Making the best use of deformation observations in centrifuge models

Optimiser l'utilisation des observations de déformation dans les modèles de centrifugeuse

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Portée de la présentation

- Pourquoi devrions-nous mesurer les déformations?
- Comment peut déformations être visualisées?
- Que voyons-nous?
- Les vecteurs de déplacement: sont-ils raisonnable?
- L'importance de tirer des mécanismes simplifiés
- Utiliser ces mécanismes de prédire les déformations
- Mécanismes de l'aide à *comprendre* les déformations
- Quelle est l'opportunité pour les modélisateurs centrifugeuse?

Pourquoi devrions-nous mesurer les déformations?

- Eurocode 7 exige que les ingénieurs vérifier déformations, mais ne fournit aucune aide réelle.
- Réaménagement urbain nous oblige à insérer de nouveaux métros, les bâtiments et les sous-sols, sans endommager les structures existantes.
- Nous avons donc besoin de faire des modèles physiques des activités de construction dans les différentes classes de sol, et de concevoir et de calibrer les méthodes pratiques de calcul de la déformation.
- Nous avons d'abord réalisé ceci pour les calculs effondrement ULS avec de Coulomb 1776 analyse des coins coulissants, poursuit Alan Bishop's 1955 analyse des cercles de glissement, etc
- Nous devons maintenant observer les mécanismes de déformation SLS.

Comment peut déformations être considéré?

- Centrifuger modèles peuvent être testés en déformation plane et une section transversale peut être vue à travers une fenêtre.
- Les grains de sable ont une texture assez pour faciliter la comparaison d'images numériques de photographies prises par des caméras numériques.
- Les argiles peuvent être donnés texture en utilisant un saupoudrage de sable fin et noir sur la terre contre la fenêtre.
- D'étalonnage et d'analyse d'une séquence d'images peut être faite par GeoPIV - White, Take & Bolton (2003)
- Les champs de vecteur de déplacement, ou de déformations de cisaillement calculée à partir de dérivés de déplacement, peuvent être tracées.

Que voyons-nous?

- Exemple: les déformations du terrain autour des excavations profondes.
- Excavations dans l'argile couper et calé en vol centrifugeuse: voir les publications par Lam & Bolton (ICPMG 2010, ASTM Geotechnical Testing Journal 2011, ASCE Geotechnical and Geoenvironmental Engineering 2011).
- Mécanismes vu en coupe lors de la construction quasi-non drainés, par exemple d'une zone de la station de métro.
- Mécanismes changent à la suite des travaux d'excavation, avec des supports placés successivement plus profond.
- Si l'excavation est maintenue ouverte et la base du mur n'est pas fixe, le gonflement et le ramollissement de l'argile au dessous peut conduire à d'autres flexion du mur de soutènement.

Centrifuge modelling of deep excavation

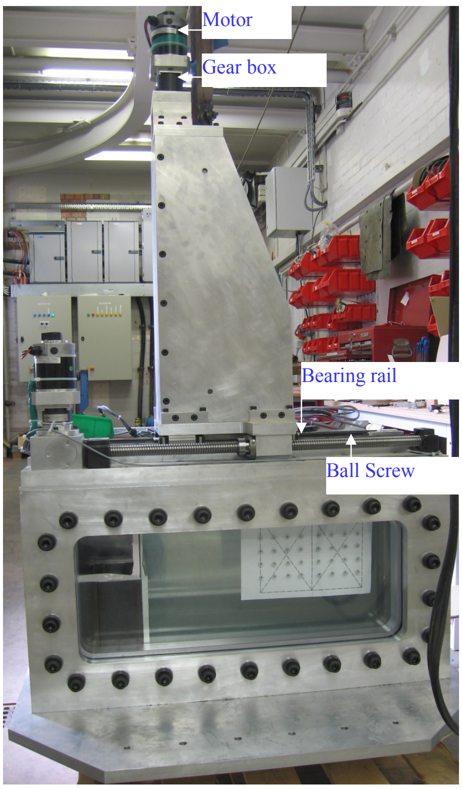
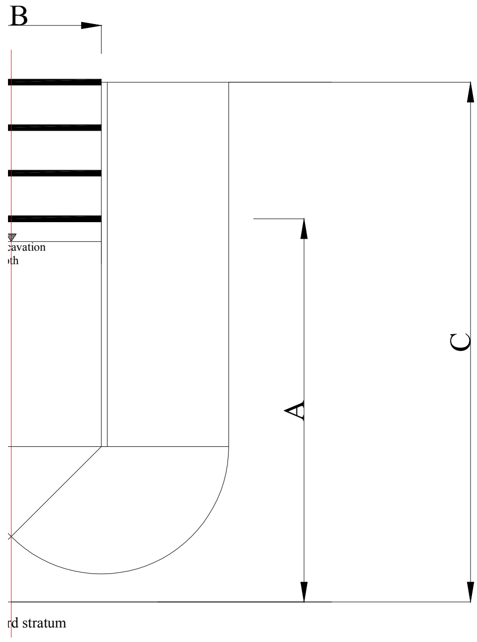
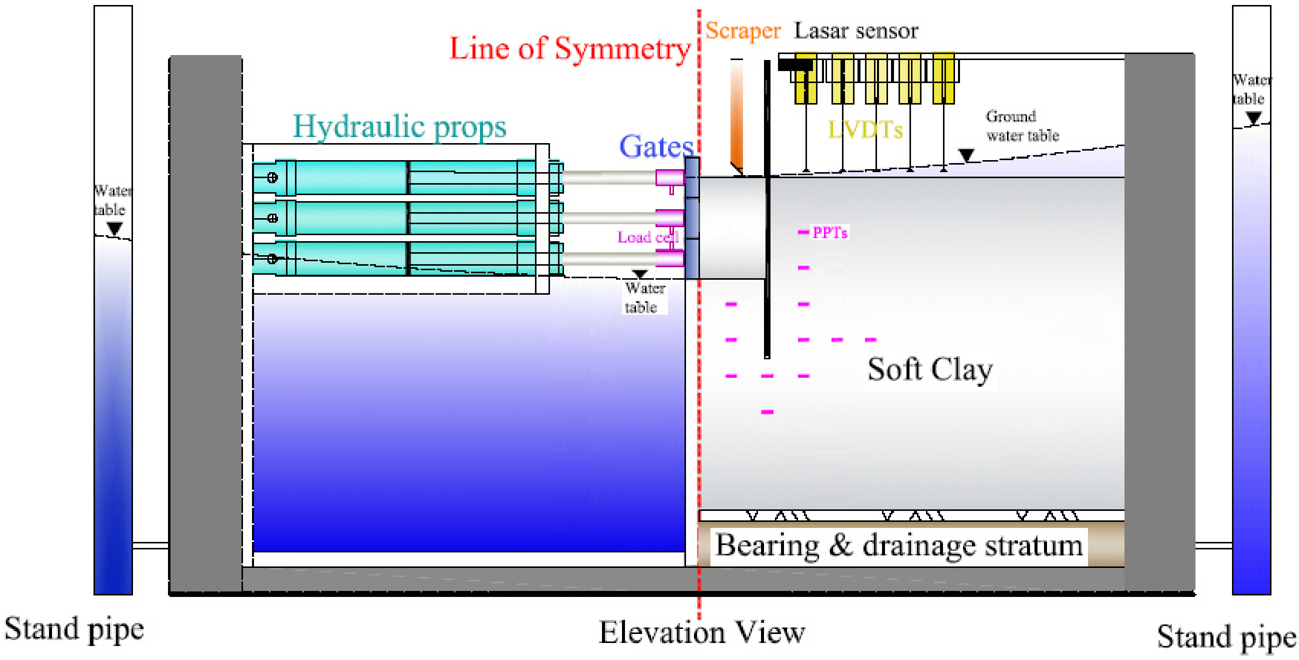


