(X)$ is the performance function associated with a failure mode. The limit state function separates the acceptable or safe region ($g(X)>0$) from that which is characterised as failure or unsafe region ($g(X)\leq 0$) (Schneider; 1997).

According to this definition, the probability of failure can be written as follows,

$$p_f=P\{g(X)\leq 0\} \tag{11}$$

As $g(X)=0$ defines a (n-1) dimensional hyper surface, denoted the *failure surface*, in the space spanned by the n basic random variables, the probability of failure may be determined through the following n dimensional integral (Thoft-Christensen; Baker; 1982, Schneider; 1997, Melchers; 1999, Haldar; Mahadevan; 2000, Faber; 2005):

$$p_f=\int \ldots \int_{g(X)\leq 0} f_X(x_1,x_2,\ldots,x_n)\, \delta x_1 \delta x_2 \ldots \delta x_n = \int_{g(X)\leq 0} f_X(X)\, \delta X \tag{12}$$

where $f_X(X)$ is the joint probability density function of the random variables, X, and the integration is performed over the failure domain.

The analytical solution of the expression (12) is possible for very simple cases. In most practical applications, numerical approximate approaches must be performed (Thoft-Christensen; Baker; 1982, Schneider; 1997, Melchers; 1999, Haldar; Mahadevan; 2000, Faber; 2005, Lemaire; 2009). Faber (2005) also highlighted that the usual numerical integration of the expression (12) is not appropriate due to the fact that the numerical effort to solve it with sufficient accuracy in case of small failure probabilities becomes overwhelming.

2.5.2 Reliability index definition

The concept of reliability index was first introduced by Cornell (1969). It can be easily understood using a simple example where the performance function is linear and the basic random variables are normally distributed (Thoft-Christensen; Baker; 1982, Schneider; 1997, Faber; 2005). Then, the limit state function is given by,

$$g(X)=a_0+\sum_{i=1}^{n} a_i \cdot x_i = 0 \tag{13}$$

As the basic random variables are normally distributed, characterize by the two first parameters - mean value and variance - the performance function, *g*, is also normally distributed (Faber; 2005) with mean value and variance given by,

$$\mu_g=a_0+\sum_{i=1}^{n} a_i \cdot \mu_{X_i} \tag{14}$$

$$\sigma_g^2=\sum_{i=1}^{n} {a_i}^2 \cdot \sigma_{X_i}^2 \tag{15}$$

where μ_{Xi} and σ_{Xi} are the mean value and the standard deviation of the basic random variable X_i, respectively.

The probability of failure is given by,

$$p_f=P\{g(X)\leq 0\}=\Phi\left(-\mu_g/\sigma_g\right)=\Phi\left(-\beta\right) \tag{16}$$

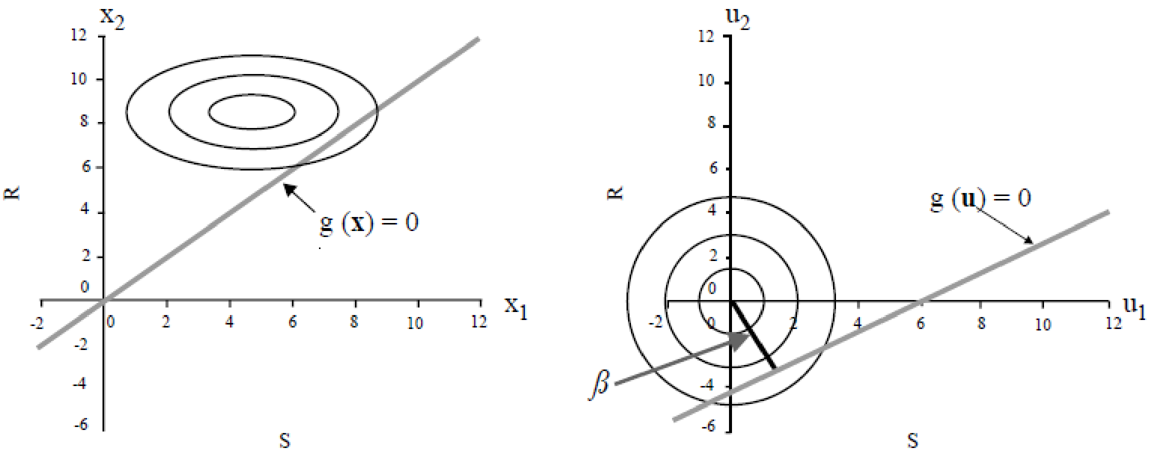
where Φ is the cumulative density function of the standard normal distribution and β, the so-called reliability index (Cornell; 1969), is given by,

