# Seismic behaviour of shallow rectangular tunnels in soft clay

*Nicolas G.L.H. Lee (nglhl2@cam.ac.uk)*

UNIVERSITY OF CAMBRIDGE

Schofield Centre
Centre for Geotechnical Process & Construction Modelling

## BGA Annual Conference 2025

## How does a shallow tunnel in soft clay respond during an earthquake?

**Earthquake-induced ground failure** can cause **uplift** in buoyant underground structures, including **shallow tunnels**. Most research on this focuses on the most critical case of liquefaction in sandy soils.

**What about soft clay? Cyclic failure** has also been observed around structures in fine-grained soils, e.g., 1999 Chi-Chi and Kocaeli earthquakes [1].

**Can, and how, does tunnel uplift occur in soft clay during an earthquake? How do existing methods to resist tunnel movement fare in soft clay?**

Figure 1. Uplift of buried conduit during 2011 Tohoku earthquake [2]

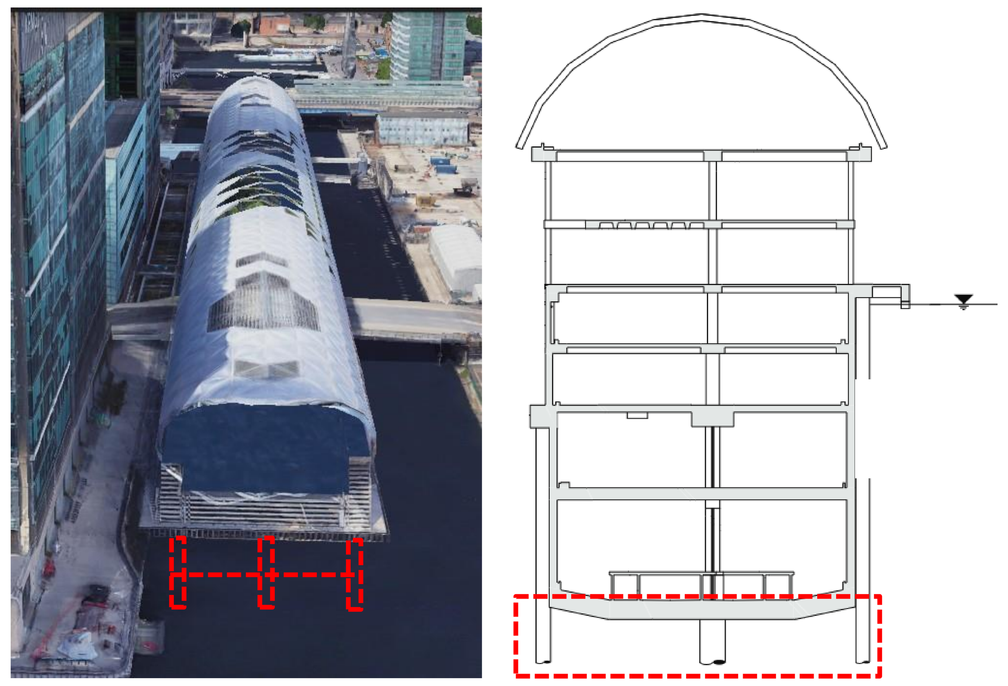

Figure 2. Tension pile design of Canary Wharf station [3]

## Methodology: Centrifuge modelling

**Dynamic centrifuge tests** were conducted at **80g** on a rectangular tunnel buried in soft clay, considering:

- **Undrained shear strength** $s_u$ profile:
  - Very soft: $4 < s_u < 8$ kPa and soft: $12 < s_u < 18$ kPa
- Use of **tension piles** embedded in dense sand to resist uplift

Models were prepared in a **rigid plane strain container** with a window front to enable **particle image velocimetry (PIV) analysis**.

A **15-cycle sinusoidal earthquake** with PGA ≈ 0.24 *g* was applied to observe the effects of **cyclic loading** on the clay.