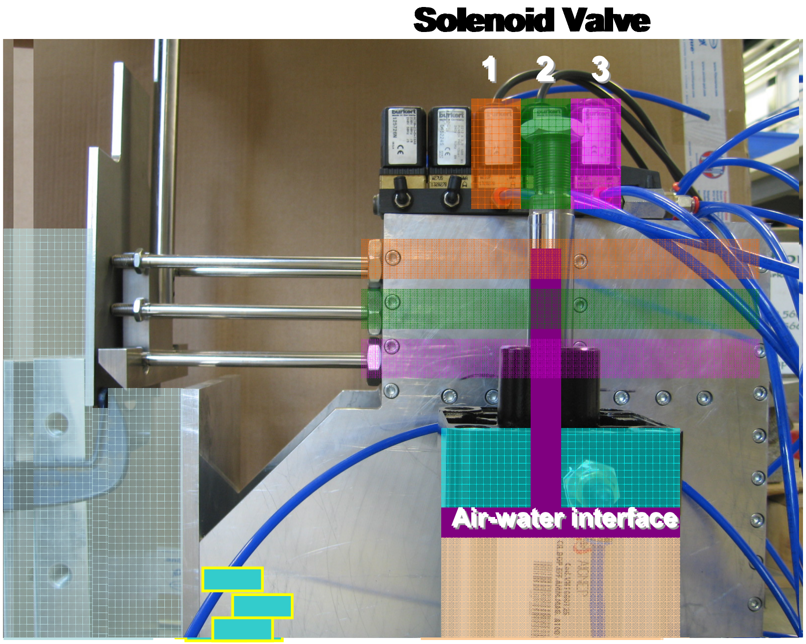
Schéma d'une excavation calé

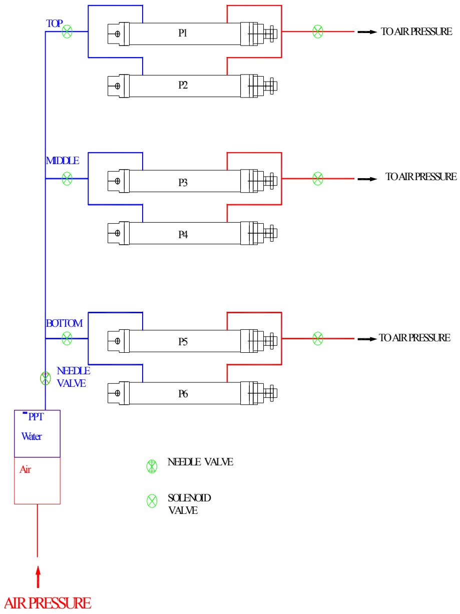


Centrifuge modelling arrangement

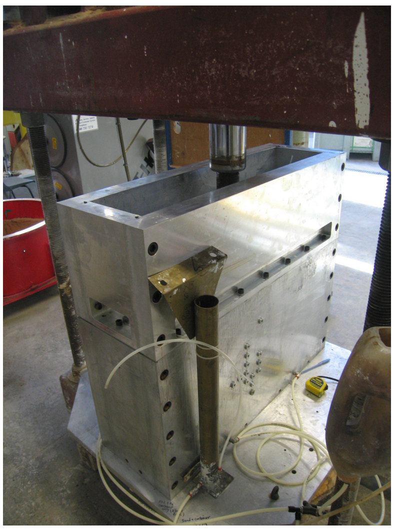


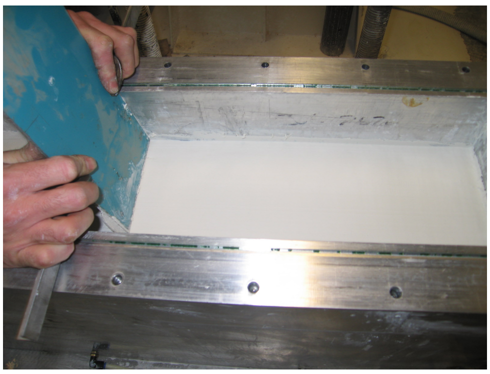
Hydraulic prop system



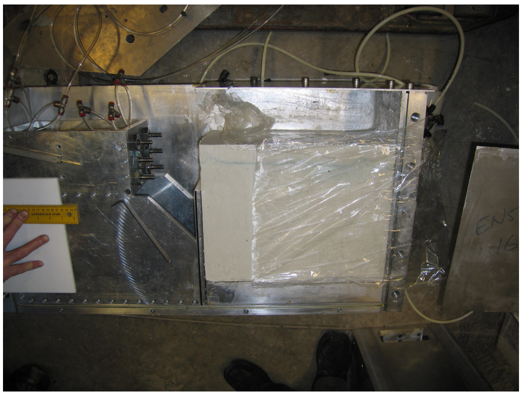


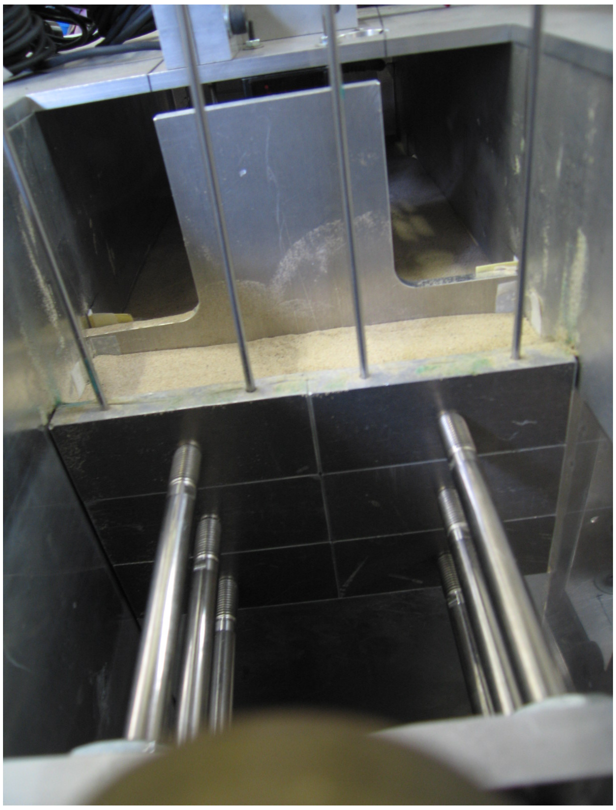
Clay preparation procedure



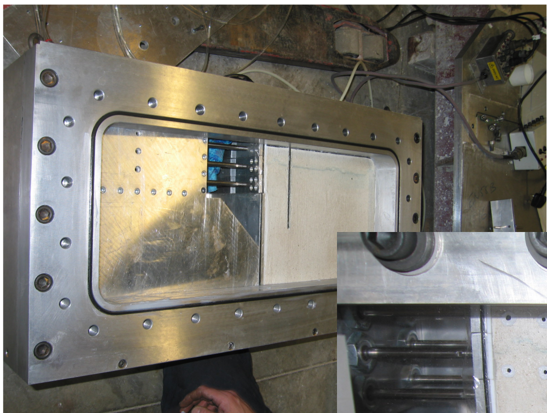


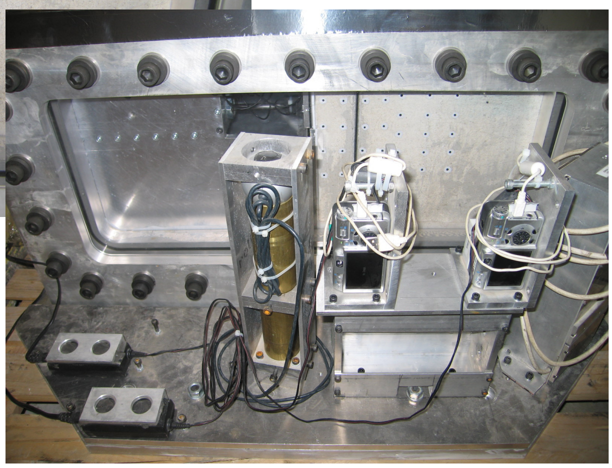
Inserting and assembling the wall



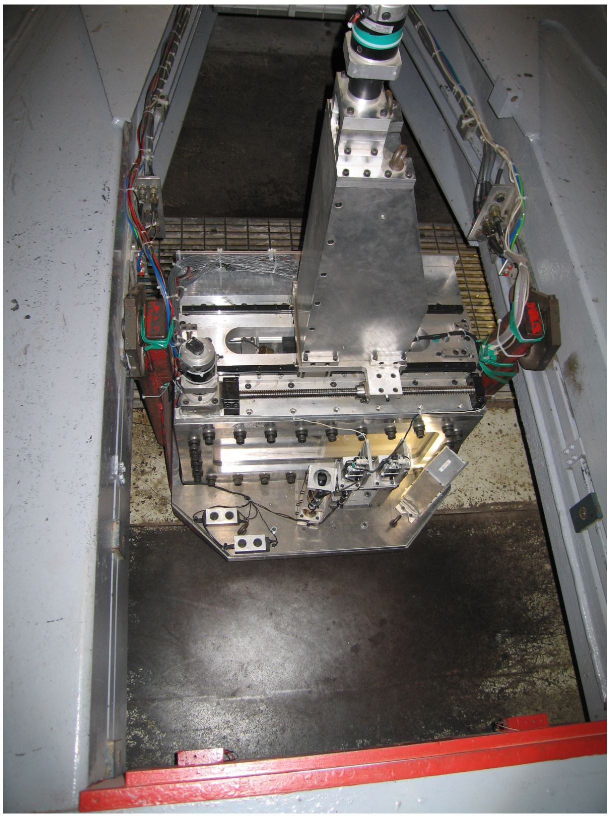


Assemble strong box

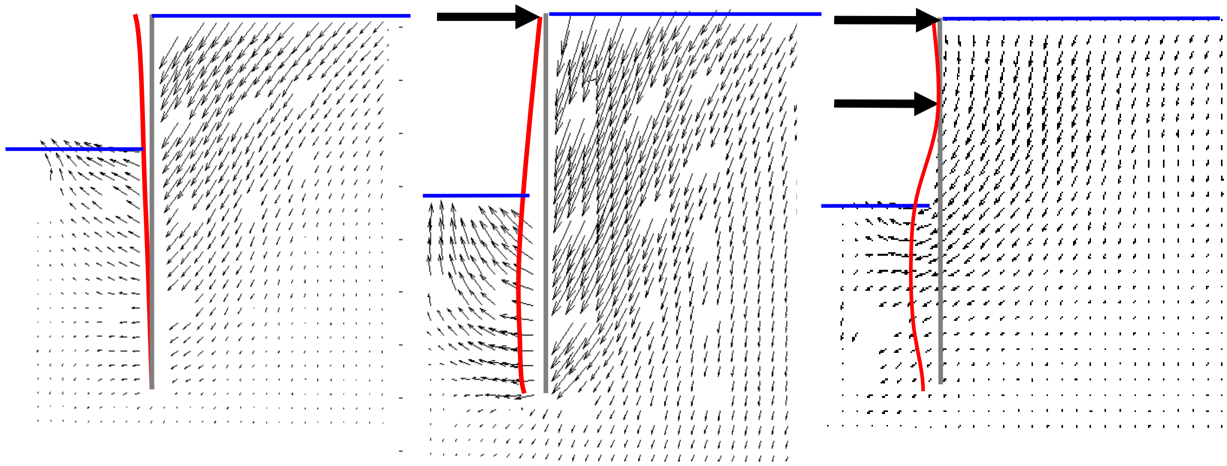




The complete model package on the rotor

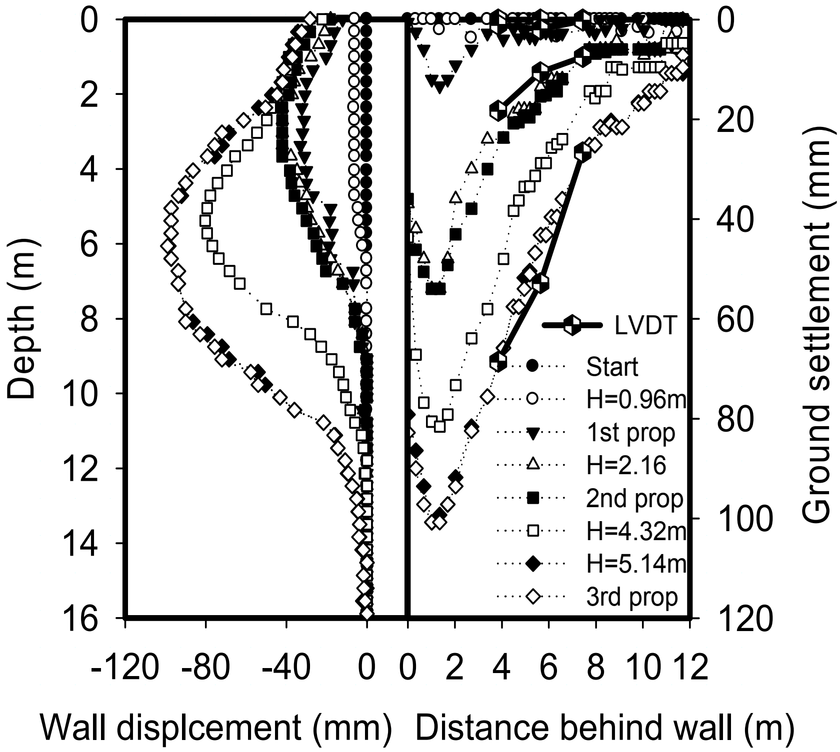


Mechanisms observed in Lam's centrifuge tests



(a) Cantilever (b) Prop en haut (c) Multi-propped