$$\beta=\mu_g/\sigma_g \tag{17}$$

2.5.3 Approximation methods

2.5.3.1 Hasofer-Lind approach

According to Schneider (1997), Ditlevsen, in 1973, stated that the results of this procedure depend on how the limit state function is formulated. Hasofer and Lind (1974) contributed for solving this problem. They transformed the limit state function from the original coordinate system (Figure 2.2a) into the standard space (Figure 2.2b). Thus, the reliability index β has gained a graphical interpretation as illustrated in Figure 2.2, where a two-dimensional case ($g=R-S$) is considered.



a) Original coordinate system

b) Standard coordinate system

Figure 2.2 – Illustration of the two-dimensional case of a linear limit state function (Faber; 2005)

In Figure 2.2 the limit state function has been transformed into the standard limit state function, *g(u)*, normalizing the random variables, into standard normal variables with zero mean and unit standard deviations. Thus, the shortest distance from the origin to the failure surface (limit state function) in the standard coordinate system is usually called the Hasofer-Lind's reliability index (Thoft-Christensen; Baker; 1982, Schneider; 1997, Melchers; 1999, Haldar; Mahadevan; 2000, Faber; 2005), that is given by,

$$\beta_{HL} = \min_{u\in\{g(u)=0\}} \sqrt{\sum_{i=1}^{n} u_i^2} \qquad (18)$$

The defined point is often denoted as design point or most probable failure point. The Hasofer-Lind's reliability index, β_{HL}, coincides with the reliability index given by expression (17) for linear limit state functions and for non-correlated normally distributed random variables. In that case, the computed probability of failure is exact. However, in the most cases neither the limit state function is as simple as a linear function nor the random variables are normally distributed (Thoft-Christensen; Baker; 1982, Schneider; 1997, Melchers; 1999, Haldar; Mahadevan; 2000).

When the limit state function is non-linear, approximate solutions can be obtained by expanding the limit state function in a Taylor series.

2.5.3.2 FORM - First Order Reliability Methods

2.5.3.2.1 Non-linear limit state functions

In the First Order Reliability Methods (FORM) only the first order term of the Taylor series is considered. As stated by Thoft-Christensen and Baker (1982), the outcome of the calculation of the reliability index linearizing the limit state function will depend on the choice of the linearization point.

In the so-called mean-value first-order second-moment (MVFOSM) or just first-order second-moment (FOSM) method, the information on the distribution of the random variables is ignored and the first-order Taylor series approximation of the limit state function is linearized at the mean values of the random variables, using only the second-moment statistics (means and covariances) of the random variables (Haldar; Mahadevan; 2000). However, this method has some important limitations. In fact, the available information on the random variables is not completely used. Moreover, as small probabilities of failure are being computed, the variable design points are certainly closer to the tail of their distributions than of their mean. Therefore, significant errors may be addressed to this method.

