Proceedings of the 11th ICPMG 2026
11th International Conference on Physical Modelling in Geotechnics
8-12 June 2026, Zurich, Switzerland

Revisiting dynamic earth pressure coefficients: shaking sideways but looking up

Srikanth S. C. Madabhushi
University of Colorado, Boulder, USA, mscs@colorado.edu

ABSTRACT: Dynamic earth pressure coefficients are widely used in seismic engineering design. Nevertheless, practical approaches have typically assumed either fully elastic or fully plastic soil behaviour. Fundamentally, uncertainty remains over the mobilized and limiting soil stresses that are generated during earthquakes that depend on the ground motion, coupled response of soils and structures, and their relative displacements. Amidst these considerations, the scope for horizontal shaking to lead to influential vertical response of the soil has often been neglected. This study revisits centrifuge experiments that revealed, at odds with longstanding assumptions, predominantly horizontal shaking leads to both horizontal and vertical soil accelerations, and thus dynamic horizontal and dynamic vertical normal stresses due to inertia of the soil body and rocking mechanisms. The findings motivate reconsideration of dynamic earth pressure coefficients and other approaches that implicitly assume geostatic vertical stresses. The implications for physical modelers instrumenting and interpreting centrifuge experiments through the lens of these rocking mechanisms are discussed. Grids of vertical accelerometers enable estimates of the cyclic vertical effective stresses and results in the current study reveal cyclic variations up to 20 % of the geostatic values in a level soil deposit confined between smooth boundaries. 2D acceleration measurements are then used to inform the 2D displacements and estimates of the 2D strain states during the shaking, offering fresh insight into the dynamic mobilization of horizontal stresses at the soil-wall boundary and provoking questions about the fundamental soil behaviour.

1 INTRODUCTION

Conventional design approaches have typically idealized retained soil behaviour using either pseudo-static limit equilibrium assumptions invoking plastic failure or elastic wave propagation solutions. Nevertheless, both approaches have generally assumed that horizontal shaking predominantly generates horizontal stress variations within the soil. Recent centrifuge investigations, however, suggest that this assumption may not always hold. In particular, retained soil subjected to horizontal earthquake loading has been observed to undergo rocking mechanisms that induce significant dynamic vertical accelerations and corresponding dynamic vertical stress variations (Madabhushi and Haigh, 2021, Madabhushi and Westcott, 2024). These mechanisms challenge conventional interpretations of mobilized and limiting seismic earth pressures and suggest that the dynamic response of retained soil may be more fundamentally two-dimensional and coupled than has commonly been assumed.

This study revisits the interpretation of a relatively simple dynamic centrifuge test that was subjected to primarily horizontal shaking, but with an emphasis on the characterization of the system and soil response both horizontally and vertically. In particular, the insights from a grid of vertically and horizontally oriented accelerometers, in terms of the vertical, horizontal, and shear stresses and/or strains induced, are discussed. More broadly, instrumentation considerations for dynamic centrifuge tests, interpretation of the dynamic stress state at the boundaries versus mid-domain, and implications for the study of earth retaining systems using dynamic centrifuge modelling, are considered.

2 ILLUSTRATIVE 2D INTERPRETATION OF A DYNAMIC CENTRIFUGE EXPERIMENT WITH 1D SHAKING

The present study revisits results from predominantly 1D shaking of a level deposit of dry sand reported by Westcott (2023) and Madabhushi and Westcott (2024), with details of the experimental setup and model preparation not repeated herein for brevity. Particular attention is given to the interpretation of vertically and horizontally propagating accelerations, the corresponding vertical, horizontal, and shear stress and strain response implied by the measurements, and the broader implications for the instrumentation and physical interpretation of results from centrifuge modelling studies.

This extended abstract provides illustrations of these results, with further interpretation and discussion anticipated in an ensuing Journal publication.

For example, Figure 1 shows dynamic vertical effective stresses distributions are constructed from a 2D grid of vertical acceleration measurements in the soil away from the rigid boundaries (a span of approximately 55 m at prototype scale). This calculation follows a simplified discrete integral of the vertical accelerations with depth from the soil surface, but clearly shows dynamic redistributions of the vertical effective stresses that instantaneously increased and decreased up to 20 % of the geostatic values at opposite sides of the soil.