The areas of subsidence and bulging are equal?



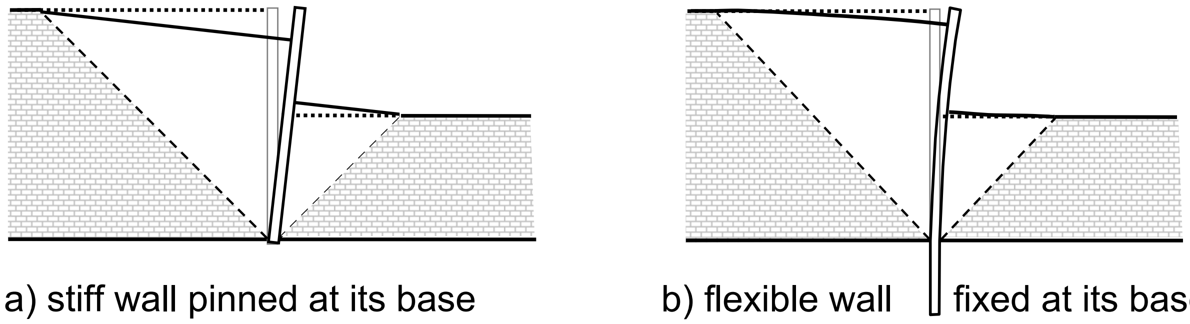
Are the observed displacements reasonable?

- The observed 2D displacement fields can be checked for consistency by checking conservation of energy.
- The loss of potential energy ΔP caused by observed subsidence can be calculated if density ρ and gravity Ng are known.
- Strains can be calculated from observed displacements.
- Knowledge of the soil stress-strain curve leads to the calculation of work ΔW_{soil} done on the soil up to the calculated strains, integrated over the volume.
- Knowledge of the stiffness of walls and props leads to the calculation of work ΔW_{wall} done on the structure.
- Lam showed an energy balance $\Delta P = \Delta W_{soil} + \Delta W_{wall}$ within about 20%.