Hasofer-Lind (1974) suggested that the limit state function should be linearized at the design point. Haldar and Mahadevan (2000) called this method as advanced first-order second-moment (AFOSM). In this case, the limit state function is approximate by the tangent of the limit state function at the design point (Thoft-Christensen; Baker; 1982, Schneider; 1997). As the limit state function is non-linear, one does not know the design point in advance (Faber; 2005). Therefore, the design point, given by expression (16), should be obtained interactively by an optimization process (Schneider; 1997, Melchers; 1999, Haldar; Mahadevan; 2000, Faber; 2005). In this method, the information on the random variables is taken into account to compute the design point.

2.5.3.2.2 Non-normal random variables

To deal with this problem, Rackwitz and Fiessler (1978) proposed that the variable distributions be replaced by equivalent normal distributions at the design point. The estimation of the equivalent normal distribution parameters follows two conditions: the cumulative distribution functions and the probability density functions of both the original variable distribution and the equivalent normal distribution should be equal at the design point. As pointed out by Haldar and Mahadevan (2000), this approximation can become more inaccurate if the original distribution becomes increasingly more skewed. In this case, Rackwitz and Fiessler (1978) stated that the equivalent normal distribution mean and probability of exceedance should be made equal to the median and the probability of exceedance of the original random variable distribution, respectively, at the design point.

Schneider (1997) also indicated another approach based on the fact that every non-normally distributed variable can be transformed into a standard-normal variable. However, Schneider (1997) also pointed out that generally this transformation affects the limit state function such a way that a linear limit state function becomes non-linear in the standard-normal space.

2.5.3.2.3 Correlated random variables

The situation where the basic random variables are stochastically dependent (or correlated) is often found in practical problems (Faber; 2005). When the basic random variables are correlated, a transformation is required to perform approximate reliability methods. This transformation may be an intermediate step before the normalization of the random variables. The approach often followed, explained in detail in Faber (2005), is the Cholesky factorization.

2.5.3.3 SORM - Second Order Reliability Methods

A linear approximation of the limit state function induces errors due to the difference between the failure domains. The curvature of the non-linear limit state function is ignored in the FORM approach. Thus, the second-order reliability methods (SORM) improve the FORM results by including additional information about the curvature of the limit state (Haldar; Mahadevan; 2000). In this case the second-order term of the Taylor series is considered to improve the approximation of the non-linear limit state functions.

Once again, non-normal random variables can be approximate by equivalent normal distributions and the probability of failure is performed interactively and the correlation between random variables is treated by performing the Rosenblatt transformation (Haldar; Mahadevan; 2000).

2.5.4 Simulation methods

2.5.4.1 General considerations

The approximation methods may successfully be applied but, as mentioned, there are a range of limitations concerning to their effectiveness. On one hand, the probability of failure may not be computed if the limit state function is either not defined analytically or not differentiable. On the other hand, in some cases, when the limit state function is too complex or when several design points contribute to the probability of failure, the accuracy of the outcome may be questioned (Faber; 2005).

According to Haldar and Mahadevan (2000), to evaluate the accuracy of reliability approximation methods, simulation is often used to independently evaluate the underlying probability of failure.

All simulation techniques have origin in the so-called Monte Carlo method (Faber; 2005). The main concept of the Monte Carlo method applied to the structural reliability analysis is that a large number of evaluations of the performance function is performed using random realizations, x_{ik}, of the random variables, X_i (Schneider; 1997). The simulation techniques consist in re-writing the probability integral of the expression (12) as,

$$p_f = \int_{g(X)\leq 0} f_X(X)\,\delta X = \int I \cdot f_X(X)\delta X \tag{19}$$

where I is an indicator function equal to 1 if $g(x)\leq 0$ and equal to zero otherwise.

Therefore, if n values of the random variables are generated, according to their distribution functions, the probability of failure is given by,

$$p_f = 1/n \cdot \sum_{i=1}^{n} I = n_f/n \tag{20}$$

where n_f is the number of failures, i.e. the number of realizations for which $g(x)\leq 0$.

