Proceedings of ISFOG 2025
5TH INTERNATIONAL SYMPOSIUM ON
FRONTIERS IN OFFSHORE GEOTECHNICS
Nantes, France | June 9-13 2025

ISBN 978-2-85782-758-0

Evaluating Triggering Mechanisms of Submarine Landslides: Insights from Centrifuge Testing and Numerical Analysis

Ali Lashgari*
*Department of the Built Environment, Aalborg University, Aalborg, Denmark, email: alil@build.aau.dk (*corresponding author)*

Amin Barari
Department of the Built Environment, Aalborg University, Aalborg, Denmark, email: abar@build.aau.dk & School of Engineering, RMIT University, Melbourne, Australia, email: amin.barari@rmit.edu.au

Jannie Sønderkær Nielsen
Department of the Built Environment, Aalborg University, Aalborg, Denmark, email: jsn@build.aau.dk

ABSTRACT: This paper presents an investigation into specific triggering mechanisms of submarine landslides, integrating centrifuge test data and numerical simulations to examine the role of pore water pressure (PWP) and ground motion intensity measures (IMs) in submarine slope failure mechanisms. A series of pulse-like ground motions (PLGMs) were selected for numerical simulations after validating the model with results from a centrifuge test. Data spanning from 1974 to 2024 highlighted static liquefaction and seismic activity as key triggers for submarine landslides. However, less than 3% of geotechnical centrifuge tests conducted over this period specifically addressed submarine landslides. The collected data revealed a clear relationship between slope failure angles and the PWP ratio (r_u), showing that even a small increase in PWP ($r_u = 0.1$) can destabilize relatively gentle slopes. Moreover, comparisons between analytical methods and empirical data demonstrated that accounting for dynamic PWP improves the accuracy of predictions for seismic submarine landslide behaviour by analytical methods. The numerical analysis further indicated that energy-based IMs, correlate more strongly with seismic submarine sliding displacement than amplitude-based IMs. Moreover, the deviatoric strains significantly contributed on the submarine slope displacement. These findings underscore the critical importance of accurate PWP estimating and advanced estimation techniques for assessing submarine slope stability, particularly in seismic environments.

Keywords: Submarine landslides; Centrifuge tests; Pore water pressure; Pulse-like ground motions; Offshore infrastructure

1 INTRODUCTION

Submarine landslides pose significant risks to offshore infrastructure, especially in regions prone to seismic activity. Physical modeling studies, particularly geotechnical centrifuge tests, are vital in understanding the triggers and failure mechanisms of these landslides. A key factor influencing submarine slope stability is the variation of PWP, which can be generated by static liquefaction or seismic activity (e.g., Maghsoudloo et al., 2021). Previous studies (e.g., Zhang et al., 2015; Zhang and Askarinejad, 2019) have demonstrated that PWP buildup can significantly affect submarine slope failure likelihood, and the critical PWP for failure varies depending on conditions, including slope angle and soil condition. For example, higher r_u values can lead to slope failure in gentle slopes, whereas lower r_u values are required for failure in steep slopes under static liquefaction conditions.

During an earthquake, factors such as ground motion characteristics, slope geometry, and soil properties all play critical roles in determining slope stability. Analytical methods are commonly used to estimate seismic sliding displacement, typically relying on simplified assumptions where slope geometry and soil properties are represented by the yield acceleration coefficient (k_y). However, recent studies (e.g., Jafarian and Lashgari, 2017) have shown that modifying k_y to account for dynamic PWP offers more accurate predictions of slope failure in liquefiable soils. Moreover, the characteristics of ground motions can significantly affect slope deformation. PLGMs, which are high-energy motions driven by the forward-directivity effect

during fault ruptures (Somerville, 2003), differ from ordinary ground motions in their intensity measures (IMs). These differences can significantly amplify shear strain and PWP accumulation, leading to large sliding displacements.

While numerous centrifuge testing studies have focused on onshore slopes (e.g., Brennan and Madabhushi, 2009), far fewer have examined submarine landslides (e.g., Zhang and Askarinejad 2019), despite their potential to cause significant damage to offshore infrastructure. A review of centrifuge tests of slope stability conducted between 1974 and 2024 revealed that less than 3% of the studies focused on submarine landslides, as shown in Figure 1. This highlights critical gaps in research, particularly in relation to the interaction between landslides and offshore infrastructure. As areas in which offshore wind farms are developed continue to expand, a deeper understanding of submarine landslide dynamics is essential for enhancing risk assessments.

