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Seismic stability of gravity retaining walls: reliability assessment and web application

Stabilité sismique des murs de soutènement gravitaires: évaluation de la fiabilité et application web

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ABSTRACT: This paper introduces a reliability-based seismic stability analysis of gravity retaining walls using a classical model and Monte Carlo simulation method. It empowers engineers to make informed design decisions based on acceptable probabilities of failure, thereby enhancing the reliability of their projects. The resulting web-based application provides an interactive platform for engineers and researchers to input seismic and soil parameters and perform the geotechnical design under seismic loads.

RÉSUMÉ: Ce document présente une analyse de stabilité sismique des murs de soutènement gravitaires basée sur la fiabilité, en utilisant un modèle classique et la méthode de simulation de Monte Carlo. Il donne aux ingénieurs la possibilité de prendre des décisions de conception éclairées en se basant sur des probabilités de défaillance acceptables, améliorant ainsi la fiabilité de leurs projets. L'application web résultante offre une plateforme interactive permettant aux ingénieurs et chercheurs de saisir des paramètres sismiques et géotechniques et d'effectuer la conception géotechnique sous des charges sismiques.

Keywords: Seismic stability; reliability-based design; retaining walls.

1 INTRODUCTION

Gravity retaining walls serve as critical components of geotechnical engineering, especially in ensuring the structural stability during seismic occurrences. This paper builds upon the extensive body of knowledge developed over the years in the domain of seismic design principles and the behaviour of gravity retaining walls. The primary aim of this paper is to introduce a reliability-based approach to analysing the seismic stability of such walls, offering both theoretical insights and practical solutions.

2 LITERATURE REVIEW

The seismic design of gravity retaining walls is a critical component of geotechnical engineering, addressing the stability of these structures during earthquake events. The study by Richards and Elms (1979) offers insights into early research on the seismic behavior of gravity retaining walls, providing a foundation for subsequent studies. Whitman et al. (1985) contributed to our understanding of seismic design principles for gravity retaining walls, providing historical context and insights into design methods. Notably, Das and Luo (2017) summarized the fundamental principles of soil behavior that underlie seismic analysis and design, providing essential groundwork for subsequent research.

In recent years, Srikar and Mittal (2020) proposed a modified pseudodynamic approach for seismic analysis and this approach is particularly relevant when assessing retaining walls subjected to surcharge loads, enhancing our methods for evaluating their seismic response. Srikar and Mittal (2021) presented a modified pseudo-dynamic analysis for rigid gravity retaining walls with specific soil and surcharge conditions and offered a more tailored approach to seismic analysis. Jadhav and Prashant (2023) developed charts for permanent displacement-based seismic design of cantilever retaining walls.

3 DESIGN MODEL

The design procedure documented in Das (2024) is used in this study for seismic stability analysis of gravity retaining walls. Figure 1 illustrates the design scheme. The wall has a height of H on the underlain soils with friction angle (ϕ_2) and unit weight (γ_2). The backfill materials have friction angle (ϕ_1) and unit weight (γ_1). The friction angle (δ) between the wall and the backfill is 2/3 of (ϕ_1). The active earth pressure coefficient under seismic condition is:

$$K_{ae} = \frac{sin^2(\phi_1+\beta-\theta\prime)}{cos\theta\prime sin^2(\beta-\theta'-\delta)\left[1+\sqrt{\frac{sin(\phi_1+\delta)sin(\phi_1-\theta'-\alpha)}{sin(\beta-\delta-\theta\prime)sin(\alpha+\beta)}}\right]} \quad (1)$$

Next, the required weight of wall for a tolerable wall displacement (Δ) is given:

$$W = \left[\frac{1}{2}\gamma_1 H^2(1-k_v)K_{ae}\right]C_{IE} \quad (2)$$

where

$$C_{IE} = \frac{sin(\beta-\delta)-cos(\beta-\delta)tan\phi_2}{(1-k_v)(tan\phi_2'-tan\theta\prime)} \quad (3)$$

$$\theta' = tan^{-1}\left(\frac{k_h}{1-k_v}\right) \quad (4)$$

$$k_h = A_a\left(\frac{0.2A_v^2}{A_a\Delta}\right) \quad (5)$$

where, α is the slope angle of the backfill, and β is the angle of the wall heel. The coefficients k_h and k_v are the horizonal seismic acceleration and vertical seismic acceleration, over the acceleration due to gravity, respectively. The values of A_a and A_v are documented in Applied Technology Council (1978).

