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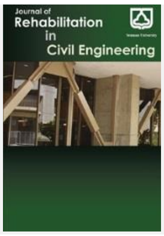

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Reliability and Sensitivity Analysis of Gravity Retaining Wall Stability: Investigating the Effect of Construction Defects

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ABSTRACT

The safety evaluation of retaining structures, especially in cases of potential instability or disaster, frequently depends on empirical methods that apply overall safety factors. In this article, an innovative approach employing probabilistic methods to assess the reliability of gravity retaining walls, considering uncertainties in parameters and their inherent variability, has been introduced. This study applies First Order Reliability Method (FORM) to assess the influence of construction defects and soil-structure friction on gravity wall reliability. his approach represents notable progress over traditional empirical methods, which rely on total safety factors and frequently manage uncertainties arbitrarily. The paper is indeed novel as it integrates probabilistic methods into the analysis of gravity retaining wall stability, offering a more nuanced understanding of the reliability of these structures. This contribution seeks to enhance safety assessments and rehabilitation strategies in civil engineering practices, with a focus on addressing uncertainties in geotechnical parameters and construction defects.

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1. Introduction

Gravity retaining walls have been widely used because of their simplicity in both design and construction at a relatively low cost. However, the retaining structures are in an environment characterized by significant variability and uncertainty [1,2]. In geotechnical engineering, uncertainties are inevitable and the properties of the soil can disperse in a significant range. In a deterministic context, safety factors are used to check the stability of retaining structure [1,3–5]. These factors can indirectly account for the variability and uncertainty of the design parameters. In addition, the use of safety factors has drawbacks as a measure of the relative reliability of geotechnical structures for different performance modes [6], since the parameters have unique values (often averages) despite their uncertainty. On the other hand, the safety factors remain the same regardless of the degree of uncertainty associated with the various geotechnical parameters. It will therefore be more realistic and indispensable to explicitly take into account these uncertainties in the design, stability analysis, and performance of the structure in a rational manner. The probabilistic approach has the advantage of being able to establish a direct link between the uncertainties in the model variables and the probability of failure related to limit state function (performance function). This probability is obtained through a reliability analysis. Great efforts have been made in recent decades by geotechnical engineers to take these uncertainties into account rigorously in computational models using stochastic approaches [7–10].

For nonlinear limit state functions, First and Second-Order Reliability Methods (FORM, SORM), are considered among the most reliable computational methods for structural reliability. These methods offer the advantage of delivering physical interpretations and do not require much computation time. In this study, the reliability analysis is conducted using the FORM method, as it effectively illustrates the sensitivity interpretation of the parameters involved in the problem.

The uncertainties caused by the random character of the soil properties and the assumptions made in the interpretation of these parameters can reduce the accuracy of analyses of the bearing capacity and the soil active pressure going, even in certain cases, to endanger the stability of the structure. Retaining walls in general and gravitational ones in particular, have been the subject of several studies in the probabilistic context [9,11–13].

Epistemic uncertainties, stemming from incomplete knowledge of the system, invariably influence all numerical models [14], influencing them through factors such as model assumptions, parameterization, model structure, data uncertainty, and model calibration. Recent studies on gravity walls have considered, in most cases, failure modes by sliding and overturning, but the bearing capacity effect is rarely mentioned. However, this mode of failure is very common in gravity walls because of their fairly large masses compared to cantilever walls. These models take into account the variability of the backfill (cohesion, friction angle) and only the concrete support soil adhesion coefficient C_a. The viability of the supporting soil is little or hardly taken into account. In this study, we have chosen to take into account all the parameters of the support soil and backfill to get closer to reality. In addition, to take into account the soil-structure friction we have considered Coulomb's theory of soil thrust.

In this paper, the analysis will first consider the variability of geotechnical properties (including cohesion, unit weight, and angle of friction) in reliability analysis. In the second step, we will take into account construction defects in the structure that will be modeled by uncertainties in terms of geometrical dimensions and concrete unit weight. An approach based on the FORM method is described in this context. The last part of this paper will highlight the impact of soil/wall interaction on the reliability of the structure. In the last part of this study, a parametric analysis taking into account various friction angles will also be presented.

2. Description of the studied retaining wall

Gravity retaining walls are commonly used to stabilize soil in hilly areas adjacent to roads, preventing slope failures and ensuring adequate drainage for the roads. This type of retaining wall will resist all external loads only by their weight. In this study, the retaining wall is made of concrete with 6 m height and a 10° backfill slope. Backfill soil and foundation have different characteristics as shown in Figure 1.

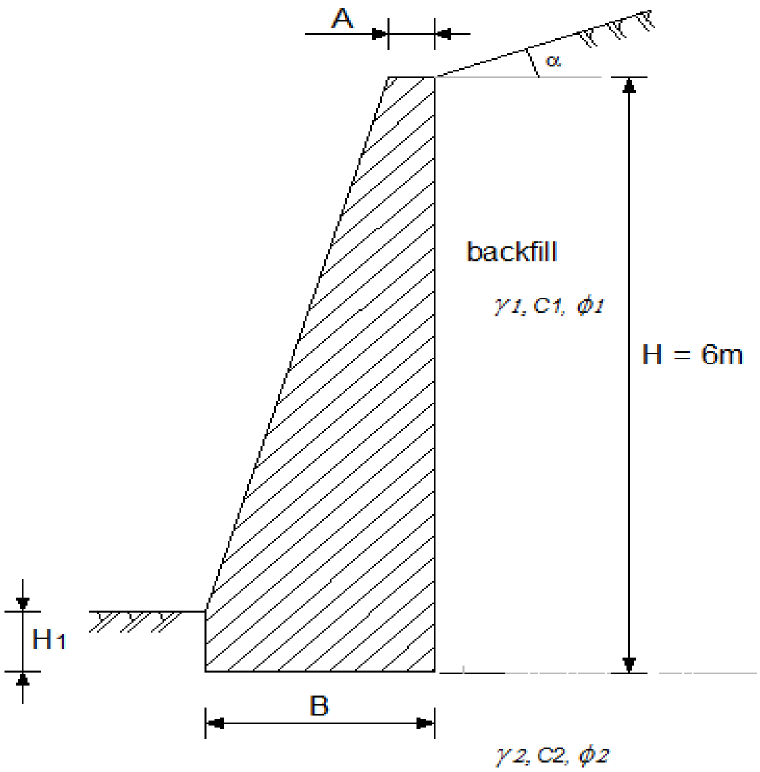

Fig. 1. Elevation view of the retaining wall.