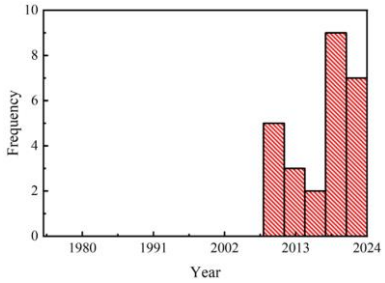

Figure 1. Performed studies in the field of centrifuge modeling from 1980-2024 focusing on submarine landslides

In this study, the essential trigger and failure mechanisms of submarine landslides are examined using collected centrifuge test data and numerical analyses. First, the key triggering mechanisms of submarine landslides are discussed. Next, the parameters influencing these landslides are analyzed based on the collated centrifuge data. Moreover, the performance of analytical methods commonly used for onshore seismic landslides is assessed in the context of submarine landslides. Finally, the performance of the submarine slopes is evaluated using a suite of PLGMs.

2 TRIGGERING MECHANISMS OF SUBMARINE LANDSLIDES

Submarine landslides can be triggered by various mechanisms, driven by a complex interplay of environmental and geotechnical factors. The primary triggers include: (1) pore water pressure (PWP) generation, either through static or seismic liquefaction, (2) seismic shaking, and (3) sediment instability due to erosion or oversteepening (e.g., Locat and Lee, 2002). Additional contributing factors include differential sedimentation, gas hydrate dissociation, and cyclic loading from ocean waves and currents. Landslide-triggering mechanisms can be broadly categorized into fault rupture (T1), site response and wave propagation (T2), and PWP generation (T3). However, the consequences of submarine landslides, such as debris flows (T4), turbidity currents (T5), and tsunamis (T6), can be distinguished from the initial triggering processes. A schematic representation of these mechanisms is shown in Figure 2. In many cases, a combination of triggers contributes to slope instability, posing potential hazards to offshore wind infrastructure.

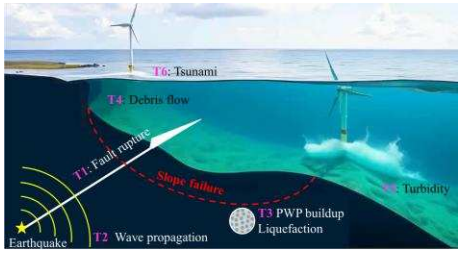

Figure 2. Schematic representation of submarine landslide triggering mechanisms and their consequences

2.1. Pore water pressure generation

PWP buildup and subsequent liquefaction are among the primary triggers of submarine landslides. The increase in PWP lowers effective stress and soil stiffness, making sediments more susceptible to failure. Even on gentle submarine slopes, rapid undrained shearing conditions in sandy soils can lead to localized failures, which further increase PWP and ultimately result in liquefaction (e.g., Maghsoudloo et al., 2021; Carey et al., 2022).

2.2. Seismic activity

Earthquake-induced shaking can lead to soil liquefaction, wave propagation, and fault rupture, all of which can initiate submarine slope failures and result in downslope accelerations within the failing slab. The seismic response of a slope is complex and important

factors such as topography and soil conditions can affect the site response. (e.g., Kramer, 1999, Lashgari et al., 2024). As a result, varying shear strains during seismic events can cause slope failure, leading to large-scale submarine sliding displacements.

3 EFFECT OF PWP IN SUBMARINE LANDSLIDES: CENTRIGURE DATA

As discussed in Section 2, one of the critical factors in submarine landslides is the variation of PWP. This section evaluates the effect of PWP generation due to static liquefaction and seismic activity, drawing insights from collected centrifuge testing data. The scope of this paper is focused on a limited set of factors that influence submarine landslides, specifically the role of PWP and ground motion IMs in triggering slope failures. While submarine landslides are governed by a range of environmental and geotechnical factors, this study explores a small number of key aspects, such as PWP generation during seismic activity and the effects of different intensity measures on slope stability.

