Deformation & failure of DM group columns

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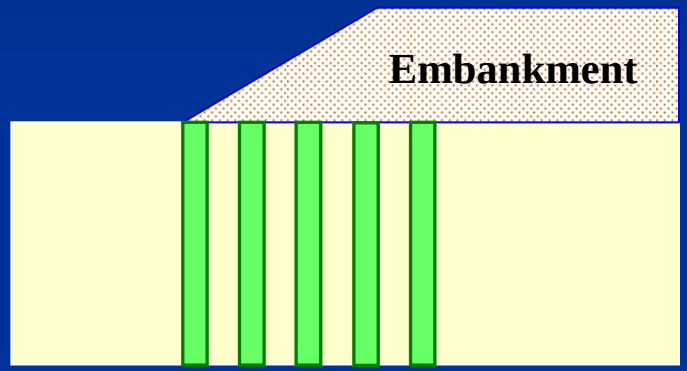
Deep Mixing Method

a deep in-situ soil admixture stabilization technique using cement or lime
column diameter : 1 to 1.5m
column strength : 200 to 2,000 kPa

Failure Pattern

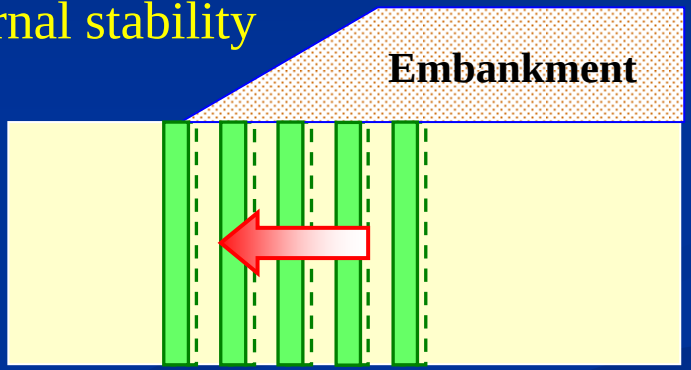
Failure pattern ?