2.5.4.2 Crude Monte Carlo method

The principle of the crude Monte Carlo method consists on the direct application of expression (20). As stated by several authors (Thoft-Christensen; Baker; 1982, Schneider; 1999, Melchers; 1999, Faber; 2005) if the number of realizations, n, tends to infinite the computed probability of failure becomes exact. However, generally the problems have some degree of complexity which leads to high computational effort and time consummation.

As pointed out by Schneider (1997), a greater number of realizations, n, leads to a more reliable value of the probability of failure, p_f. Then, this problem becomes a question of the degree of confidence one must has in the value of the probability of failure. For small p_f, according to Schneider (1997) and Faber (2005), the coefficient of variation of the probability of failure, v_{pf}, is given by,

$$v_{p_f} \approx 1/\sqrt{n \cdot p_f} \tag{21}$$

If a small coefficient of variation is desired, e.g. 10%, then for a probability of failure of, e.g., 10^{-6}, 10^{8} realizations are required.

To reduce the number of realizations required, refinements of the crude Monte Carlo method must be taken. These methods have the purpose of reduce the variance of the estimate (Faber; 2005).

2.5.4.3 Variance reduction methods

2.5.4.3.1 Importance sampling simulation method

The main concept of the importance sampling method is to concentrate the sampling points in the area that mainly contributes to the probability of failure (Haldar; Mahadevan; 2000), i.e. around the design point. Therefore, the design point must be previously estimated by FORM/SORM analysis. By centring the simulations on this point, a higher success rate is obtained and the variance of the estimated probability of failure is reduced (Faber; 2005). Then, the probability of failure may be re-written as,

$$p_f = \int I \cdot f_X(X) \delta X = \int I \cdot (f_X(X)/f_s(X)) \cdot f_s(X) \delta X \tag{22}$$

in which $f_s(x)$ is denoted the importance sampling density function. The accuracy of the importance sampling estimate depends on the choice of the sampling density function. One approach is presented in Faber (2005), where the sampling density function is a n-dimensional normal probability function with uncorrelated components, mean equals to the design point and standard deviation corresponding to the standard deviations of the random variables.

2.5.4.3.2 Stratified sampling

In the stratified sampling method, the domain of integration is divided into several regions, so that emphasis can be placed by simulating more from the regions that contribute to the failure event (Haldar; Mahadevan; 2000). The domain of integration is divided into m equal regions, $R_1, R_2, \ldots, R_m$, and the probability of failure may be estimate by,

$$p_f = \sum_{j=1}^{m} \left[P(R_j) \cdot (1/N_j) \cdot \sum_{i=1}^{N_j} I \right] \tag{23}$$

where $P(R_j)$ is the probability of region R_j and N_j is the number of simulation cycles performed in region R_j. This strategy ensures that no region is missed (Haldar; Mahadevan; 2000). An extensively explanation about this sampling technique can be found in Cochran (1977).

2.5.4.3.3 Adaptive sampling

In the importance sampling method, the region of importance is usually not known in advance. However, the efficiency of the simulation can be improved if it can be updated using the information obtained from the first few simulation cycles (Haldar; Mahadevan; 2000). This observation led to the development of the adaptive sampling methods.

The basis of this method is that as the simulation progresses, the sampling density, *fs(x)*, is updated. The methods of the adaptive sampling can be found in Haldar and Mahadeven (2000).

2.6 Recent studies and codes considering the probabilistic-based approach on concrete dams' safety evaluation

According to Ruggeri (2004), the Chinese standards are the first example of a semi-probabilistic approach, regarding the dam safety evaluation, distributing the uncertainties among various partial safety factors and applying them to the loads, material properties, etc.

The new French guidelines (CFBR; 2012) also uses concepts issued from the semi-probabilistic approach. It was published a first provisory version, dated from 2006. The 2012 version was adapted considering the results of the implementation of the first one.