3.1. PWP generation during static liquefaction

Figure 3 illustrates a correlation between the submarine slope failure angle and the values of r_u based on the collected centrifuge data. The centrifuge data used in Figure 3 reveal distinct trends between datasets. The data of Zhang et al. (2015) indicates the slope failure angles ranging from 20° to 25°, with r_u values between 0.9 and 2.1. In contrast, Zhang and Askarinejad (2019) recorded much lower slope failure angles, between 5° and 15°, with r_u values ranging from 0.1 to 0.7 at soils with relative density between 35-49%. It is noted that other factors, such as soil conditions and layering, contribute to this difference. Some form of normalization by strength would be beneficial; however, the necessary data were not available in these studies for inclusion in this study.

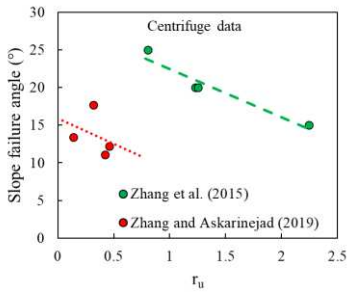

Figure 3. Correlation between submarine slope failure angles and r_u

It is noted that during static liquefaction, the value of r_u can sometimes exceed 1.0. This occurs due to applying PWP during centrifuge tests to induce slope flow failure. Figure 3 demonstrates that higher r_u values, indicating greater excess PWP (EPWP), generally correspond to lower slope angles at failure. This shows that increased PWP, especially under static conditions, can destabilize submarine slopes even at gentle slopes.

3.2. PWP generation during seismic activity

The response of a submarine slope to seismic loading is influenced by ground motion characteristics, slope geometry, and the geotechnical properties of the sliding mass. Accordingly, it is necessary to consider all these parameters for a suitable evaluation. k_y is used in sliding block-based models to estimate seismic sliding displacement. Jibson (2011) provides a method to estimate k_y based on static factor of safety as follows:

$$k_y = (FS_{static} - 1)g\ sin\beta \quad (1a)$$

$$FS_{static} = \frac{c' + \gamma' H cos^2\beta tan\phi'}{\gamma H sin\beta cos\beta} \quad (1b)$$

where and ϕ', c', γ, γ', $H, \beta, and\ g$ are effective friction angle, cohesion of sliding mass, total unit weight of the soil, effective unit weight of soil, slope height, slope angle, and acceleration of gravity. However, these equations do not account for dynamic PWP variations during a seismic event. To address this, Jafarian and Lashgari (2017) developed a more comprehensive method to estimate k_y by incorporating seismic excess pore pressure:

$$k_y = \frac{\sigma'_{v_0}}{\sigma_{v_0}}\left(\frac{\tau_{dyn}}{\sigma'_{v_0}} - sin\beta\right) \quad (2a)$$

$$\tau_{dyn} = \left(\sigma_{v_0} - u_{dyn}\right)tan\phi' + c' \quad (2b)$$

$$u_{dyn} = u_{static} + \quad (2c)$$

$$\Delta u = r_u \sigma'_{v_0} \quad (2d)$$

where τ_{dyn}, $\sigma_{v_0}$and σ'_{v_0} are dynamic shear resistance in each time step, total vertical stress ($= \gamma H\ cos^2\beta$), and effective vertical stress at the base of sliding mass and u_{dyn}, u_{static}, Δu, and r_u are seismic excess pore pressure at each time step, static water pressure ($= nH\gamma_w\ cos^2\beta$), EPWP, and pore water pressure ratio during an earthquake, respectively.

Figure 4 compares centrifuge test data from Takahashi et al. (2020) with two different methods for estimating k_y/PGA (PGA: peak ground acceleration). The relationship between r_u and k_y/PGA has been shown in Figure 4(a). The data estimated using Equation (1) show a weak correlation with an R^2=0.25. However, the data estimated using Equation (2) show a stronger correlation with R^2=0.5. Moreover, Figure 4(b) illustrates the relationship between displacement and k_y/PGA. Equation (1) again provides a lower correlation (R^2=0.5), while Equation (2) achieves a higher correlation (R^2=0.61). However, the values of k_y/PGA have a difference in magnitude - around three times. These findings indicate that different methods for estimating k_y yield vary in degrees of accuracy in predicting the behavior of seismic submarine landslides. Parameters such as PWP play a critical role in these predictions.