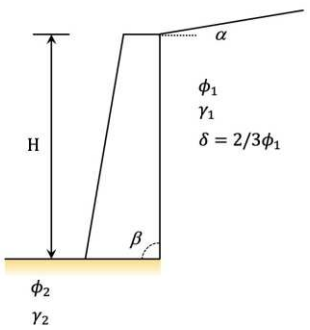

Figure 1. Scheme of a gravity retaining wall for earthquake conditions.

The parameter values in the design of a gravity retaining wall under seismic condition documented in Das (2024) are adopted and shown in Table 1. Additionally, α is zero and β equals 90°. Following Eq. (2), the required weight of wall that meets the displacement requirement is determined to be 54.1 kN/m. This result does not consider the factor of safety.

Table 1. Parameters and their values in the design of a gravity retaining wall under seismic condition.

Variable	Symbol	Value
Height of wall	H	5 m
Limiting wall horizontal displacement	Δ	38 mm
Friction angle of backfill	ϕ_1	36°
Unit weight of backfill	γ_1	16 kN/m^3
Friction angle of underlain soil	ϕ_2	36°
Normalized vertical seismic acceleration	k_v	0
Coefficient	A_a	0.2
Coefficient	A_v	0.2

4 PROBABILISTIC DESIGN

Next, the above procedure is repeated in a Monte Carlo simulation (MCS) framework. For simplicity, only the soil strength parameters (ϕ_1 and ϕ_2) are chosen as normally distributed variables, while all other parameters are assumed to be constant. It is assumed that the coefficient of variation (*COV*) of ϕ_1 is 0.10 and the *COV* of ϕ_2 is 0.15, respectively. Their mean values follow Table 1 and are 36°.

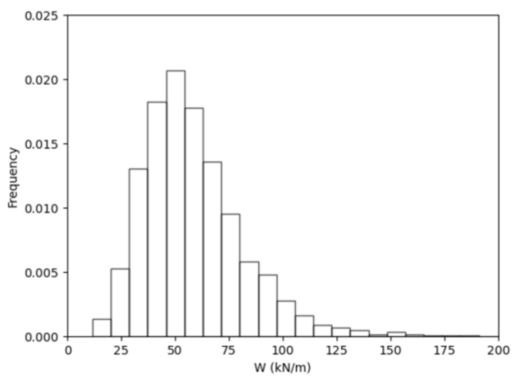

Figure 2. Resulting histogram of wall weight (W) from Monte Carlo simulation.

The number of MCS is 5000. Figure 2 shows the resulting histogram of the required wall weight. The Shapiro-Wilk test shows that this resulting distribution does not follow a lognormal distribution. Based on Figure 2, the 95th percentile of W is 100.7 kN/m. It indicates that if the design target is to ensure there is only 5% of chance to fail, the designed wall weight should be 100.7kN/m. Similarly, the 99.75th percentile of W is 161.5 kN/m. If the wall weight is designed to be 161.5 kN/m, the probability of failing to meet the required wall displacement is reduced to 0.25%. The smaller the target probability of failure is, the larger designed wall weight will be, leading to more project cost. This demonstrates that the probabilistic approach can not only quantify the uncertain of soil parameters, but also ensure a rational design based on the acceptable probability of failure.

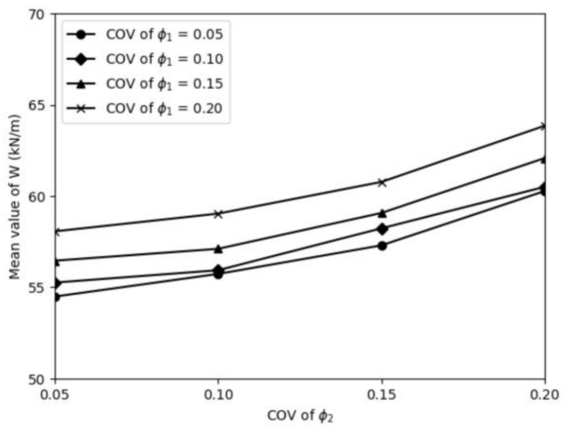

Figure 3. The mean values of wall weight (W) for various pairs of coefficient of variation (COV) for ϕ_1 and ϕ_2.