In recent years, studies have been carried out about the probabilistic assessment of concrete dam safety. Westberg (2010) showed the applicability of the structural reliability analysis and pointed out the most important sources of uncertainty involved in the concrete gravity dam safety. Westberg (2010) also highlighted that the reliability index depends on the dam type, the dam height and the cross-sectional design.

An extensive and sustained study on dam risk analysis was performed by a working group from *Universidad Politécnica de Valencia* in which Altarejos (2009) focused on a structural reliability analysis using the information of a Spanish concrete gravity dam in which a range of reliability methods were applied and the influence of different structural models was tested.

Farinha *et al.* (2014) used a discrete element model and the limit state design (LSD) method to access the dam foundation sliding safety, considering the partial safety factors prescribed in the Eurocode 7 (EN1997-1; 2004).

The framework of these studies will be used as a guide to the proper development of this thesis.

3 | Probabilistic-based safety analysis of concrete dams

3.1 General considerations

The proposed thesis aims at contributing to the improvement of the general knowledge on the concrete dam safety analysis and to take steps towards to propose partial safety factors to be used in a semi-probabilistic format for the design of concrete dams.

Because the Portuguese dam safety regulation (RSB; 2007) is based on deterministic concepts, dams designed according to it will have different probabilities of failure and, consequently, different risks associated with their operation. This fact justifies the convenience of a probabilistic-based structural safety analysis and its consideration in the design codes.

Although the full risk analysis requires the study of the hazard scenarios, the structural reliability and the consequences, a probabilistic-based design code, grouping dams into classes of consequences and defining the loading events according to the dam location and height, allows to take indirectly the risks into account. Therefore, as the Portuguese dam safety regulation (RSB; 2007) already identifies the consequences of a dam operation, by defining classes of consequences based on the occupation of the downstream valley, and the critical hazard scenarios, by quantifying the return-period of the extreme events, the study of the structural reliability becomes more relevant.

Thus, it is intended to study the probability of failure during improbable events (floods and earthquake whose return period is already defined). In order to compute the probability of failure using the reliability theory, uncertainties must be quantified. Thus, models of the uncertainties related to the material properties and loads (except loads with high return-period which will be considered as deterministic variables) will be proposed, sustained by the existing data of the monitoring of the concrete dam behaviour, tests carried out and bibliographic references. Each source of uncertainty will be considered as a random variable.

As the drawn up of a semi-probabilistic code is also objective of this study, such code shall fulfil the risk acceptance criteria. Even though the risk analysis is not performed completely, the target reliability index, or the maximum allowed probability of failure, representing the required reliability level, can be calibrated to the actual practice, assuming that this practice is optimal. Therefore, theoretical dam shapes, designed in accordance with such practice, should be taken and the structural reliability analysis performed.

For each failure mode, the structural reliability analysis provides the probability of failure conditioned to the occurrence of high return-period loading scenarios. Considering the independence between the failure and the occurrence of extreme loading scenarios, the absolute probability of failure can be estimated by the product between them.

Furthermore, the structural reliability will provide the design value of the random variables which can be transformed into partial safety factors based on the characteristic values of the random variables.

In summary, the main aspects that this thesis aims to address are the followings:

- Uncertainties modelling: propose models of the uncertainties involved in the concrete dam safety sustained by the existing data of the monitoring of the concrete dam behaviour and tests carried out;
- Computation of the probability of failure: using the reliability theory, the probability of failure of the models to be tested, for specific failure modes, can be computed by approximation and simulation methods as stated before;
- Definition of a semi-probabilistic format of the concrete dam safety: establish design criteria and partial safety factors to be used in a probabilistic-based design code, based on the design values from the structural reliability analysis.

3.2 General study plan

3.2.1 Uncertainties characterization

As mentioned before, several variables are involved in the concrete dam structural analysis. These variables, representing physical features, are naturally uncertain.