The importance of deriving simplified mechanisms

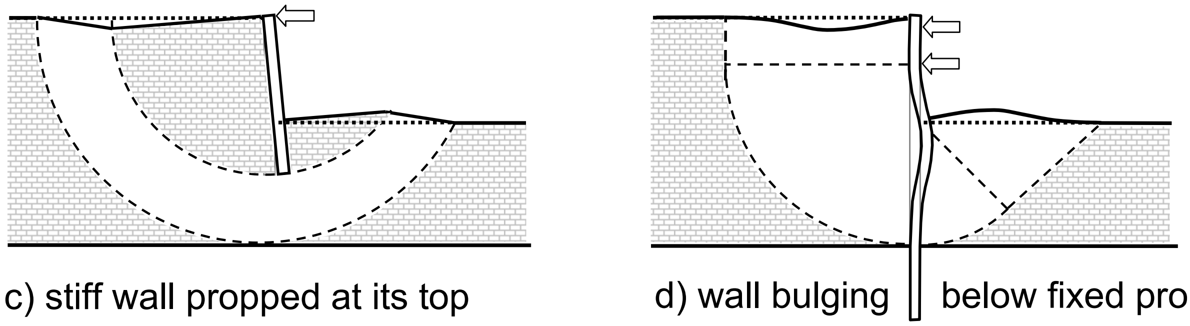
- Although observed mechanisms may be consistent, they need to be simplified and generalised to apply the Mobilizable Strength Design method to calculating soil-structure deformations.
- Simplified mechanisms can be scaled according to some maximum boundary displacement, e.g. δw_{max}.
- Each of the components δP, δW_{soil} and δW_{wall} can be expressed analytically as some function of δw_{max}.
- Then, at each stage of construction, the increment δw_{max} can be found numerically by solving $\delta P = \delta W_{soil} + \delta W_{wall}$ through iteration.
- Previous displacements have to be stored so that non-linearity can properly be allowed for.