3. Retaining wall failure modes

The design of the retaining wall must consider the soil parameters that influence earth pressure and bearing capacity, using both in-situ and laboratory measurements. The most influential parameters should be taken into account such as unit weight of the soil, angle of internal friction, cohesion and the angle of wall-soil friction.

After the evaluation of soil pressure and the bearing capacity of the support soil, the stability of the retaining wall against sliding, overturning and bearing capacity failure can be carried out.

Ensuring the stability of a retaining wall involves the following steps:

- Examine the potential for overturning about its toe (figure 2-a),
- Check for sliding along its base (Figure 2-b),
- Verify the bearing capacity of the base (Figure 2-c),
- Check for settlement,
- Check for overall stability.

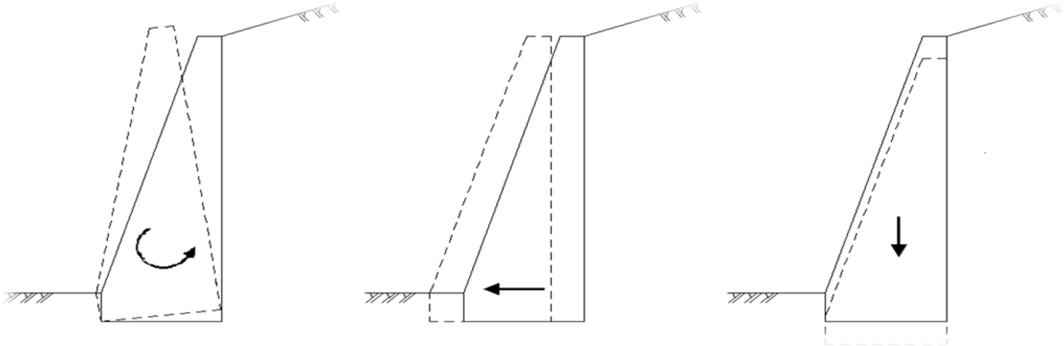

Fig. 2. Overturning (a), sliding (b) and bearing capacity (c) failure modes.

The present study will focus on the three first modes of failure: overturning, sliding and bearing capacity. Figure 3, shows the loads considered for the studied structure.

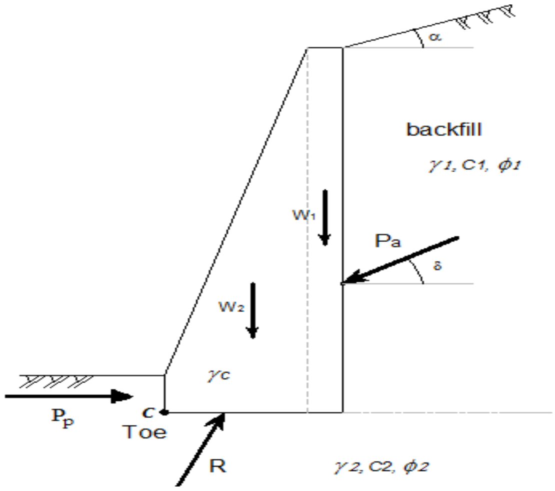

Fig. 3. Description of the studied structure.

The wall characteristics are given in table 1. The thickness of the wall at its base (B) and its top (A) will be evaluated in section below.

Table 1. Deterministic parameters of the problem.

Parameter	γ_c	H	H_1	α
	(kN/m^3)	(m)	(m)	(°)
value	24	6	0.5	10

3.1. Overturning risk

To check the stability of the retaining wall against overturning, it is necessary to verify moment equilibrium. The horizontal component of active force causes overturning of retaining wall about its toe point C by moment called the overturning moment (M_{ot}) (see Figure 3). This overturning moment will be opposed by a resistant moment such:

- moment due to the weight of each element (1 & 2) of the retaining wall M_w
- moment due to the vertical component of the active force

$$M_w = \gamma_c.\{A * H(B - A/2) + ((1/3.(B - A)^2.(H - H_1)) + H_1(B - A)^2/2)\} \tag{1}$$

$$M_v = Pa_v.B \tag{2}$$

$$M_r = M_w + M_v \tag{3}$$

$$M_{ot} = Pa_h.(H/3) \tag{4}$$

where :

γ_c is the concrete weight, $\gamma_c = 24kN/m^3$

$Pa = \frac{1}{2}ka.\gamma_1.H^2$

$Pa_v = Pa.sin\delta,$

$Pa_h = Pa.cos\delta,$

δ is the wall friction angle, in this study $\delta \neq 0$ so the coulomb's theory for active pressure is used:

$$k_a = \left(\frac{sin\,(\lambda-\phi_1)/sin\lambda}{\sqrt{(sin\,(\lambda+\delta)} + \sqrt{\frac{(sin(\phi_1+\delta).sin(\phi_1-\alpha))}{sin(\lambda-\alpha)}}}\right)^2 \tag{5}$$

where λ is the vertical angle of the wall $\lambda = \pi/2$

The equilibrium against overturning can be expressed as follow:

$$\mathcal{F}_1 = M_r - M_{ot} \tag{6}$$

The Factor of safety against overturning risk can be characterized as:

$$FS_1 = \frac{M_r}{M_{ot}} \tag{7}$$

3.2. Sliding risk

The sum of the horizontal resisting forces can be written as follow:

$$FR = V.tan(k_1.\phi_2) + (k_1.C_2.B) + P_p \tag{8}$$

where:

$V = Pa_v + \gamma_c.A.(H - H_1) + \frac{1}{2}.\gamma_c.(B - A).(H - H_1) + H_1.B.\gamma_c$;

$k_1 = 2/3;$

$k_p = \tan^2(45 + \frac{\phi_2}{2})$;

$P_p = P_1 + P_2;$

$P_1 = 2.C_2\sqrt{k_p}.H_1;$

$P_2 = \frac{1}{2}.(\gamma_2.H_1.k_p).H_1$;

The mathematical expression defining the performance function (limit state) associated to sliding risk is given by:

$$\mathcal{F}_2 = FR - Pah \tag{9}$$

The factor of safety against sliding failure mode can be defined as

$$FS_2 = \frac{FR}{Pah} \tag{10}$$

3.3. Bearing capacity risk

Bearing capacity is the ability of soil to safely carry the pressure placed on the soil from any engineered structure without undergoing a shear failure with accompanying large settlements [15].

In the literature, many models are available for the estimation of bearing capacity such as the Terzaghi [16], Meyerhof, Hansen, and Vesic models [17]. Each of these models offers distinct capabilities for taking into account foundation geometry and soil conditions.. The ultimate load-bearing capacity of a shallow foundation situated beneath the base slab of the wall is determined by:

$$q_u = cN_cF_{cd}F_{ci} + qN_qF_{qd}F_{qi} + 0.5\gamma_2(B-2e)N_\gamma F_{\gamma d}F_{\gamma i} \tag{11}$$

where q is the effective stress at the depth of the wall base. It is calculated as $q = \gamma_2.h$, where h is the height of the soil at the toe side of the wall.

F_{cd}, F_{qd} and $F_{\gamma d}$ are depth factors; F_{ci} , F_{qi} and $F_{\gamma i}$ are the load inclination factors; and N_c, N_q, N_γ bearing capacity factors[18]. e is the eccentricity of the resultant force (Figure 4).

$$e = \frac{B}{2} - \frac{M_r - M_{ot}}{V} \tag{12}$$

where V is the resultant of vertical forces as given in Figure 4.

The peak soil pressure at the base can be expressed as:

$$\text{if} < \frac{B}{6} : q_{max} = \frac{V}{B.1}\left(1 + \frac{6.e}{B}\right)$$

$$\text{if} \geq \frac{B}{6} : q_{max} = \frac{4.V}{3.(B-2e)}$$

The limit state function (performance function) associated to this failure mode is given by:

$$\mathcal{F}_3 = q_u - q_{max} \tag{13}$$

The factor of safety against bearing capacity failure can be defined as

$$FS_3 = \frac{q_u}{q_{max}} \tag{14}$$

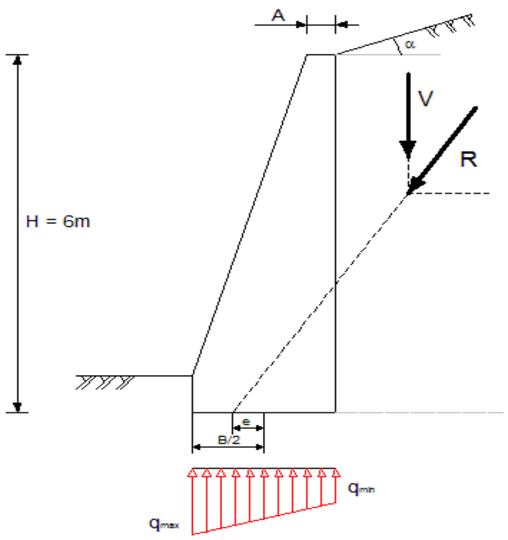

Fig. 4. Bearing capacity equilibrium.

4. Probabilistic modeling

The variability of geotechnical properties can be approached from various perspectives. While stochastic fields offer a natural means to model them and incorporate spatial variability, the challenge lies in accurately estimating their characteristics (such as correlation) based on experimental data.

In this study, a 2D section is analyzed so variation along the length of the wall is not an issue and the 6m height and a base B of about 2m may be "small" relative to the soil correlation distances. Consequently, in our initial approach, we overlooked the spatial variability of these quantities and instead modeled them using r.v

4.1. Modeling of uncertain parameters

In this study, the uncertain parameters pertain to the characteristics of the two soil layers. The backfill is a coarse-grained soil with a unit weight γ_1 , and friction angle of φ_1 and a cohesion C_1. The existing soil below the base has the following properties: γ_2 , φ_2 and C_2, respectively, the unit weight, the friction angle and the cohesion. Furthermore, the wall friction angle δ will be also considered nondeterministic, the mean of δ will be taken equal to $\delta = 2/3 * \varphi_1$ as recommended in literature [15,19]. These parameters are considered as r.v.'s $Y_1,\ldots,Y_7$ with the following notations:

$$Y_1 = \gamma_1, Y_2 = \varphi_1, Y_3 = C_1 , Y_4 = \gamma_2, Y_5 = \varphi_2, Y_6 = C_2, Y_7 = \delta$$

$Y = (Y_1,\ldots,Y_7)^T$ is the probabilistic model of these uncertain parameters. The lognormal distribution is adopted for representing the distribution of uncertain parameters. Even considering normal (Gaussian) distribution would be also appropriate for geotechnical parameters with small coefficient of variation, as the negative value would be negligible. Studies ([20,21]) have demonstrated that the outcomes exhibit minimal variation when assuming either normal or lognormal distributions. Some components of Y exhibit statistical correlation, as indicated by the following correlation matrix:

$$[\rho_Y] = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0.8 & 0 & 0 & 0 & 0 \\ 0 & 0.8 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0.8 & 0.8 & 0 \\ 0 & 0 & 0 & 0.8 & 1 & 0.8 & 0 \\ 0 & 0 & 0 & 0.8 & 0.8 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{15}$$

The mean m_{Yi}, the standard deviation σ_{Yi} and the coefficient of variation $CoV_{Yi} = \sigma_{Yi}/m_{Yi}$ of Y components are summarized in table 2.