Considering concrete dams, one can point out the loads and resistances involved in its safety: dead-weight, temperature variations, hydrostatic pressure, uplift pressure, earthquake effects (seismic loads and hydrodynamic pressure) and material characteristics (rock mass foundation interface and concrete properties). One can understand that these features are somehow uncertain and the lack of certainty about its intensity, location or distribution should be taken into account in the form of basic random variables. Also other source of uncertainties should be considered, namely the model uncertainties due to simplifications and assumptions made.

On this subject, by the time that this work is presented, models for the quantification of the uncertainty related to the uplift pressures and the reservoir water level in normal operation conditions are already defined. The uncertainty models proposed by the fellow can be found in LNEC (2016a; 2016b), respectively. A synthesis of those proposals is presented below.

3.2.1.1 Uplift pressure uncertainty model

The seepage through dam foundations induces hydraulic pressures in the discontinuities surfaces. In the vicinity of the dam-foundation interface, these pressures, called uplift pressures, reduce the effective stresses and, consequently, the shear resistance. According to the Portuguese dam safety regulation (RSB; 2007), foundation treatment works shall be taken and be able to reduce the uplift pressure to, at least, one third of the reservoir water pressure. However, through the continuous observation of Portuguese dams, it has been verified that the average pressure values downstream of the drainage curtain, present significant scatter.

Considering the bi-linear distribution of the uplift pressure, the percentage of pressure reduction at the drainage line is considered uncertain. Using the gathered data from 16 Portuguese gravity, arch and arch-gravity large dams, an exponential stochastic process, linearly proportional to the reservoir water level variation, is proposed (LNEC; 2016a). As different behaviour between dams founded on highly and slightly fractured rock masses was noticed, the samples were divided into two data sets representing that feature. Finally, using the maximum likelihood method (MLE), the samples were used to estimate the distribution parameters of each random variable that comprise this model.

3.2.1.2 Reservoir water level uncertainty model

The Portuguese dam safety regulation (RSB; 2007) indicates that, during normal operation periods, one should consider the reservoir water level at the retention water level (RWL). However, due to several facts related to dam management policy and discharge capacity, in some situations this assumption may be non-conservative, as it is proved by the continuous monitoring of the reservoir water level that at least once a year the reservoir level may be above the RWL during a certain period of time.

It was then proposed a sinusoidal stochastic process to characterize the uncertainty in the annual variation of the reservoir water level in normal operation conditions, based on the monitored data since the beginning of the operation period in a range of Portuguese concrete dams (LNEC; 2016b). In order to use the reservoir water level from 27 geometrically different concrete dams, the model represents the percentage of the maximum height that the reservoir can reach in operation conditions. As a difference in the magnitude of reservoir level of run-of-river and storage dams was noticed, the samples were also divided into two data sets. The MLE was then used to estimate the distribution parameters of each random variable.

3.2.2 Structural analysis models and methods

In this thesis, concrete gravity and arch dams will be considered. The conditioning failure modes related to these types of structures are different.

In the case of gravity dams, the structural stability is guaranteed by its weight. The hydrostatic pressure upstream tends to destabilize the dam, inducing translation along a weak plane at the vicinity of the dam foundation (sliding) or rotating about its toes (overturning). Therefore, the dam shape and its foundation insertion play a major role and the engineer aims to design a structure heavy enough to guarantee its safety. To counteract the overturning and the sliding tendency, the gravity dams usually have a triangular shape.

In arch dams, stability is obtained by a combination of gravity and arch effects. This type of dams is used in narrow valleys with good rock mass abutments. The safety of an arch dam is then dependent on the strength of the abutment rock mass and of the concrete.

The failure modes to be tested in this thesis are related only to the concrete mass stability and resistance, disregarding the rock mass failure modes. Therefore, for gravity dams, the sliding and overturning failure modes on different surfaces will be tested for the simplest case. The conditioning mechanism will later be tested for the remaining cases. For arch dams, the sliding and concrete overstressing will be considered.