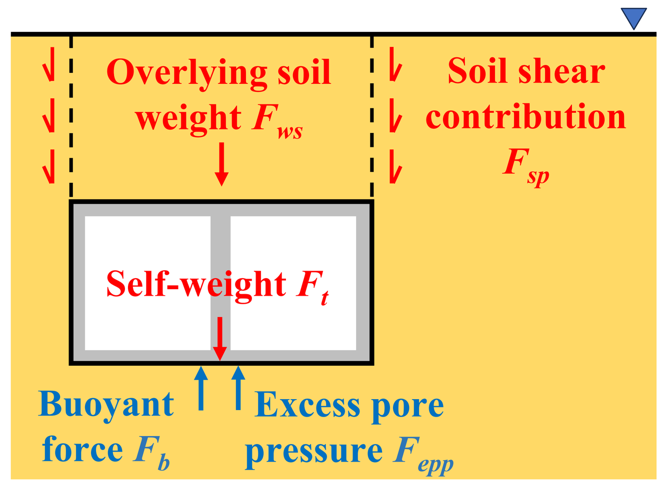


Figure 3. Vertical forces during earthquake considered in test design

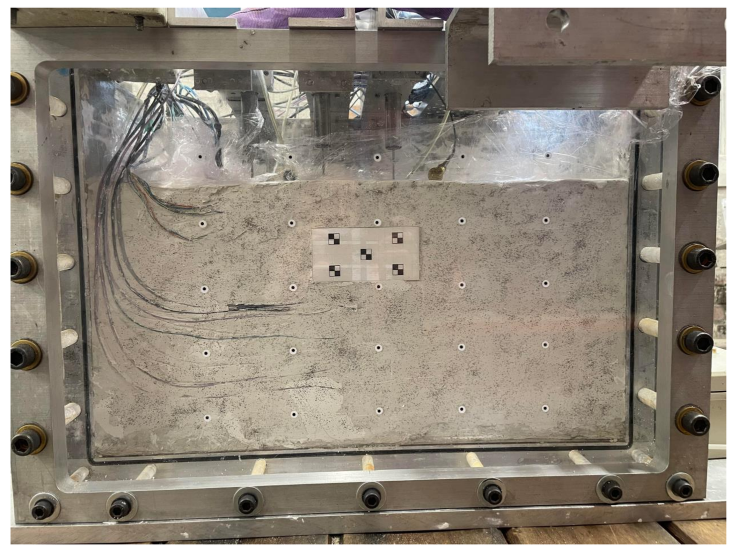

Figure 4. Centrifuge model

## Results: Dynamic soil response

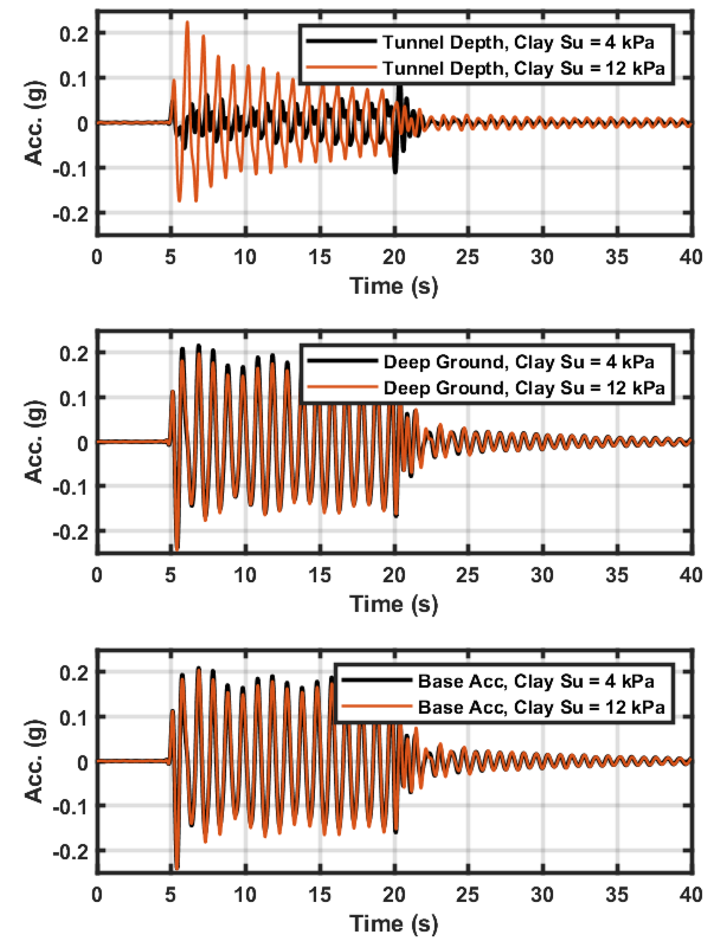


Figure 5. Horizontal accelerations in soft and very soft clay

**Progressive degradation** was seen in the clay **with depth**, as well as **over time.**

**Horizontal accelerations amplified** upwards until the clay **yields, limiting further accelerations propagated upward.**

**Cyclic softening** also resulted in **attenuation over time** at the tunnel depth.

In the case of **tunnel uplift, circular displacement loops** formed beside the tunnel.
**However,** the "flow" mechanism typically observed in liquefied soil is limited, as **the surrounding clay does not lose all stiffness:**

- Clay **above** the tunnel **heaves together with the tunnel**, resulting in **similar surface displacements relative to tunnel uplift.**
- Clay **below** the tunnel is unable to "fill" the void, resulting in a **gap forming** at the tunnel base.