As suggested by Phoon et al. [22] who recommend a statistical analysis including the coefficient of variation and the scale of fluctuation. Although the literature provides references for sands and clays [6], quantitative studies devoted to the variability of residual soils are rare and their characteristics require specific treatment. Harr [23] provided a "rule of thumb" by which coefficients of variation below 10% are considered low", between 15% and 30% "moderate", and greater than 30%, "high".

Table 2. Means and CoV of r.v.

	$Y_1 = \gamma_1$	$Y_2 = \varphi_1$	$Y_3 = C_1$	$Y_4 = \gamma_2$	$Y_5 = \varphi_2$	$Y_6 = C_2$	$Y_7 = \delta$
	$[kN/m^3]$	[°]	$[kN/m^2]$	$[kN/m^3]$	[°]	$[kN/m^2]$	[°]
m_{Yi}	18	30	5	19	30	20	20
CoV_{Yi}	10%	10%	10%	10%	10%	10%	10%

4.2. Structural reliability analysis

The main objective of reliability analysis is to evaluate the probability of failure of a system considering specified criteria. To quantify the probability of failure (risk), we define a safety margin, namely a limit state function, which delimits the safety domain (Δ_s) from the failure domain (Δ_f). The limit state function ($\mathcal{F}$) defines the security events and failure events associated to reliable ($\mathcal{F}(\mathbf{y}) > 0$) and failure events ($\mathcal{F}(\mathbf{y}) \leq 0$). Such function is defined as follow:

$$\mathcal{F}(\mathrm{y}) = Z(\mathrm{y}) - \overline{Z} \tag{16}$$

where $Z(\mathrm{y})$ is an observation on the response process and $\overline{Z}$ is the maximum acceptable for the considered observation. We express the probability of failure P_f as:

$$P_f = \mathbb{P}(\mathcal{F}(\mathrm{y})) < 0 \tag{17}$$

y is the vector of the random parameters and $\mathcal{F}$ is the mapping from $\mathbb{R}^p$ into $\mathbb{R}$ defined in equation (16). The probability of failure can be obtained as follow:

$$P_f = \int_{I \quad R^p} {}_{\Delta_f}(\mathrm{y}) p_{\mathrm{Y}}(\mathrm{y}) d\mathrm{y} \tag{18}$$

In order to avoid integrating equation (18), several methods have been developed: simulation methods (such as Monte-Carlo Simulations (MCS) ([1],[3]) whose computational cost is prohibitive) and approximation methods: FORM ([24],[25],[26],[27]) and SORM ([24,28]) methods.

In FORM/SORM reliability methods, the approximation of the limit state surface is made in the standard random space. In this space, the vector of uncertain input parameters $\mathbf{y} = (y_1, \ldots, y_p)^T$ is represented by independent standard Gaussian r.v. denoted by the vector $\mathbf{x} = (x_1, \ldots, x_p)^T$.

Transition from the original random space **y** to the standardized random space **x** is achieved through a probabilistic transformation **T** (Rosenblatt's or Nataf's transformations [29,30]) for example), such that:

$$\mathrm{y} = \mathrm{T}(\mathrm{x}) \tag{19}$$

The limit state function can then be written in Gaussian context:

$$\Gamma(\mathrm{x}) = \mathcal{F}\mathrm{o}\mathrm{T}(\mathrm{y}) \tag{20}$$

The probability of equation (17) is obtained by integrating the probability density $p_{\mathbf{x}}$ of the random mapping $\mathrm{y} = \mathrm{T}(\mathrm{x})$ as follows:

$$P_f = \int_{I \quad R^p} {}_{\Delta_f}(\mathrm{x}) p_{\mathrm{X}}(\mathrm{x}) d\mathrm{x} \tag{21}$$

where p_{X} is the probability density function of the p-dimensional standard Gaussian r.v. x, such that, $\forall \mathrm{x} \in \mathbb{R}^{\,p}$:

$$p_{\mathrm{x}}(\mathrm{x}) = \frac{1}{(2\pi)^{p/2}} \exp\left(-\frac{||\mathrm{x}||^2}{2}\right) \tag{22}$$

where $||\mathrm{x}||^2 = \langle \mathrm{x}, \mathrm{x} \rangle$

This paper deals with the approximation using FORM method allowing the identification of "the design point" which is the Most Probable Point (MPP) P^* associated with the highest probability of failure.

The probability (21) is equal to $\Phi(-\beta)$; where Φ is the cumulative distribution function of the centered-standard Gaussian distribution, and β is the reliability index. The most popular reliability index is the Hasofer-Lind index (β_{HL}), it corresponds to the distance between the origin of space and the point P^* as given in Figure 5, and is obtained by solving the minimization problem:

$$\begin{cases}\beta_{HL} = min(||\mathrm{x}||^2) \\ \Gamma(\mathrm{x}) = 0\end{cases} \tag{23}$$

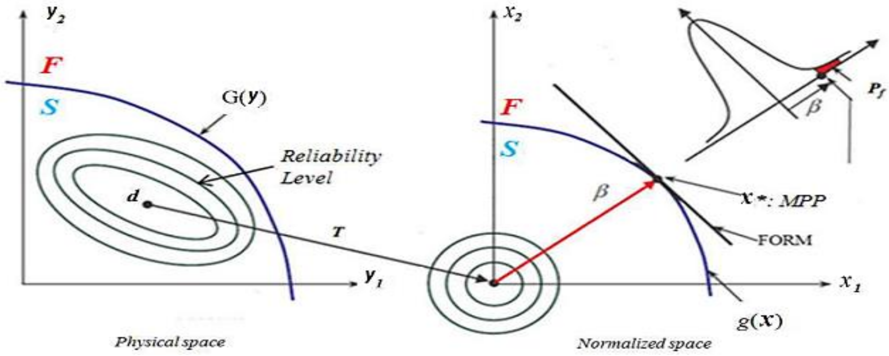

Fig. 5. Illustration of Transformation T and FORM index.