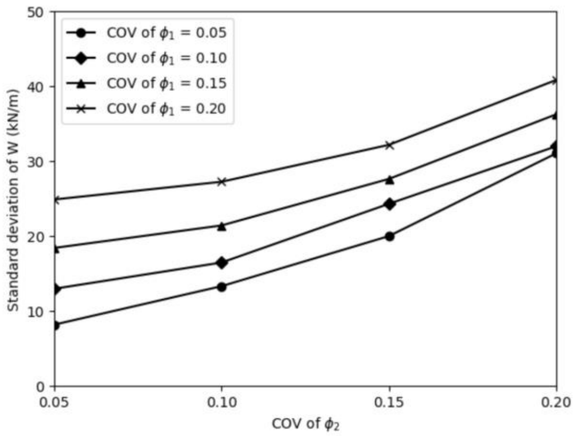

Figure 4. The standard deviations of wall weight (W) for various pairs of coefficient of variation (COV) for ϕ_1 and ϕ_2.

To better understand the uncertainty propagation in the geotechnical design of gravity retaining walls under seismic condition, a series of parametric study is performed. The following *COV* values for ϕ_1 and ϕ_2 are considered: 0.05, 0.10, 0.15 and 0.20. For each pair of *COV*, a number of 5000 MCS is performed. Based on the resulting distributions of the required all weight (*W*), the mean values and standard deviations are obtained and presented in Figure 3 and Figure 4, respectively. Figure 3 shows that when the *COV* of ϕ_1 is held constant, the mean *W* increases with the *COV* of ϕ_2. For the same level of *COV* of ϕ_2, the mean W increases with *COV* of ϕ_1. It indicates that the mean required wall weight to satisfy the required wall displacement in seismic condition increases in the variability in either ϕ_1 or ϕ_2.

Figure 4 shows that when the *COV* of ϕ_1 is held constant, the standard deviation (*SD*) of *W* increases with *COV* of ϕ_2. For the same level of *COV* of ϕ_2, the *STD* of *W* increases with the *COV* of ϕ_1. It indicates that the variation in the required wall weight to satisfy the required wall displacement in seismic condition increases in the variability in either ϕ_1 or ϕ_2.

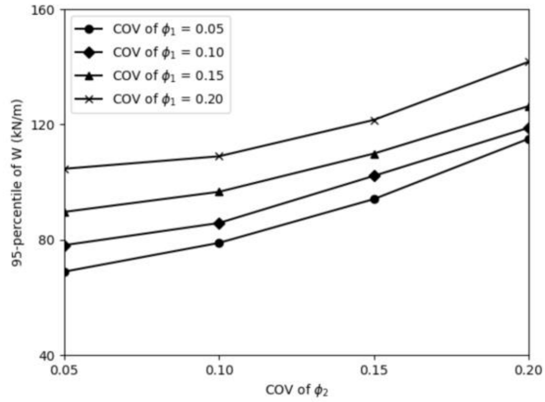

Figure 5. The 95[th] percentile of the required wall weight (W) for various pairs of coefficient of variation (COV) for ϕ_1 and ϕ_2.

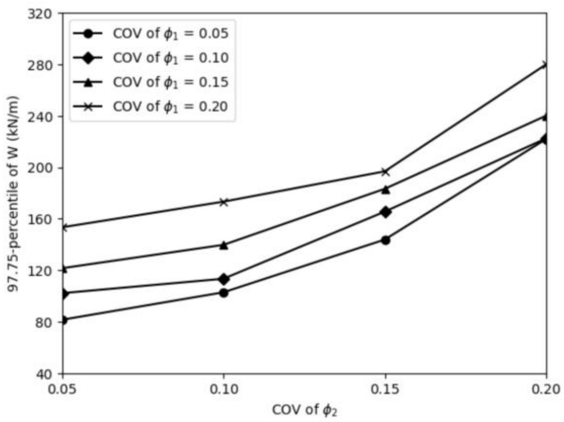

Figure 6. The 99.75[th] percentile of the required wall weight (W) for various pairs of coefficient of variation (COV) for ϕ_1 and ϕ_2.

Figure 3 and Figure 4 explicitly demonstrate that the uncertainty in soil strength parameters has inevitable impact on the geotechnical design of gravity retaining walls under seismic condition. The geotechnical design can then be realized based on the outcomes of MCS. The percentiles of the resulting probability distribution of *W* can be readily obtained for some target probability of failure. Figure 5 shows the 95[th] percentile of the required W that satisfies the required wall displacement for various pairs of coefficient of variation (*COV*) for ϕ_1 and ϕ_2. Figure 5 can serve as a design chart for the target probability of failure of 5%. Given a known pair of *COV* for ϕ_1 and ϕ_2, the designed *W* can then be interpolated in this chart. Similarly, Figure 6 shows the 99.75th percentile of the required *W* that satisfies the required wall displacement for various pairs of coefficient of variation (*COV*) for ϕ_1 and ϕ_2. Figure 6 corresponds to the design chart for the target probability of failure of 0.25%. It is obvious that compared to 5% probability of failure, the designed *W* values in Figure 6 are much greater.