DM improved ground

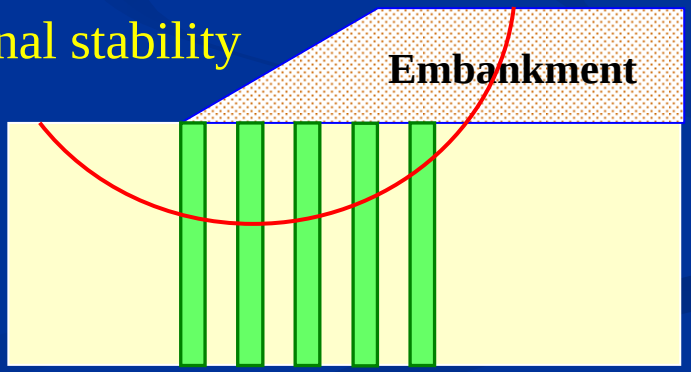
assumed failure modes in design

External stability



sliding failure mode

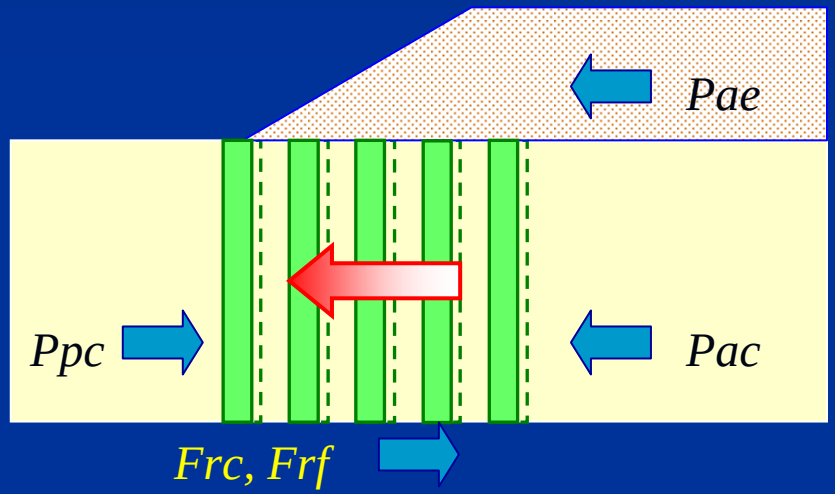
Internal stability



shear failure mode

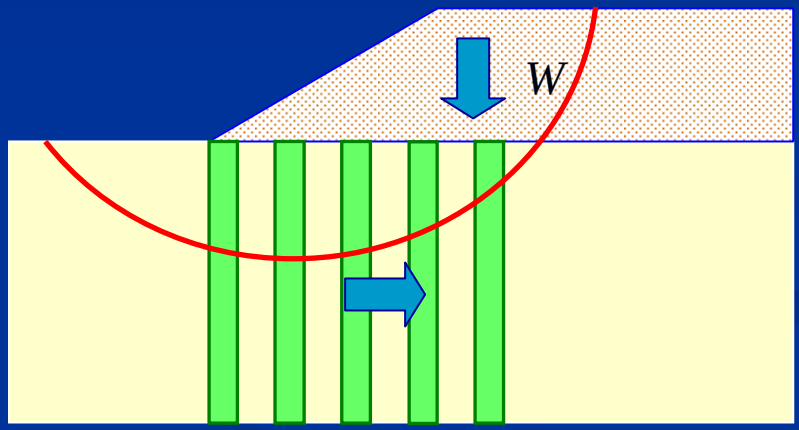
Current design
- External and internal stability -

sliding failure



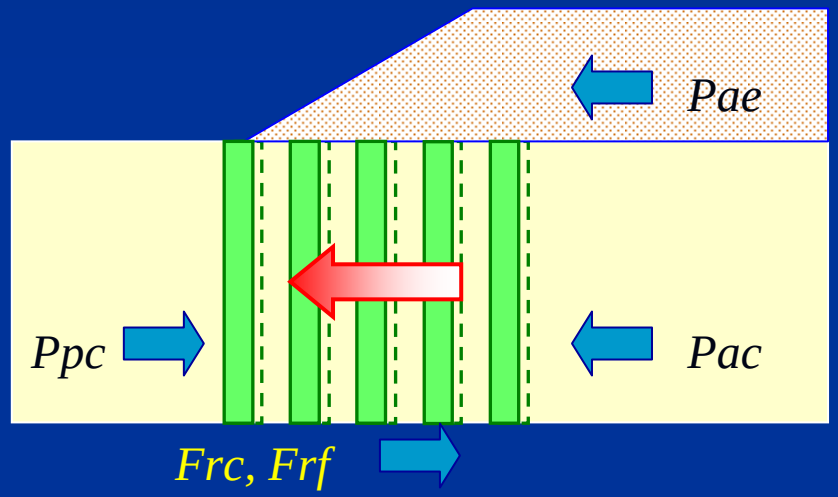
$$Fs = \frac{P_{pc} + F_{rf} + F_{rc}}{P_{ae} + P_{ac}}$$