Simplified deformation mechanisms



a) stiff wall pinned at its base

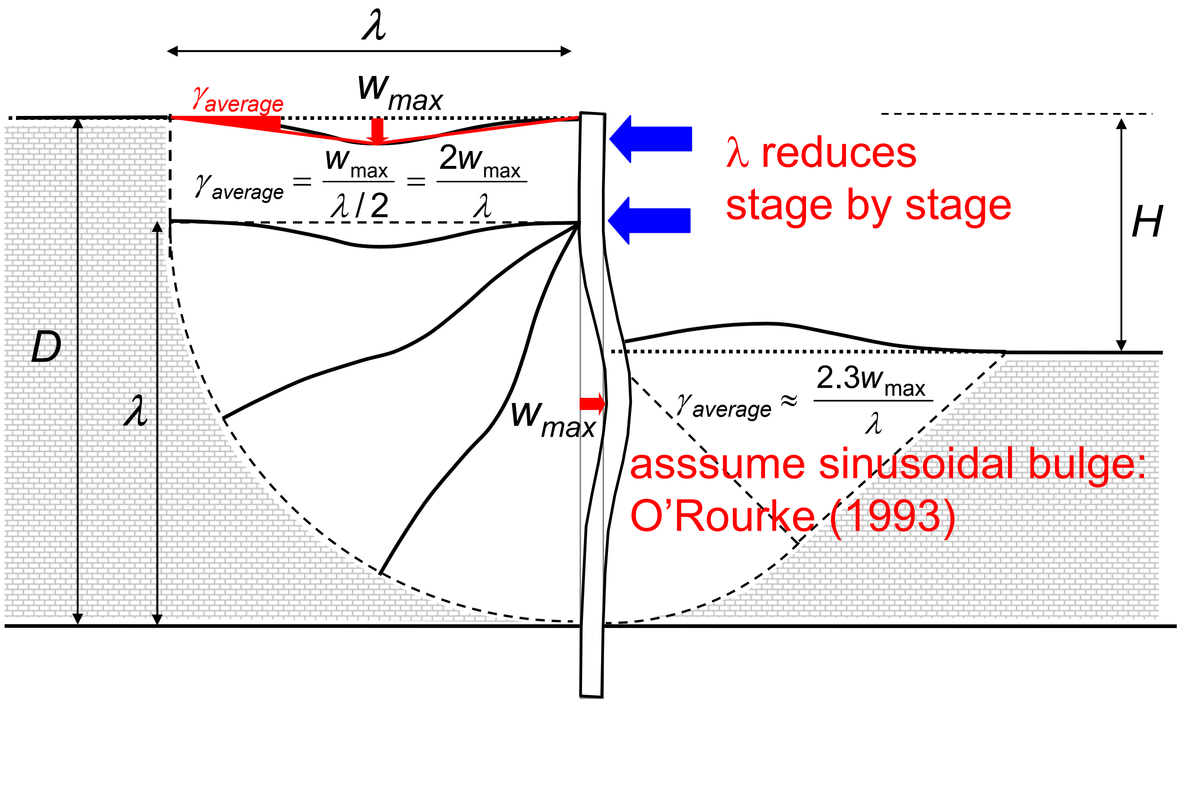
b) flexible wall fixed at its base



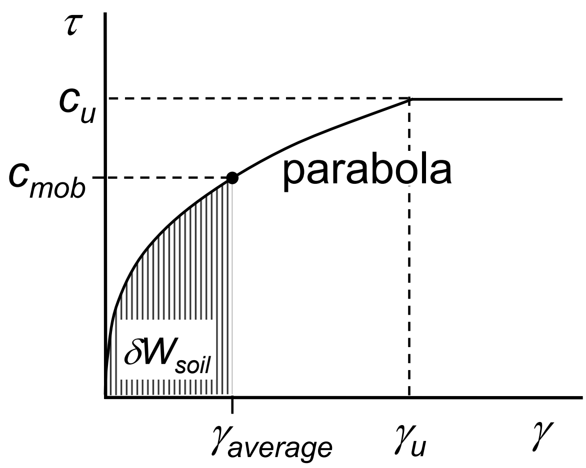
c) stiff wall propped at its top

d) wall bulging below fixed props

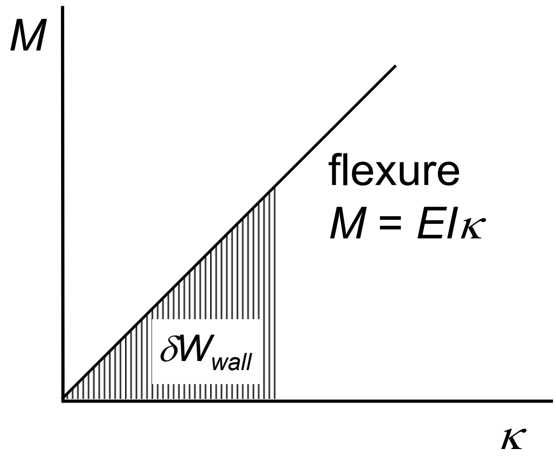
Shear strains inside the bulging mechanism