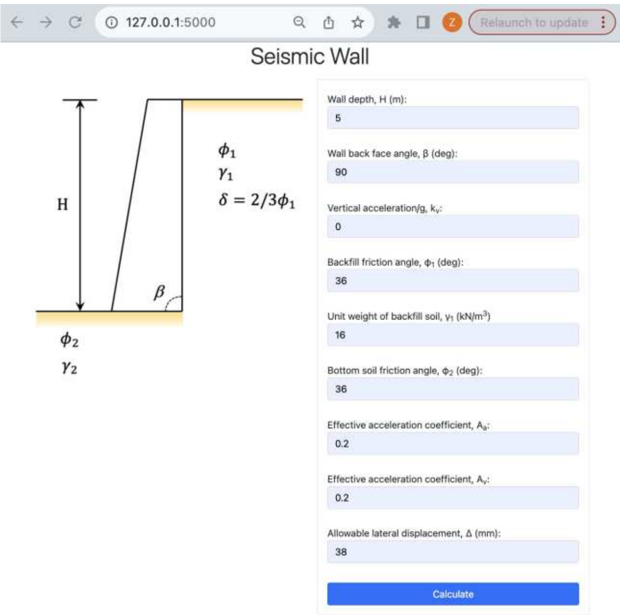

Figure 7. User interface of the developed application

5 WEB APPLICATION

A Flask application has been created to support the seismic design of gravity retaining walls, with a specific focus on implementing the mathematical model described in Eq (2) for deterministic analysis. The application addresses the time-consuming and error-prone nature of manual seismic design calculations for such structures. Engineers and designers often face challenges in performing these calculations, which involve intricate parameters like wall geometry, soil properties, and seismic coefficients. Our Flask app aims to simplify this process, reduce errors, and provide a user-friendly interface to efficiently obtain critical design information, such as the required unit weight of the wall (in kN/m). By streamlining seismic design calculations, this application contributes to the safety and reliability of gravity retaining walls during seismic events.

6 DISCUSSION AND CONCLUSION

This paper ventures into the realm of probabilistic design by conducting a Monte Carlo simulation, demonstrating the capacity to quantify uncertainties in soil strength parameters. It is commonly understood that reliability is represented by one minus the probability of failure. This approach empowers engineers to make informed design decisions based on acceptable probabilities of failure, thereby enhancing the reliability of their projects. The significance of uncertainty in geotechnical design is underscored through parametric studies, highlighting the influence of soil strength parameter variations on the required wall weight. This reinforces the importance of considering uncertainty as an integral part of the design process. Lastly, the research transcends theory to practicality with the introduction of a user-friendly Flask web application.

REFERENCES

Applied Technology Council. (1978). Tentative Provisions for the Development of Seismic Regulations for Buildings. Publication ATC-3-06.

Das, B.M. (2024). Principles of Foundation Engineering, 10th Edition. Cengage Learning. ISBN-10: 0357684656. ISBN-13: 9780357684658.

Das, B.M. and Luo, Z. (2017). Principles of Soil Dynamics, 3rd Edition. Cengage Learning. ISBN-10: 1305389433. ISBN-13: 9781305389434.

Jadhav, P.R. and Prashant, A. (2023). Charts for Permanent Displacement-Based Seismic Design of Cantilever Retaining Walls. Journal of Earthquake Engineering, 27:12, 3341-3361. https://doi.org/10.1080/13632469.2022.2134943

Richards Jr, R., and Elms, D. G. (1979). Seismic behavior of gravity retaining walls. Journal of the Geotechnical Engineering Division, 105(4), 449-464.

Srikar, G., and Mittal, S. (2020). Seismic analysis of retaining wall subjected to surcharge: A modified pseudodynamic approach. International Journal of Geomechanics, 20(9), 06020022. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001780

Srikar, G., and Mittal, S. (2021). Modified pseudo-dynamic analysis of rigid gravity retaining wall with cohesion-less backfill and uniform surcharge. Geomechanics and Engineering, 26(5), 453-464. https://doi.org/10.12989/gae.2021.26.5.453

Whitman, R. V., Liao, S., and Massachusetts Institute of Technology. Department of Civil Engineering. (1985). Seismic design of gravity retaining walls (pp. 533-540). US Army Engineer Waterways Experiment Station.