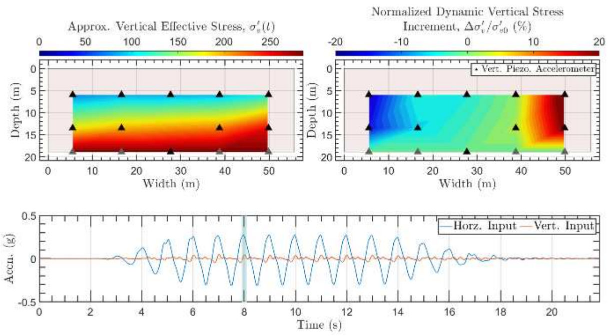

Figure 1. Inferred instantaneous distribution of vertical effective stress from integration of vertical acceleration measurements with depth, demonstrating significant dynamic increments with respect to the geostatic value in the level dry sand deposit experiencing predominantly horizontal shaking

With the context of a rocking soil body and dynamically altered vertical effective stresses, Figure 2 illustrates how arrays of horizontal accelerometers can be used to abstract lateral strain distributions. These 1D strain estimates are constructed following double integration and filtering of the horizontal accelerations with respect to time, informing the cyclic component of the soil displacements relative to the rigid container boundary. The comparatively small strains away from the boundaries supports simplification of the soil in this region to a 1D column with negligible lateral variations. By contrast, adjacent to the soil-wall boundary Figure 2 shows one side of the soil compresses at the same time as the opposite side extends, i.e., reflecting soil being driven towards passive and active stress mobilization or at least positive and negative dynamic horizontal normal stress increments, respectively. The coincidence of increased vertical stresses with large lateral strains is noteworthy, as it implies the potential for greater lateral stresses and loads on retaining structures due to the rocking mechanisms.

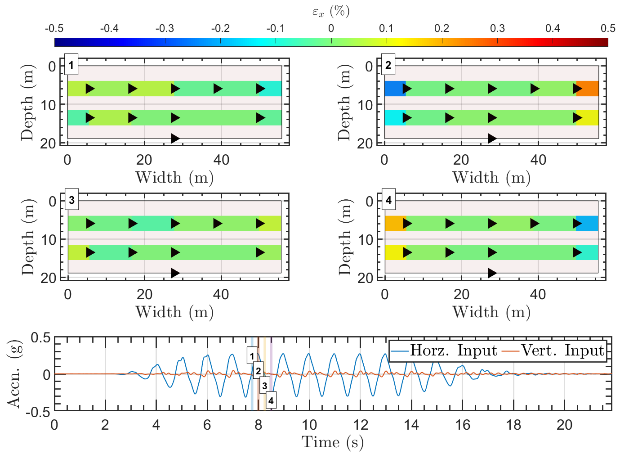

Figure 2. Inferred instantaneous slices of horizontal strains inferred from double integration of horizontal accelerometers with time, demonstrating cyclic variation of soil zones extending and compressing adjacent to the soil-wall boundary

3 CONCLUSIONS

This study will emphasize the importance of observing the coupled horizontal and vertical dynamic response of soil in centrifuge models subjected to seismic loading even when the primary excitation direction is horizontal (i.e., as is the case with the majority of centrifuge shake tables worldwide at the time of writing). Arrays of vertical and horizontal accelerometers prove useful to abstract dynamic normal vertical effective stress increments, and vertical and lateral increments of strain, in addition to cyclic shear-stress strain responses that are commonly obtained. Ultimately, important connections between 2D characterization of the soil response from centrifuge experiments, dynamic rocking mechanisms of retained soil, and interpretations of the stress states to inform the soil's constitutive behavior during dynamic loading are discussed.

REFERENCES

Madabhushi, S. S. C, & Haigh, S. K. (2022). On the dynamic response of flexible dual-row retaining walls in dry sand. *Géotechnique*, 72(11), 941-956.

Madabhushi, S. S. C, & Westcott, J. (2024). An Alternative Approach to Dynamic Earth Pressure Coefficients to Improve the Seismic Limit State Design of Earth-Retaining Structures. *Journal of Geotechnical and Geoenvironmental Engineering*, 150(10), 04024085.

Westcott, J. (2023). *An investigation into dynamic normal vertical effective stresses induced by horizontal shaking*. Master's thesis, University of Colorado at Boulder.