Unit work calculations



Work done per unit volume of soil



Work done per unit length of wall

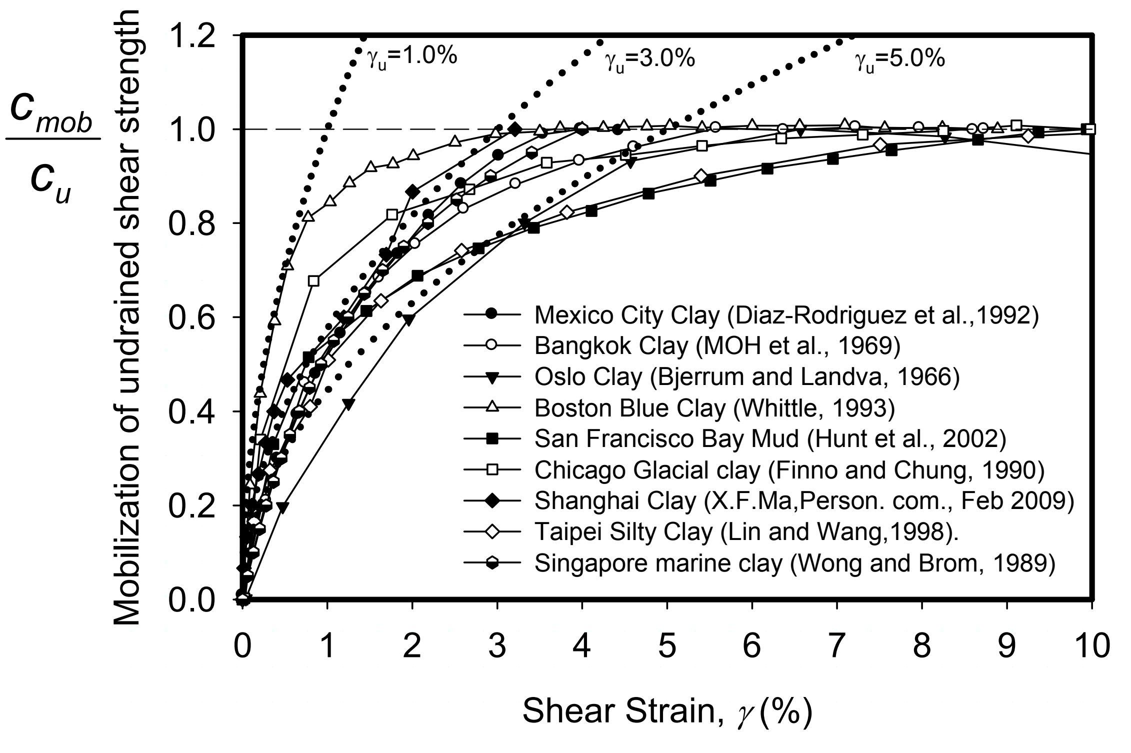
Using MSD to predict full-scale movements

- Sidney Lam collected 110 field case studies from 9 cities around the world, for which soil stress-strain data is available from the original publications.
- Every wall was constructed in soft to firm clays but had its base located in a stiff layer, so fixity in a stiff base layer was assumed in MSD back-analysis.
- He performed an MSD back-analysis of staged construction in every case, and compared his “predictions” of maximum wall movement with the original authors’ field measurements.

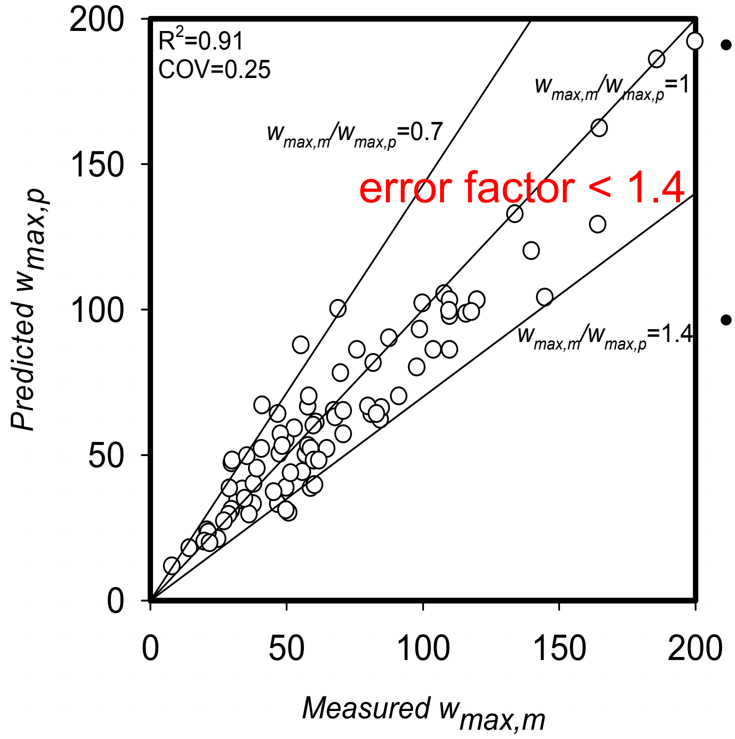
Lam's new database of field case studies

- Nine authors report in detail on a total of 110 deep excavations in soft clay under nine famous cities :
  - Bangkok (2 sites) Moh et al (1969)
  - Boston (5 sites) Whittle (1993)
  - Chicago (10 sites) Finno & Chung (1990)
  - Mexico City (1 site) Diaz-Rodriguez et al (2002)
  - Oslo (9 sites) Bjerrum & Landva (1966)
  - San Francisco (4 sites) Hunt et al (2002)
  - Shanghai (67 sites) Ma (2009)
  - Singapore (21 sites) Wong & Broms (1989)
  - Taipei (36 sites) Lin & Wang (1998)

Soft clays beneath 9 world cities: parabolas, γ_u



MSD "predictions" using c_u profile and γ_u



- MSD incremental calculations based on expected construction sequence, summed on a spreadsheet.
- variation may be due to
  - authors' c_u profile
  - our estimate of γ_u
  - "workmanship", i.e. propping delays or gaps, over-dig, etc

Mechanisms help us to understand deformations

- Understanding is achieved only when we have a robust framework of ideas with clear expectations of the significant parameters and their functional relationship to the pattern and magnitude of ground movements.
- We need dimensionless groups based on mechanics.
- Maximum wall bulging movements, and the lateral extent of ground deformations, should be normalised by the size λ of the deformation mechanism, *not* by the depth of excavation H: compare Clough & O'Rourke (1990).
- Although the "safety factor against base heave" offers some correlation with wall movements, its application is unclear and imprecise: see Mana & Clough (1981).