The Rackwitz-Fiessler algorithm [26,28] is used to estimate β_{HL} and can be summarized as described in figure 6.

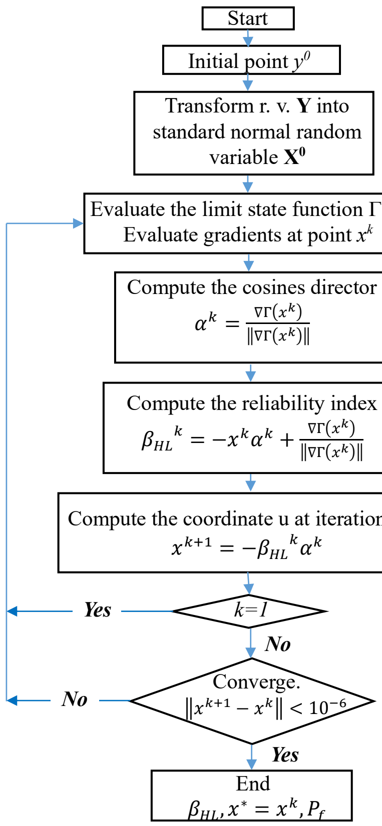

Fig. 6. Flowchart of Hasofer-Lind-Rackwitz-Fiessler algorithm.

4.3. Reliability index (β_{HL}) and sensitivity analysis

Further information known as importance factors, can be obtained from FORM results as discussed in introduction section. These factors aim to assess the significance (weight) of each input r.v. in the physical model regarding the likelihood of failure. Consequently, we seek to understand the impact of each r.v. on system failure, as quantified by the reliability index β at the design point.

The sensitivity of the reliability index to the variables can be deduced from the linearized limit state function Γ calculated using FORM in Equation (21). Here, we note that the direction cosines of α depict the sensitivity of the reliability index β to the independent standard Gaussian variables as follows:

$$\alpha^k = \frac{\nabla\Gamma(x^k)}{\|\nabla\Gamma(x^k)\|} \tag{24}$$

The sensitivity factors indicate the importance on the Hasofer-Lind reliability index of the value of the parameters used to define the distribution of the random vector x**.**

5. Retaining wall dimensioning

In deterministic approach, the geometrical dimensions of the retaining wall are chosen condidering safety factors related to failure modesIn this work we will provide the dimensions of the wall while considering the variability of the soil parameters. Considering all parameters of the problem, dimensioning the retaining wall is reduced to the determination of wall base width (B) and top width (A).

We will consider several values of A and B values, and for each pair of values, we will evaluate the Hasofer-Lind index and the probability of failure. To simplify the task we have taken fixed ratios $\frac{A}{B} = 0.2, 0.3, 0.4, 0.5$ and 0.6. So the problem is reduced to looking for a single variable (B), the latter will be examined in a range of variation from 1.8 m to 2.3 m.

The results of this analysis, giving the evolution of β_{HL} as a function of B and for the five ratios (A/B) for each mode of failure are given in Figure 7.

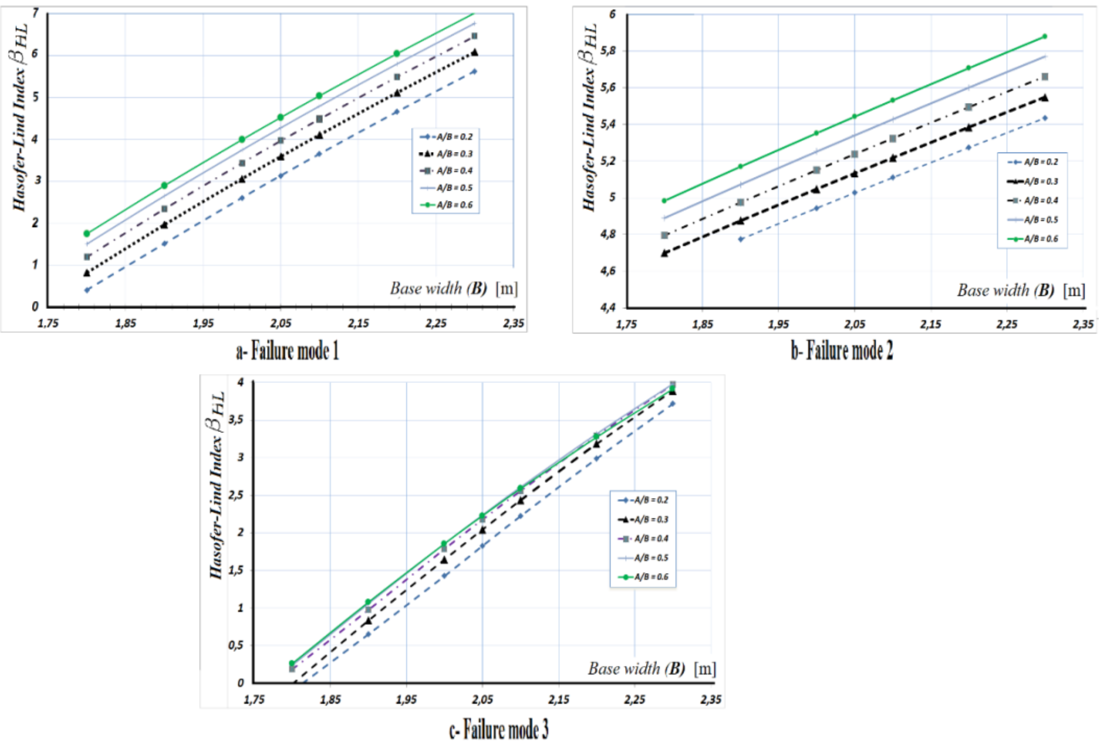

Fig. 7. Evolution of β_{HL} as a function of B for the 3 failure modes.