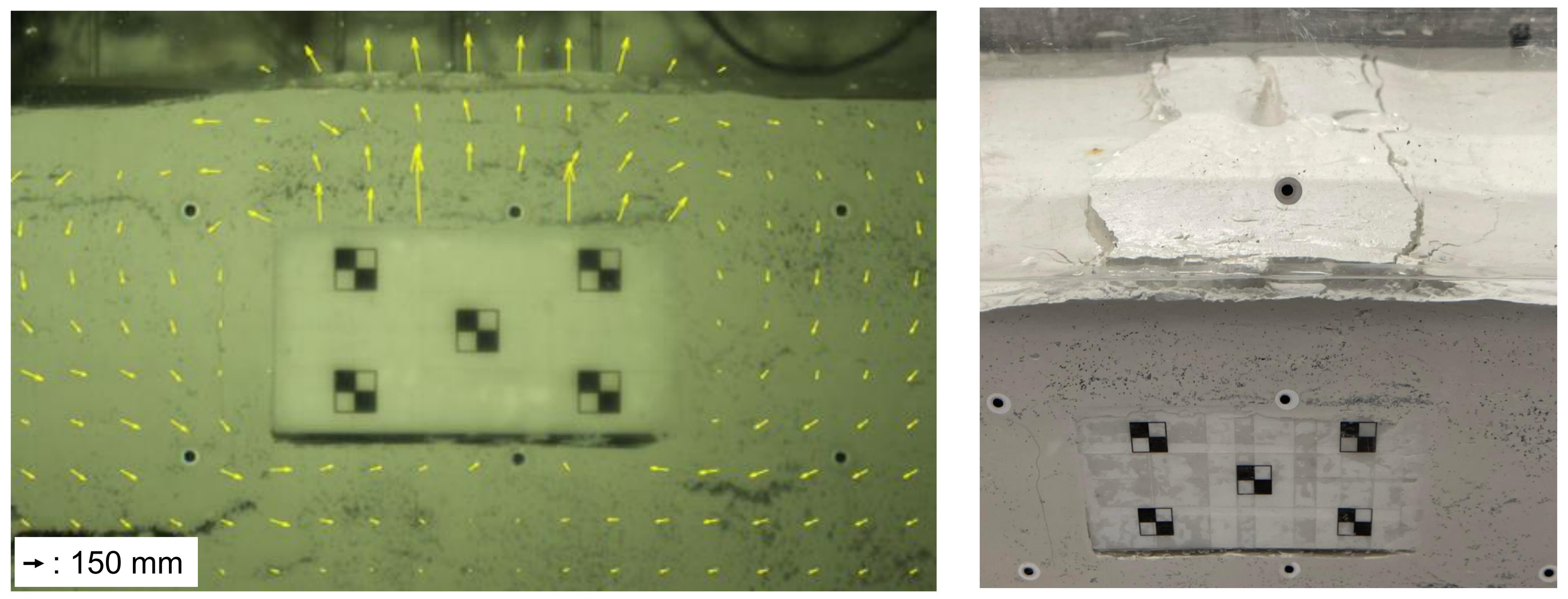


Figure 6. Cumulative soil displacements in very soft clay during earthquake, and surface heave observed post-test

## Results: Dynamic tunnel response

**Ratcheting** was observed **with tunnel uplift** in a **very soft clay** profile.
**However, significant lateral movement** occurred even when uplift was minimal (consistently approx. ± 0.05 m).

- These are **much larger than** that observed for a similar configuration in **loose, liquefiable sand** [4].
- Due to the clay's **higher compressibility**, the tunnel can displace further into the surrounding clay during shaking.