Structural Response Ratio S

- Consider bulging w_{max} to occur over the *average* wavelength $\lambda = D - 0.5H$.
- The net lateral pressure change required to achieve this, by elastic beam theory, is Δp such that:

$$\Delta p \propto w_{\max} \frac{EI}{\lambda^4}$$

- The cause of bulging is vertical pressure reduction ρgH.
- So define the dimensionless Structural Response Ratio

$$S = \frac{w_{\max}}{\rho gH} \frac{EI}{\lambda^4}$$

- It is similar to an earth pressure cell registration factor!

Secant soil stiffness G

- For "parabolic" soil with (c_u, γ_u), mobilized stiffness G is:

$$G = \frac{c_{mob}}{\gamma} = \frac{c_u}{\gamma}\left(\frac{\gamma}{\gamma_u}\right)^{0.5} = \frac{c_u}{\gamma_u}\left(\frac{\gamma_u}{\gamma}\right)^{0.5} = \frac{c_u}{\gamma_u} M$$

- The mobilization factor M may take the form:

$$M \propto \frac{c_u}{\rho gH}$$

- So the soil stiffness might be written in the form:

$$G \propto \frac{c_u}{\gamma_u} \frac{c_u}{\rho gH}$$

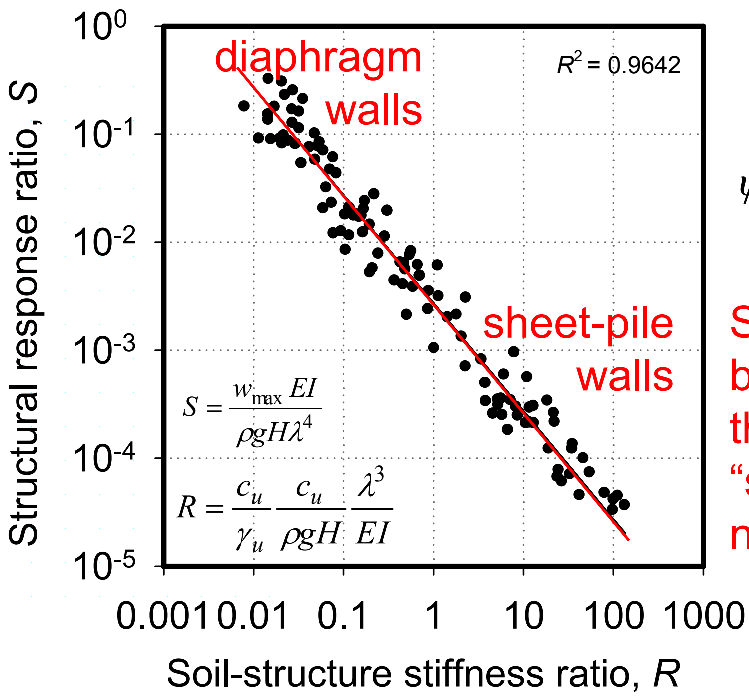
Soil-Structure Stiffness ratio *R*

- To obtain a dimensionless group, we should normalise the secant soil stiffness G with the flexural stiffness EI of a fixed-ended wall segment of length λ projecting below the bottom prop.
- So define Soil-Structure Stiffness ratio *R*:

$$R = \frac{G\lambda^3}{EI} = \frac{c_u}{\gamma_u}\frac{c_u}{\rho g H}\frac{\lambda^3}{EI}$$

- *R* reduces as excavation depth *H* increases, which is logical because the soil is losing secant stiffness as it approaches its peak strength.