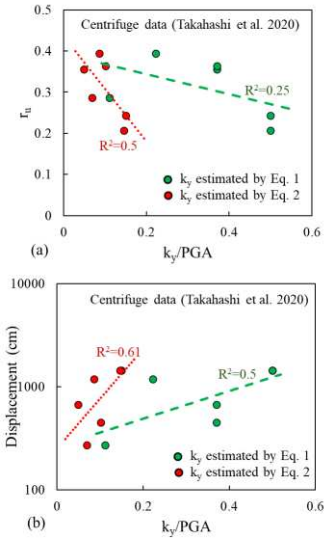

Figure 4. Comparison of centrifuge data from Takahashi et al. (2020) with two different methods for estimating k_y/PGA

4 SEISMIC EFFECT: NUMERICAL ANALYSIS

Carey et al. (2022) conducted a series of centrifuge tests to investigate the effect of sand gradation on the performance of submerged gentle embankments (slope angle=10°) during liquefaction, as shown in Figure 5(a). These tests were performed at two relative densities (40% and 63%) and subjected to a sequence of seismic motions. During Shake 3, maximum horizontal and vertical displacements of 85 cm and 10 cm, respectively, were recorded at the mid-slope surface (marked with a red circle in Figure 5). More detailed findings are presented in Carey et al. (2022). In this study, we simulated the test using the finite difference software FLAC. The model setup and mesh conditions are illustrated in Figure 5(b). The PM4Sand constitutive model was used for the numerical simulation, with calibration parameters provided by Guarachi (2022). For this analysis, two parameters, h_{p0} and n^b, were adjusted to 3 and 0.7 at the prototype scale modeling. The verification results, shown in Figure 5(b), indicate that the numerical model closely replicated the experimental data, with final horizontal and vertical displacements of 92 cm and 11 cm at the mid-slope, respectively.

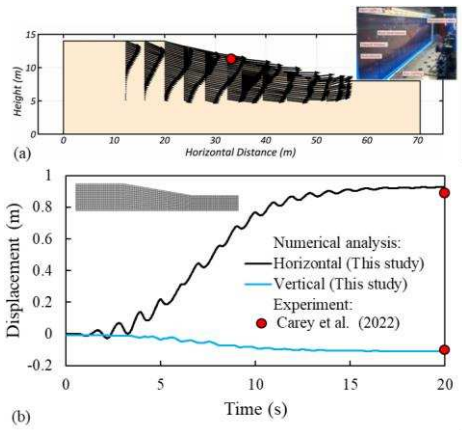

Figure 5. Verification of numerical modeling (a) Centrifuge test conducted by Carey et al. (2022) (b) Comparison between numerical and experimental displacements

PLGMs, characterized by strong velocity pulses, are primarily caused by the forward-directivity effect during fault rupture. This occurs when the ground motion energy along the direction of rupture propagation is greater than in the opposite direction (Somerville, 2003). These high-energy pulses can significantly impact submarine landslides by amplifying displacements and pore pressure accumulation. In this study, we selected five pulse-like ground motions from the database of Hayden et al. (2014) for seismic analysis, all with pulse periods of 10 seconds or more. The properties of these selected motions are summarized in Table 1.

Figure 6 shows the relationship between computed slope displacement by numerical analysis and various intensity measures (IMs), including PGA (peak ground acceleration, max|a(t)|), PGV (peak ground velocity, max|v(t)|), I_a (Arias Intensity, $\pi\int a^2(t)dt$), and SIR (ratio of Arias Intensity to significant duration, I_a/D_u). As illustrated in the figure, energy-based IMs

(I_a and SIR) exhibit a stronger correlation with displacement compared to amplitude-based IMs (PGA and PGV). A linear regression model fitted to the data confirms this trend, showing higher R^2 values for I_a and SIR compared to PGA and PGV. This finding is in good agreement with the results reported by Farahani and Barari (2023) for suction caissons on liquefiable soils.