To perform the structural analysis, at least three models with different heights of each dam type, representing the current design practice, will be tested. The following structural analysis methods will be used:

- For gravity dams (two-dimensional models):
    - The limit equilibrium method, in which the limit state is characterize by a simple equilibrium equation.
    - The discrete element method, in which the limit state is characterize by allowable displacements or stresses.
- For arch dams (three-dimensional models), the discrete element method in which the limit state is characterize by allowable displacements or stresses.

While for static load combinations linear and nonlinear structural analysis will be used, for dynamic load combinations pseudo-static methods, pseudo-dynamic methods, linear time history analysis and nonlinear time history analysis will be considered (Bretas; *et al.*; 2014).

3.2.3 Structural reliability analysis

Taking into account the uncertainties involved in the structural safety, the reliability analysis allows to determine the probability of failure of a structure. In order to do this, the range of models to be tested and the uncertainties should be already defined.

For the structural reliability analysis, the first approach will be based on approximation methods, mentioned before. The reliability of these methods can be assessed by differences between the outcomes. However, the approximation methods (FORM and SORM) can provide a first estimation about the structural reliability and the variable design values.

Later, the simulation methods will be used. As mentioned before, the crude Monte Carlo technique requires high computational effort and its applicability is only possible for simple-defined limit state functions, such as for the limit equilibrium method. For the join of the discrete element models with the structural reliability analysis, where the computational effort to perform one simple simulation is higher, the number of simulations needed to become this method feasible should be extremely smaller. Thus, to reduce the number of simulations, variance reduction methods will be used so that the reliability of the outcomes will not be affected.

3.3 General study plan

In this section the main expected tasks for the development of this thesis are presented, namely:

Task 1 – Achievement of the ECTS credits required for the Ph.D. degree.

Task 2 – Bibliographic review and state of the art.

Task 3 – Uncertainty modelling:

> **Subtask 3.1** – Statistical inference of the uplift pressure, in the foundation, at the drainage line, using the information from the continuous monitoring of several Portuguese concrete dams.
>
> **Subtask 3.2** – Statistical inference of the reservoir water level in normal operation conditions, using the information from the continuous monitoring of several Portuguese concrete dams.
>
> **Subtask 3.3** – Statistical inference of the dam concrete mechanical characteristics, using the information from the tests performed on the specimens, from a set of dams, at different ages.

Task 4 – Concrete dam structural modelling:

> **Subtask 4.1** – Define two-dimensional finite element models of the concrete gravity dams to be analysed.
>
> **Subtask 4.2** – Define three-dimensional discrete element models of the concrete arch dams to be analysed.

Task 5 – Revision on the reliability methods and algorithmic development to perform the probabilistic analysis.

Task 6 – Result analysis, calibration of the partial safety factors and purpose of a semi-probabilistic format of the concrete dam safety evaluation.

Task 7 – Writing and dissemination.

In Table 3.1, the expected schedule for the execution of this work plan is presented.

Table 3.1 – Tasks execution schedule

Tasks	1st year				2nd year				3rd year				4th year			
Task 1			▨	▨			▨	▨			▨	▨				
Task 2	▨	▨	▨	▨												
Task 3	▨	▨	▨	▨	▨	▨	▨	▨								
Task 4							▨	▨	▨	▨						
Task 5									▨	▨	▨	▨	▨			
Task 6											▨	▨	▨			
Task 7					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

By the time that this work plan is presented, about two years of dedicated work has already been fulfilled. After finishing the subtask 3.3, the fellow is currently working on the task 4.