After a careful review of the results, we concluded that a value of $B = 2.15\,m$ and $A = 0.4\,m$ represents a good compromise between an acceptable level of safety for each failure mode and the quantity of material required for the realization of the retaining wall.

The geometrical parameters of the support wall model have been established considering deterministic analysis. For this study we have considered the following safety factors: $S_1 > 1.5$, $FS_2 > 2$, and $FS_3 > 3$. These values will be kept for the rest of the analyses.

6. Reliability analysis

6.1. Probabilistic vs classical approaches

To illustrate the importance of probabilistic calculation in evaluating the stability of retaining walls, a comparative study is conducted to compare the results between probabilistic calculation and classical deterministic approaches based on safety factors (FOS). In this study, FOS is assessed by considering the variables Y as deterministic, with values equal to their means. Simultaneously, failure probabilities were calculated by accounting for the variability of model parameters, with coefficients of variation (CoV) of 5%, 10%, 15%, and 20% around their means. The obtained results are summarized in table 3.

Table. 3. Obtained results for both deterministic and probabilistic approaches

			Mode 1	Mode 2	Mode 3
Deterministic Analysis	*FOS*		1.5	2	3
Probabilistic Analysis	*CoV 5 %*	P_f	0.1e-05	0.814	1.02
	CoV 10 %	P_f	2.6e-5	1.257	2.192
	CoV 15 %	P_f	0.021	4.562	10.326
	CoV 20 %	P_f	2.023	10.912	26.32

These results highlight that the risk expressed by the probability of failure continuously increases with the increase in CoV, while maintaining a constant FOS. For instance, for the overturning failure mode, the risk exceeds 26% (a significant or even concerning level) for a CoV of 20%. This comparative study underscores the importance of probabilistic calculation, enabling the evaluation of the structure's condition while considering the variability of model parameters. Conversely, deterministic calculation risks overestimating the structure if variability is low and underestimating it if parameters exhibit significant dispersion (e.g., a very high CoV).

These observations are widely recognized and shared by various authors in the field of construction in general ([31,32],[14]), and specifically in geotechnical engineering ([1,2],[7],[4]), where parameter variability is more pronounced.

6.2. Reliability analysis

In this section, we will examine the retaining wall behavior by calculating the probability of failure taking into account the variability of the model parameters. At first we will examine the wall by considering the variability of the soil parameters whose r.v are given in table 1, where mode 1, 2 and 3 refer to the three failure modes described above.

For each mode of failure, values of Hasofer-Lind index and correspondent probability of failure and the coordinate of the MPP in the standard Gaussian space (x^*) and physical space y^* are given in table 4.

As shown in table 4, results in terms of probabilities of failure show that the third mode (bearing capacity) is the most feared scenario with the presence of uncertainties: $P_f = 2.2$ %, however, overturning failure mode (mode 2) presents a very low risk ($P_f = 1.25$ %). On the other hand, the sliding failure (mode 1) presents no risk and the probability of failure is of the order of 10^{-3} %. It is therefore important for the designer to pay close attention to Mode 3 more than the other two modes.

Table 4. Probability of failure and MPP coordinates for the three failure modes.

		Mode 1	Mode 2	Mode 3
$\boldsymbol{\beta_{HL}}$		5.0171	2.2404	2.0166
$\boldsymbol{P_f}$		2.65e-05	1.2575	2.1920
1	x^*	4.9617	1.5852	1.5916
	y^*	28.5490	22.3663	22.3800
2	x^*	0.6466	0.6203	0.6212
	y^*	31.1859	31.1247	31.1263
3	x^*	0.3302	0.1208	0.1212
	y^*	5.0444	5.0162	5.0163
4	x^*	0	-0.0719	-0.1168
	y^*	19.0000	14.6915	15.7394
5	x^*	0	-0.7243	-0.6587
	y^*	20.0000	18.1265	18.5480
6	x*	0	-1.2553	-0.8270
	y*	30.0000	27.9758	28.6666
7	x*	-0.1589	-0.0365	-0.0366
	y*	19.6822	19.9271	19.9268

As mentioned in previous sections, the design point represents the worst possible combination of the r.v. that can potentially lead to failure. The coordinate of the design point in the standard normal space x^* and corresponding values in the physical space y^* are also given in table 4 for each failure mode.

7. Evaluation of the impact of construction defects

A construction defect is generally defined as a defect in the design, the workmanship, and/or in the materials or systems used on a project that results in a failure of a component of a building or structure and causes damage to persons or properties. Workmanship defects typically result from the contractor's failure to build a structure or a part of a structure concerning the construction documents. Workmanship defects may include items such as the non-respect of the specifications in terms of dimensions and the quality of materials used.

In this section, we will consider defects in the construction of the retaining wall. These defects will be presented in the model as additional r.v. in the reliability analysis. These parameters are:

- γ_c is the concrete weight initially taken equal to $\gamma_c = 24kN/m^3$
- dimensions of the wall B and A initially considered as deterministic parameters with values taken equal to 2 m and 0.4 m
- a false-plumb: this lack of verticality of the work is characterized by an angle slightly different from that of $\lambda = 90°$ expected.

These four supplementary r.v. will be represented by normal r.v. having means and coefficient of variance as given in table 5. Mean values of the supplementary r.v. are taken equal to the deterministic values used in previous sections. For CoV, we consider that geometrical parameters (A, B and λ) have a small variation around the mean value (errors in dimensions are unlikely). On the other hand, the density of the concrete (γ_c) presents a greater variability linked to the dosages, mode of execution and presence or not of a good vibration. So we considered for this last parameter a CoV of 5%.

Table 5. Means and CoV of supplementary r.v. related to execution defects.