110 field records show log*S* ≈ -2.6 - log*R*

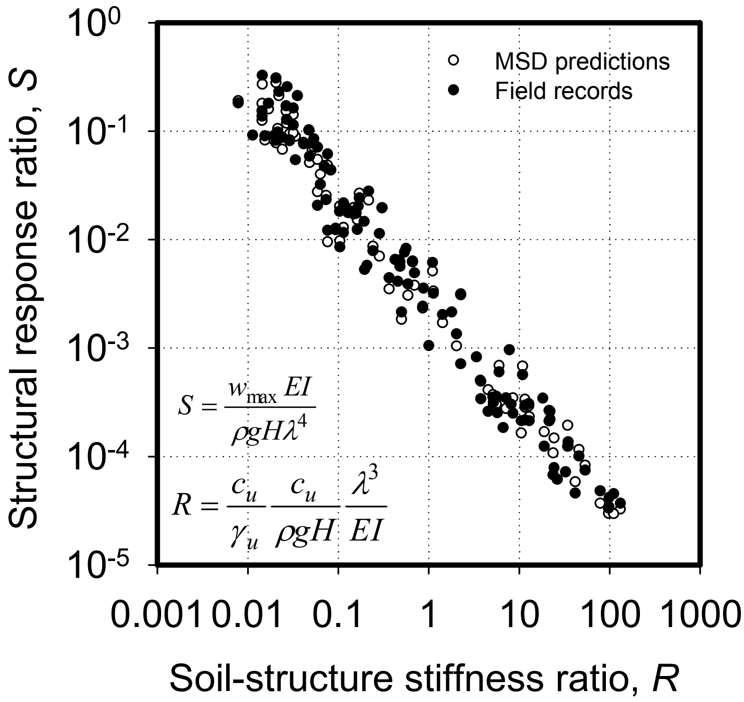


SR = ψ (say) ≈ constant

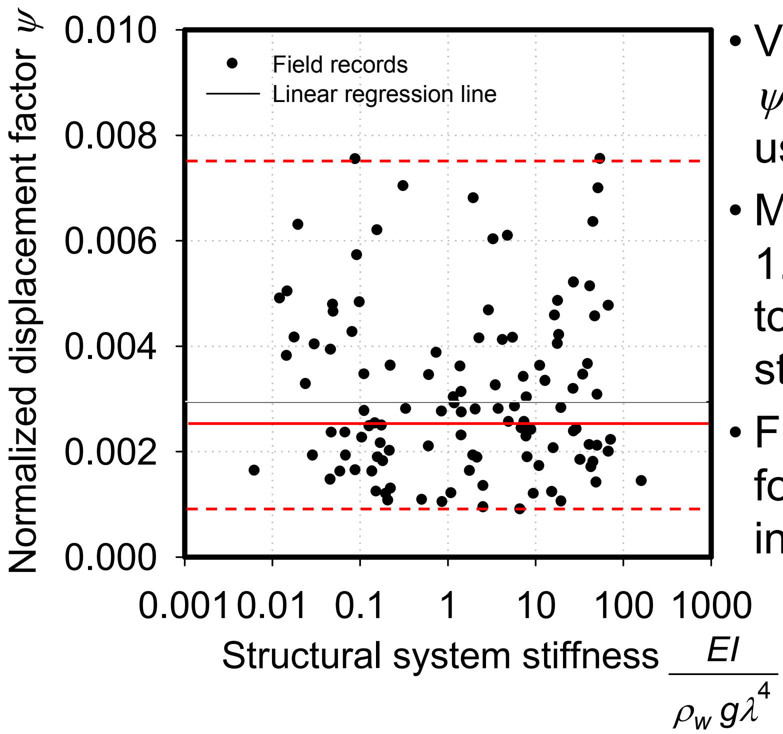
$$\psi = \frac{w_{max}}{\lambda}\frac{1}{\gamma_u}\left(\frac{c_u}{\rho g H}\right)^2 \approx \frac{1}{400}$$

So *EI* cancels out! The bulge depends mainly on the soil stiffness. Even a “stiff” diaphragm wall is negligible in comparison!

MSD predictions follow field measurements



Scatter in ψ: factor 2.9 (2 standard deviations)



- Variation factor 2.9 on ψ is mainly due to using a single λ value.
- MSD variation factor is 1.4 when λ is allowed to change stage by stage.
- Further analysis should formulate the factor 2.0 influence of propping.

Limiting w_{max}: the soil

- Because the soil is, literally, doing all the work, it would be unwise to permit $M < 1.2$, even with close monitoring.
- This limits $\gamma_{average}/\gamma_u < 1/1.2^2$ or 0.7 .
- But $\gamma_{average} \approx 2w_{max}/\lambda \approx \frac{1}{200}\gamma_u\left(\frac{\rho g H}{c_u}\right)^2$
- So we should create additional in situ "props" between the insitu walls, prior to excavation, e.g. by soil stabilization, and adopt close prop spacing, in critical cases where stability number $N_H = \rho gH/c_u > 12$.

Limiting w_{max}: the wall

- The maximum bending strain induced in a wall of thickness d bulging w_{max} over sinusoidal wavelength λ is:

$$\varepsilon_{\max} = \pi^2 \frac{w_{\max} d}{\lambda^2}$$

- e.g. a 0.8 m thick diaphragm wall bulging 0.2 m over a 20 m wavelength gives $\varepsilon_{max} \approx 2 \times 10^{-3}$. Tensile cracking begins in concrete at $\varepsilon_{crack} \approx 10^{-4}$, longitudinal steel yields at $\varepsilon_{yield} \approx 1.5 \times 10^{-3}$ and concrete begins to crush at $\varepsilon_{crush} \approx 4 \times 10^{-3}$: Park and Gamble (2000).
- The structural engineer must maintain ductility and continuity, and this will also place a limit on w_{max}.

Limiting w_{max}: the neighbours

- Whereas engineers currently define a lateral zone of influence in terms of excavation depth H, e.g. 2H or 3H, evidence of mechanisms now suggests this could simply be taken as the depth D of soft material.
- Burland et al (2001) affirm that a typical building would suffer severe damage if relative settlement $\Delta/L > 0.2\%$.
- So we avoid severe damage if $w_{max}/\lambda_{\text{average}} < 0.2\%$ and the deduction from our new database is that this requires good propping and $\gamma_u N_H^2/400 < 0.2\%$, i.e. $\gamma_u N_H^2 < 0.8$.
- Braced walls alone will not prevent severe collateral damage to adjacent structures founded on nc clays. Additional soil stabilization, or similar, will be needed.

Conclusions: predicting wall bulging w_{max}

- New definitions of Structural Response Ratio *R* and Soil-Structural Stiffness Ratio *S*, and a new database of case studies, enable us to show that the stiffness *EI* of typical braced walls is irrelevant to wall deflection.
- It is the soil that offers most of the resistance, not the wall.
- w_{max} is shown to be proportional to:
  - the typical size of the mechanism $\lambda = D - 0.5H$
  - the strain γ_u to reach peak strength
  - the square of the stability number $N_H = \rho gH/c_u$

Conclusions: controlling wall bulging w_{max}

- No formula yet links w_{max} to prop spacing, but the prop system may contribute a factor of 2 either side of the mean displacement obtained from the new database.
- However, w_{max} in each case can be predicted stage by stage using MSD, within an uncertainty factor of 1.4 according to the new database of 110 field case studies. This can be done quickly, on a spreadsheet, in the spirit of limit equilibrium analysis.
- It has been shown that normally consolidated clays will very likely provoke unacceptable wall deformations. Additional measures such as soil stabilization carried out in advance of excavation, will be required.

Nicoll Highway subway site, Singapore, 20-04-04

Quelle est l'opportunité pour les modélisateurs centrifugeuse?

- Ce niveau de compréhension peut être réalisé dans d'autres problèmes de déformation du sol en appliquant la modélisation centrifuge, en déduire les mécanismes de déformation simplifiée, et en utilisant les principes de MSD basée sur la conservation de l'énergie.
- Nous pouvons résoudre des problèmes très longue échelle de temps, tels que le ramollissement saisonnière des pentes argileuses: Take & Bolton (2011) dans le prochain numéro Géotechnique.
- Nous avons pour objectif de résoudre intense, à court problèmes de déformation des délais tels que des tremblements de terre ou le chargement de tempête.
- Méthodes de calcul objectives et pratiques sont nécessaires pour les déformations du terrain dans toutes les situations possibles, et nous pouvons fournir et de les justifier.

Enfin

Mes sincères remerciements à vous tous pour écouter patiemment, et à la barre de traduction Google pour fournir de l'aide pour moi et, sans doute, un certain amusement supplémentaire pour vous.