Table .1 Properties of the employed pulse-like motions

NGA No.	Earthquake	Station	M_w
170	Imperial Valley-06	EC County Center FF	6.5
1491	Chi-Chi, Taiwan	TCU051	7.6
1492	Chi-Chi, Taiwan	TCU052	7.6
1494	Chi-Chi, Taiwan	TCU054	7.6
1515	Chi-Chi, Taiwan	TCU082	7.6

While PGA and PGV are commonly used to estimate seismic sliding displacement for onshore slopes, they do not accurately capture the behavior of submarine landslides due to distinct governing failure mechanisms. In submarine slopes, the accumulation of EPWP during seismic shaking significantly alters the soil response, leading to gradual shear strength loss and the cycle-by-cycle accumulation of shear strain, resulting in large permanent displacements. Given that PLGMs deliver high energy in a short duration, amplitude-based IMs are not sufficient to characterize the intensity of these motions accurately. Therefore, energy-based IMs, which effectively describe the total energy imparted to the slope, turn out to be more appropriate for evaluating displacement of seismically-triggered submarine landslides.

Figure 7 further examines displacement in relation to EPWP and maximum shear strain (γ_{max}) for a given set of input motions. As shown in Figure 7(a), displacement is strongly correlated with EPWP. Figure 7(b) demonstrates the correlation between shear strain and displacement, though this relationship is nonlinear. A fitted regression model confirms this trend, yielding high R^2 values for both EPWP and shear strain. These results indicate that increasing EPWP and shear strain significantly contribute to the total displacement of the submarine slope.

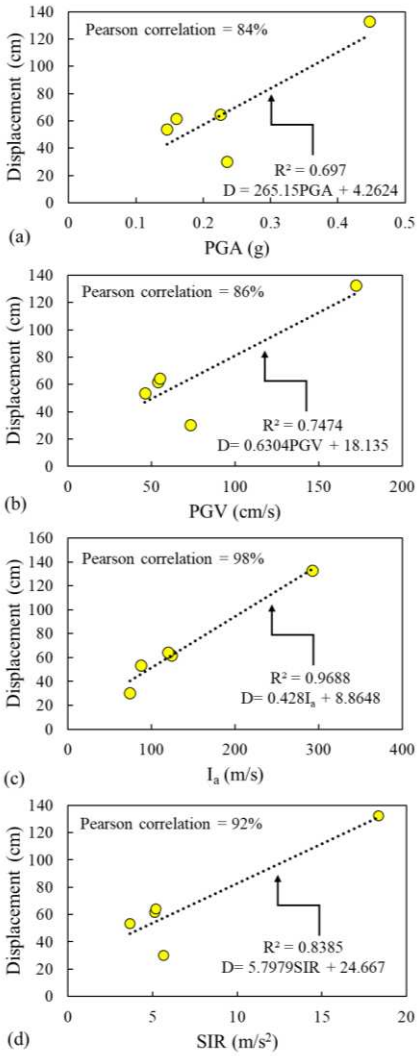

Figure 6. Correlation between seismic submarine displacement with different IMs

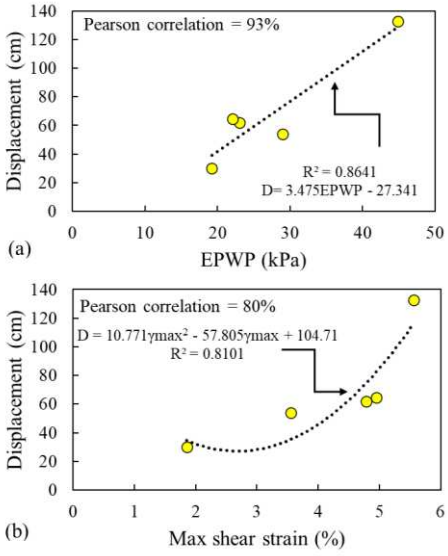

Figure 7. Displacement versus (a) EPWP and (b) maximum shear strain

5 CONCLUSIONS

This study provided key insights into the mechanisms and influential parameters governing submarine landslides, based on centrifuge test data and numerical analysis. PWP emerged as a critical factor that plays a significant role in submarine slope instability, particularly during static liquefaction and seismic events. The variations of PWP destabilize slopes, even at gentle angles. Under seismic loading, modified analytical methods for estimating the k_y, which incorporates dynamic PWP, offer better accuracy in predicting slope behaviour. PLGMs, which deliver high energy over short durations, were found to significantly amplify PWP accumulation, shear strain, and sliding displacement. Energy-based IMs, such as I_a and SIR, were more effective in correlating with submarine slope displacement compared to amplitude-based IMs like PGA. Moreover, shear strain significantly contributes to slope displacement.