	$Y_8 = \gamma_c$	$Y_9 = B$	$Y_{10} = A$	$Y_{11} = \lambda$
	$[kN/m^3]$	[m]	[m]	[°]
m_{Yi}	24	2.15	0.4	90
CoV_{Yi}	5%	2%	2%	2 %

The results of reliability analysis of the wall with construction defects are given in table 6.

Table 6. Obtained Results considering execution defects.

		Mode 1	Mode 2	Mode 3
$\boldsymbol{\beta_{HL}}$		3.2764	2.0442	1.6638
$\boldsymbol{P_f}$ (%)		0.0530	2.0515	4.8127
1	$x*$	2.1257	1.3294	1.1099
	$y*$	23.7730	21.8130	21.2348
2	$x*$	0.7977	0.5830	0.5082
	$y*$	31.4466	31.0564	30.9205
3	$x*$	0.1608	0.1037	0.0872
	$y*$	5.0216	5.0139	5.0117
4	$x*$	0	-0.0589	-0.0682
	$y*$	19.0000	15.5165	17.0683
5	$x*$	0	-0.5847	-0.3953
	$y*$	20.0000	18.4863	19.1357
6	$x*$	0	-1.0150	-0.4874
	$y*$	30.0000	28.3633	29.2142
7	$x*$	-0.0217	-0.0201	-0.0179
	$y*$	19.9566	19.9598	19.9643
8	$x*$	-1.5191	-0.2717	-0.4755
	$y*$	22.1771	23.6740	23.4295
9	$x*$	-1.2137	-0.1975	-0.5199
	$y*$	2.0977	2.1415	2.1276
10	$x*$	-0.0885	-0.0182	-0.0291
	$y*$	0.3993	0.3999	0.3998
11	$x*$	1.3285	0.7560	0.6120
	$y*$	92.3913	91.3608	91.1016

As for the previous analysis, we note that the third mode of failure is the most likely mode. Compared with a wall without construction defects, the probability of failure increases in a very clear way with the existence of defects. For mode 2 and mode 3, the probabilities have nearly doubled but remain at a level that is not too alarming (<5%). For mode 1, the risk is still not very significant (0.05%) despite the increase. This study shows that the construction phase is as important as the design phase in preventing risks

8. Sensitivity analysis

Effect of the every r.v. on the failure probability is expressed in FORM analysis through the "sensitivity factor" (Eq 24), which is measured in terms of the directional cosines of the position vector of the MPP, in the standard Gaussian space. Results of this analysis are given in table 7. The cosines α_i give the impact of each variable i for each failure mode. It is therefore a tool for herarchizing parameters. We note that variable 1 ie $Y_1 = \gamma_1$ is the most influential parameter in the 3 modes with or without construction fault and $Y_3 = C_1$ are also influential parameters in the three modes of failure. The other parameters have a more or less negligible impact. For the case of a wall with a construction fault, in addition to $Y_1 = \gamma_1$ errors in the parameters $Y_8 = \gamma_c$ and $Y_9 = B$ have a significant impact, especially for modes 1 and 3.

Table 7. Results of sensitivity analysis.

	without construction defects						with construction defects					
	mode 1		mode 2		mode 3		mode 1		mode 2		mode 3	
	α_i	rank	α_i	rank	α_i	rank	α_i	rank	α_i	rank	α_i	rank
$\boldsymbol{\gamma_1}$	0.9485	1	0.4325	1	0.6212	1	0.4076	1	0.3669	1	0.4338	1
$\boldsymbol{\varphi_1}$	0.0220	3	0.0639	4	0.1013	4	0.0628	5	0.0699	5	0.0963	3
$\boldsymbol{C_1}$	0.0043	4	0.0024	7	0.0036	6	0.0023	7	0.0022	10	0.0027	9
$\boldsymbol{\gamma_2}$	0		0.0076	5	0.0032	7	0		0.0060	8	0.0015	10
$\boldsymbol{\varphi_2}$	0		0.1307	3	0.1028	3	0		0.1026	4	0.0535	7
$\boldsymbol{C_2}$	0		0.3576	2	0.1610	2	0		0.2792	2	0.0809	5
$\boldsymbol{\delta}$	0.0251	2	0.0049	6	0.0066	5	0.0077	6	0.0051	9	0.0048	8
$\boldsymbol{\gamma_c}$							0.2017	2	0.0141	6	0.0784	6
$\boldsymbol{B}$							0.1299	4	0.0075	7	0.0935	4
$\boldsymbol{A}$							0.0007	8	6.e-05	11	0.0003	11
$\boldsymbol{\lambda}$							0.1869	3	0.1416	3	0.1539	2

9. Effect of the friction angle soil-wall

In this section, we are interested in the effect of the soil interaction structure characterized by the friction angle: δ. As discussed above, the Coulomb thrust theory takes into account the coefficient of soil-structure friction in active and passive pressure coefficients (k_a and k_p respectively) (Eq. 5). The active force per unit length of the wall (P_a) will be angled at δ relative to the normal of the back face of the wall. The value of inclination angle depend son wall materials and nature of the soil (precisely the friction angle φ_1. In general, the value of the wall friction angle, δ is between $(\varphi_1/2)$ and $(2\varphi_1/3)$.

Terzaghi [16] indicates that the relation between the soil friction angle and that of the soil wall (δ/φ) varies from $1/3$ to $2/3$. Table 8 presents the range of friction angles (δ°) for concrete walls concerning various backfill materials.

Table 8. Range of concrete wall friction angle δ(°) for backfill material.

Soil	gravel	coarse sand	silty clay	stiff clay	fine sand
$\boldsymbol{\delta}$(°)	27-30	20-28	12-16	15-20	15-25

In recent research conducted by Ferreira [33], it was demonstrated that the roughness of the surface or the presence of a coating influences the evaluation of soil-wall friction for different materials. The relation between (δ/φ) varies from 0 for a smooth coating (cemented or tar) to 1 for coating a rough wall. The works do not report the type of soil contact with the surface and do not quantify the roughness of the surfaces.