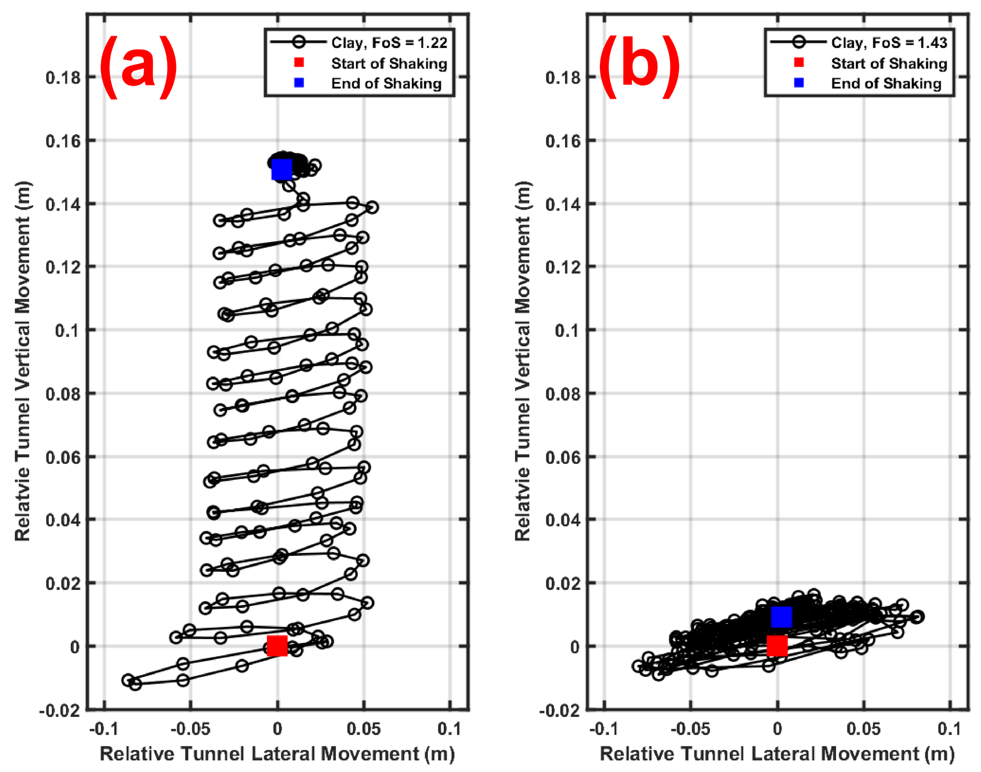


Figure 7. Vertical and horizontal movement in (a) very soft clay and (b) soft clay

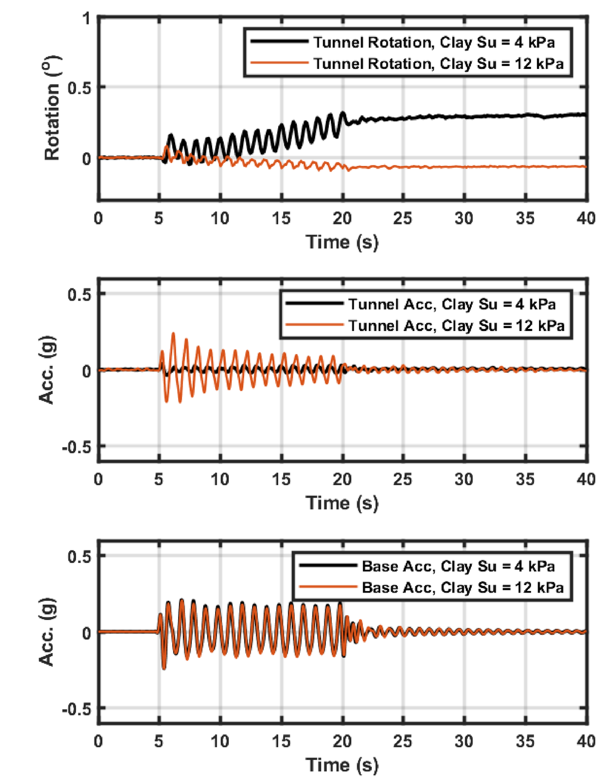


Figure 8. Tunnel acceleration and rotation in soft and very soft clay

## Key findings and ongoing work

The **seismic response** of a **tunnel in soft clay**, even **when uplift occurs**, is unique from its well-investigated counterpart in sandy soils.
**Relative to tunnel uplift,** we can expect:

- **More lateral tunnel movement**
- **More surface heave above the tunnel**

Figure 9. Model tunnel with tension piles connected

**How can this affect the performance of tension piles**? How does the clay's dynamic behaviour affect its **kinematic and inertial forces** during shaking?

## Acknowledgements

The author wishes to express his utmost gratitude to his supervisor, Prof. Gopal Madabhushi, for his invaluable guidance, as well as the technicians at Schofield Centre, John Chandler, Kristian Pether, Mark Smith, Chris McGinnie, and David Layfield, for their continuous support and counsel in the preparation and execution of this work.

## References

[1] Boulanger, R.W. & Idriss, I.M. (2004). *Evaluating the potential for liquefaction or cyclic failure of silts and clays.* [Report No. UCD/CGM-04/01]. Center for Geotechnical Modeling, University of California, Davis, California.
[2] Tokimatsu, K., Tamura, S., Suzuki, H., & Katsumata, K. (2011). Damage to soils in the 2011 Tohoku Pacific earthquake. *Research Reports on Earthquake Engineering*, 118, 21-47.
[3] Worsfold, T., Bryant, B., & Crack, J. (2018). Design of Canary Wharf Elizabeth line station and Crossrail Place oversite development. *The Structural Engineer.*
[4] He, Z.Y. & Madabhushi, S. P. G. (2024). Experimental study of the dynamic tunnel response adjacent to a building. *Soil Dynamics and Earthquake Engineering*, 182.