AUTHOR CONTRIBUTION STATEMENT

Ali Lashgari: Data curation, Formal Analysis, Visualization, Investigation, Writing- Original draft. **Amin Barari**: Conceptualization, Methodology, Supervision. **Jannie Sønderkær Nielsen**: Supervision, Writing- Reviewing and Editing.

ACKNOWLEDGEMENTS

The research received support from the European Union under the Marie Skłodowska-Curie Postdoctoral Fellowships grant agreement No 101106129.

REFERENCES

Brennan, A. J., and Madabhushi, S. P. G. (2009). Amplification of seismic accelerations at slope crests. *Canadian Geotechnical Journal*, *46*(5), 585-594.

Carey, T. J., Chiaradonna, A., Love, N. C., Wilson, D. W., Ziotopoulou, K., Martinez, A., and DeJong, J. T. (2022). Effect of soil gradation on embankment response during liquefaction: A centrifuge testing program. *Soil dynamics and earthquake engineering*, *157*, 107221.

Fang, K., Tang, H., Li, C., Su, X., An, P., and Sun, S. (2023). Centrifuge modelling of landslides and landslide hazard mitigation: A review. *Geoscience Frontiers*, *14*(1), 101493.

Farahani, S., and Barari, A. (2023). A simplified procedure for the prediction of liquefaction-induced settlement of offshore wind turbines supported by suction caisson foundation based on effective stress analyses and an ML-based group method of data handling. *Earthquake Engineering and Structural Dynamics*, *52*(15), 5072-5098.

Guarachi, H. F. A. (2022). *Liquefaction and post-liquefaction behavior of coarse-grained soils* (Doctoral dissertation, UC Davis).

Hayden, C. P., Bray, J. D., & Abrahamson, N. A. (2014). Selection of near-fault pulse motions. *Journal of Geotechnical and Geoenvironmental Engineering*, *140*(7), 04014030.

Kramer, S. L. (1996). Geotechnical earthquake engineering. CRC Press.

Jafarian, Y., and Lashgari, A. (2017). Seismic sliding analysis of sandy slopes subjected to pore-water pressure buildup. *International Journal of Geomechanics*, *17*(11), 04017106.

Jibson, R. W. (2011). Methods for assessing the stability of slopes during earthquakes—A retrospective. *Engineering geology*, *122*(1-2), 43-50.

Lashgari, A., Rahimi, L., Ahmadisharaf, E., & Barari, A. (2024). Probabilistic pre-conditioned compound landslide hazard assessment framework: integrating seismic and precipitation data and applications. *Landslides*, 1-22.

Locat, J., and Lee, H. J. (2002). Submarine landslides: advances and challenges. *Canadian Geotechnical Journal*, *39*(1), 193-212.

Maghsoudloo, A., Askarinejad, A., de Jager, R. R., Molenkamp, F., and Hicks, M. A. (2021). Large-scale physical modelling of static liquefaction in gentle submarine slopes. *Landslides*, *18*(10), 3315-3335.

Somerville, P. G. (2003). Magnitude scaling of the near fault rupture directivity pulse. *Physics of the earth and planetary interiors*, *137*(1-4), 201-212.

Takahashi, H., Fujii, N., & Sassa, S. (2020). Centrifuge model tests of earthquake-induced submarine landslide. *International Journal of Physical Modelling in Geotechnics*, *20*(4), 254-266.

Zhang, J. H., Lin, H. L., and Wang, K. Z. (2015). Centrifuge modeling and analysis of submarine landslides triggered by elevated pore pressure. *Ocean Engineering*, *109*, 419-429.

Zhang, W., & Askarinejad, A. (2019). Centrifuge modelling of submarine landslides due to static liquefaction. *Landslides*, *16*(10), 1921-1938.