Friction coefficient can vary depending on the roughness of the wall surface in contact with the soil. We will therefore examine this effect on the probabilities of failure for the 3 failure modes, by considering in this analysis of the values of the mean of δ variable: m_δ = 5, 10, 15, 20, 25 and 30.

For these different values we evaluate the probability of failure for each mode of ruin according to the ratio δ/φ.

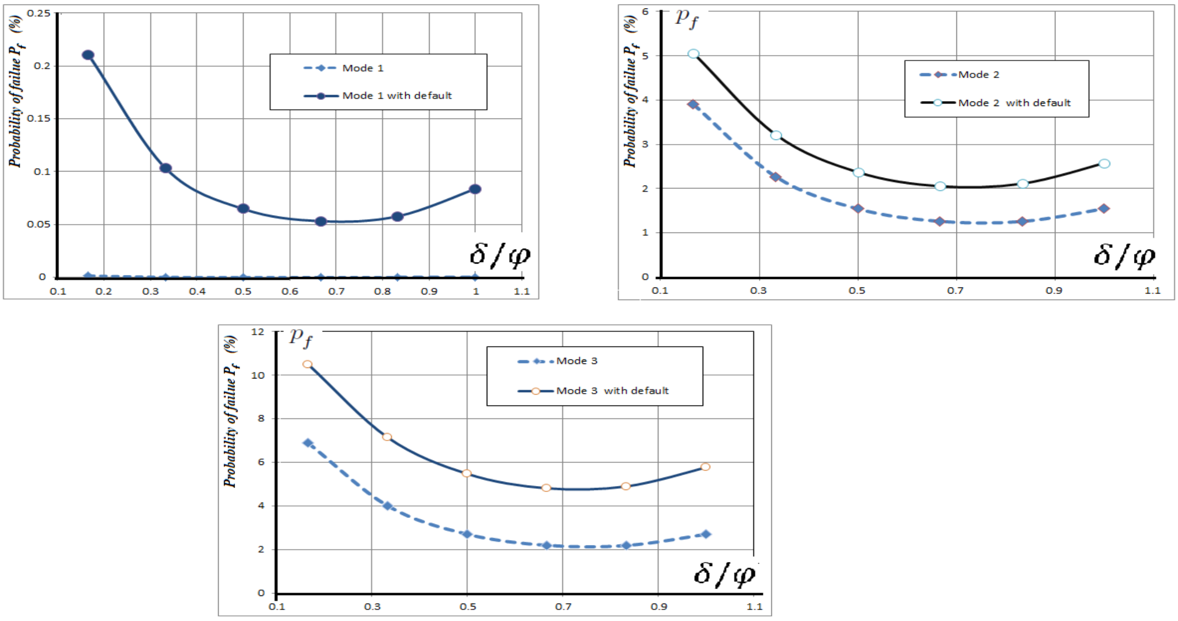

Fig. 8. Evolution of p_f as a function of δ/φ for the three failures modes.

The results obtained are illustrated in the graphs of Figure 8 Obtained results clearly show that the values of the probability of failure, for the three modes, are very sensitive to the values of the angle of friction. The effect is sharper for the risk of overturning (mode 2) and the bearing capacity (mode 3). We note also, that the shape of the curves p_f as a function of (δ/φ) is parabolic. The maximum values are observed at the two extremities of the interval δ/φ, *i.e* $\delta/\varphi \in [0, 0.4] \cup [0.75, 1]$ these two intervals correspond to very smooth surfaces for the first and a very rough surface for the second.

The lowest values of probabilities are in the range $[0.4, 0.75]$, which corresponds to a rough surface obtained by respecting the rules of formwork and pouring of concrete and especially the consistency of the concrete. It is well noted that this interval corresponds well to the interval recommended by Terzagui [16] $[1/3, 2/3]$. This analysis highlights the importance for the engineer to respect the rules and the best practices in construction because in the opposite case, the notes and assumptions of calculations will not be respected and the probabilities of failures can be double of those expected. This risk is amplified when it is accompanied by defects of construction

10. Conclusions

Retaining wall failures are most often caused by incorrect design or construction parameters. Geotechnical engineers should be vigilant in selecting the appropriate backfill, designing the wall for overloads, and suggesting measures for backfill drainage when suitable materials are not available. In this study, the stability of gravity retaining wall was analyzed using a probabilistic approach. The external stability of the wall under static conditions has been taken into account by analyzing the bearing capacity, the sliding and overturning failure modes are considered as a performance function.

This article introduces an innovative approach that employs probabilistic methods to assess the reliability of gravity retaining walls, taking into account uncertainties in parameters and their inherent variability. The FORM method is applied in this study to analyze the influence of construction defects and soil/structure friction on the reliability of gravity walls. This approach stands out from traditional empirical methods, which essentially rely on total safety factors and handle uncertainties arbitrarily.

The incorporation of probabilistic methods into the analysis of gravity retaining wall stability represents a groundbreaking advancement, providing deeper insights into the reliability of these structures. Such an approach holds significant promise for improving safety assessments and rehabilitation strategies within civil engineering practices. It highlights the crucial importance of taking into account the uncertainties in geotechnical parameters and construction defects.

While this article presents interesting results, it also suggests avenues for future research. Investigating the long-term performance of gravity retaining walls and assessing the effects of climatic changes on soil properties and water levels would introduce additional uncertainty into our reliability analysis. This would provide opportunities for further investigation. Additionally, developing an approach for Reliability-Based Design Optimization (RBDO) using automated numerical tools [34] would enhance accessibility and efficiency for practitioners.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Noureddine Rhayma: Conceptualization; Formal analysis; Software; Validation; Visualization; Methodology; Roles/Writing – original draft

Mohamed Khorchani: Investigation; Formal analysis; Methodology; Writing – review & editing.

Pierre Breul: Supervision; Formal analysis; Validation; Writing – review & editing.

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