3.4 Thesis outline

The thesis will be structured according to the present planning. Therefore, it is expected that the thesis will be organized in the following chapters:

1. Introduction;
2. State of the art about probabilistic-based structural safety analysis of concrete dams:
    - 2.1. Risk analysis concepts;
    - 2.2. Safety evaluation methods;
    - 2.3. Structural reliability methods;
    - 2.4. Concrete dam material behaviour models;
    - 2.5. Concrete dam structural analysis models and methods.
3. Probabilistic characterization of the concrete dam safety:
    - 3.1. Uncertainties modelling;
    - 3.2. Ultimate limit states associated with the failure modes;
    - 3.3. Definition of the theoretical models.
4. Applications:
    - 4.1. Gravity dams:
        - 4.1.1. Limit equilibrium method – Analytical solution;
            - 4.1.1.1. Reliability approximation methods;
            - 4.1.1.2. Simulation methods.
        - 4.1.2. Gravity dam discrete element models: Simulation methods.
    - 4.2. Arch dam discrete element models: Simulation methods.
5. Result analysis:
    - 5.1. Calibration of the partial safety factors;
    - 5.2. Semi-probabilistic format of concrete dams’ safety evaluation.
6. Conclusions.

3.5 Available resources to be used

3.5.1 Uncertainties modelling

As mentioned, the uncertainties involved in the concrete dam safety are the primary motivation for the use of probabilistic methods. Then, the most important sources of uncertainty must be modelled. While the rock mass mechanical characteristics will be based on bibliographic search, the information on the other features is scarce. This is the case of the uplift pressures, the water level in the reservoir in normal operation conditions and the mechanical characteristics of the dam concrete. Information available at LNEC about those properties, resulting from the monitoring of the concrete dam behaviour during the construction, first filling and operation, will be used accordingly.

3.5.2 Numerical modelling

Regarding to the performing of the structural reliability analysis, complex models in which the failure may be represented will be used. In the case of the concrete gravity dams, the analysis will be based initially on the limit equilibrium method which admits the dam movement as a rigid body and later on the two-dimensional finite and discrete element models in which the failure will be defined in terms of displacements and stresses. In the case of the concrete arch dams, the analysis will be based on the three-dimensional discrete element models in which the failure will be defined in terms of the concept of crack index.

Regarding the dam structural analysis, computational codes available at LNEC, based on the finite (Oliveira; 2000) and discrete element (Lemos; 2001) methods, will be used.

4 | Supervision

Although the work will be developed at DBB/LNEC, where the fellow has hosting, this doctoral plan is intended to be also submitted at FCT-UNL, during the meeting for the thesis monitoring commission (CAT) to be held in the beginning of 2016.

Since the research programme combines topics from dam engineering and reliability analysis, the supervisors, Dr. António Lopes Batista and Dr. Luís Canhoto Neves, fulfilled, respectively, the required characteristics. A synthesis of their academic curriculum and professional career are presented below.

Dr. António Lopes Batista obtained the licentiate degree (in 1983) and the PhD degree (in 1998) at the University of Lisbon (IST). His research experience in the field of concrete dam engineering is related to the monitoring and safety control, the modelling and interpretation of the structural behaviour and the analysis of the structural effects of swelling processes. He is senior researcher and currently head of DBB/LNEC. He is also Invited Associated Professor at FCT-UNL.

Dr. Luís Canhoto Neves obtained the licentiate degree (in 1998) at IST and the PhD degree (in 2006) at the University of Minho. His work has focused on life-cycle analysis of existing structures and structural risk analysis. He was Assistant Professor at FCT-UNL until 2014 and currently is Lecturer at the Nottingham Transport Engineering Centre (NTEC) at the University of Nottingham (UoN).

5 | Resources and financing

The LNEC resources to be used in this thesis are the results of the monitoring of the concrete dam behaviour during the construction, first filling and operation, in order to model the most important sources of uncertainty. Also computational codes, available at LNEC, based on the finite and discrete element methods, will be used to perform the structural analysis.

The LNEC financing resources result from the allocation of the researches involved in the on-going research project “ReliConDam”, established in DBB/LNEC. The PhD studentship was assigned to the fellow during the *2012 call for PhD Studentships, PhD Studentships in Industry and Post-Doctoral fellowships* of the FCT.

Lisbon, LNEC, April of 2016

APPROVED

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