shear failure

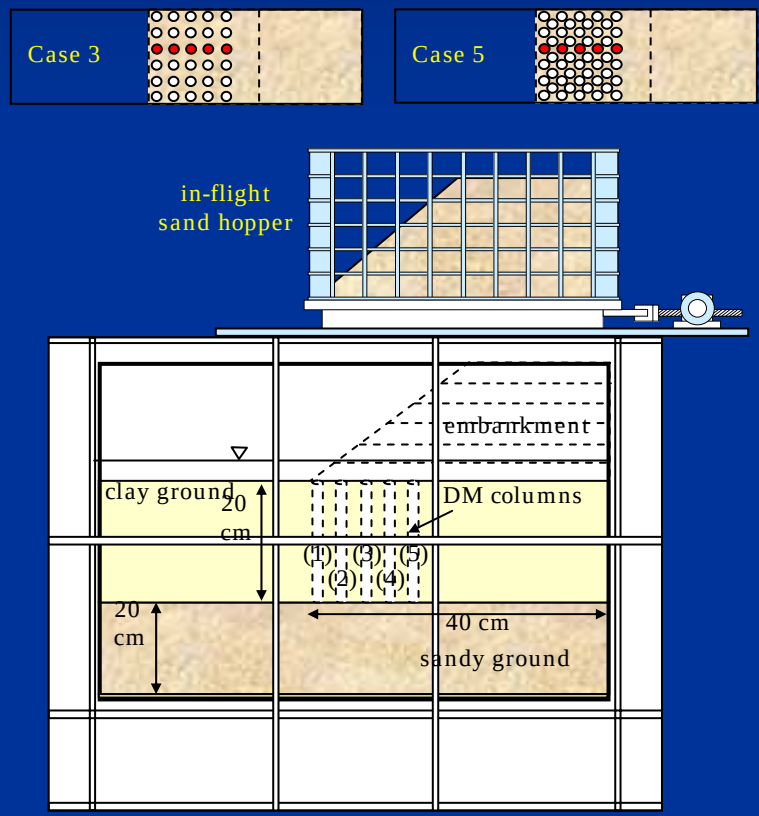


$$Fs = \frac{\{a_s \cdot q_u / 2 + (1 - a_s) \cdot c_u\} \cdot R}{W \cdot x}$$

External Stability



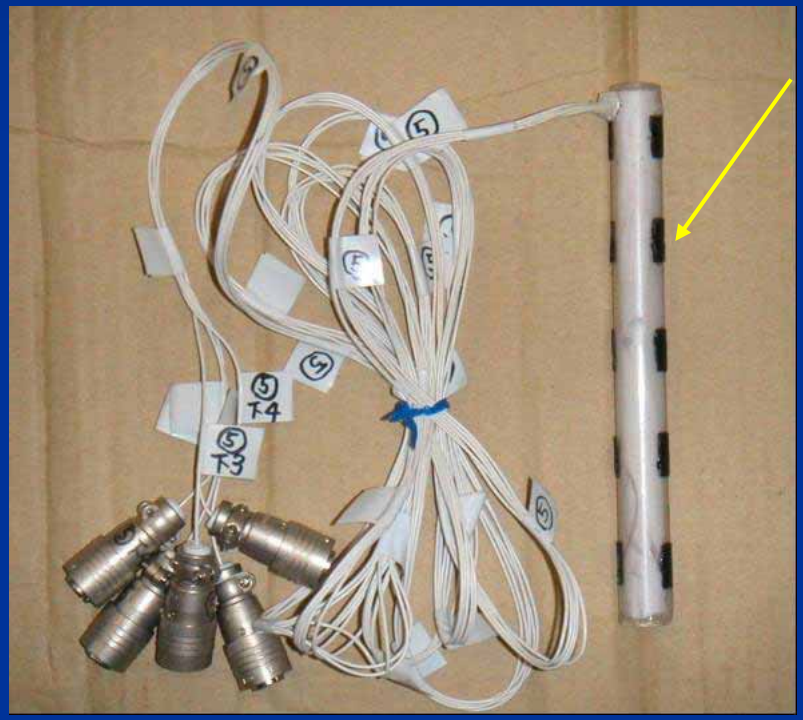
centrifuge model test



Test case and P_{ef} (kPa)

		3 rows	5 rows	7 rows
unimp.	10.8	-	-	-
acryl (infinite)	-	26.5	42.2	50.0
high (1300 kPa)	-	33.3	34.2	47.9
low (400 kPa)	-	16.9	26.2	25.4

Model treated column for external stability

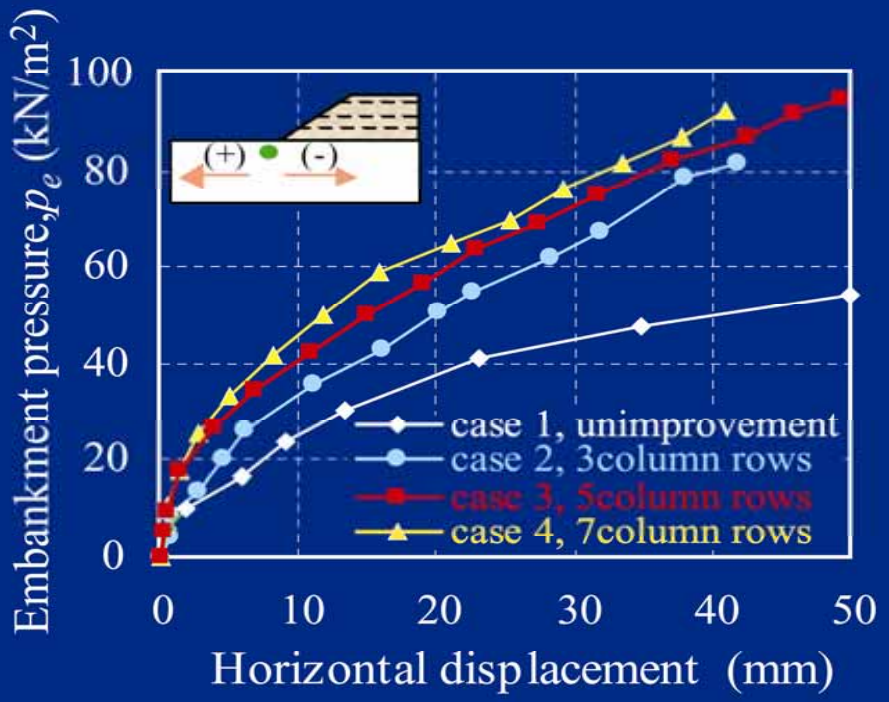


strain gauge

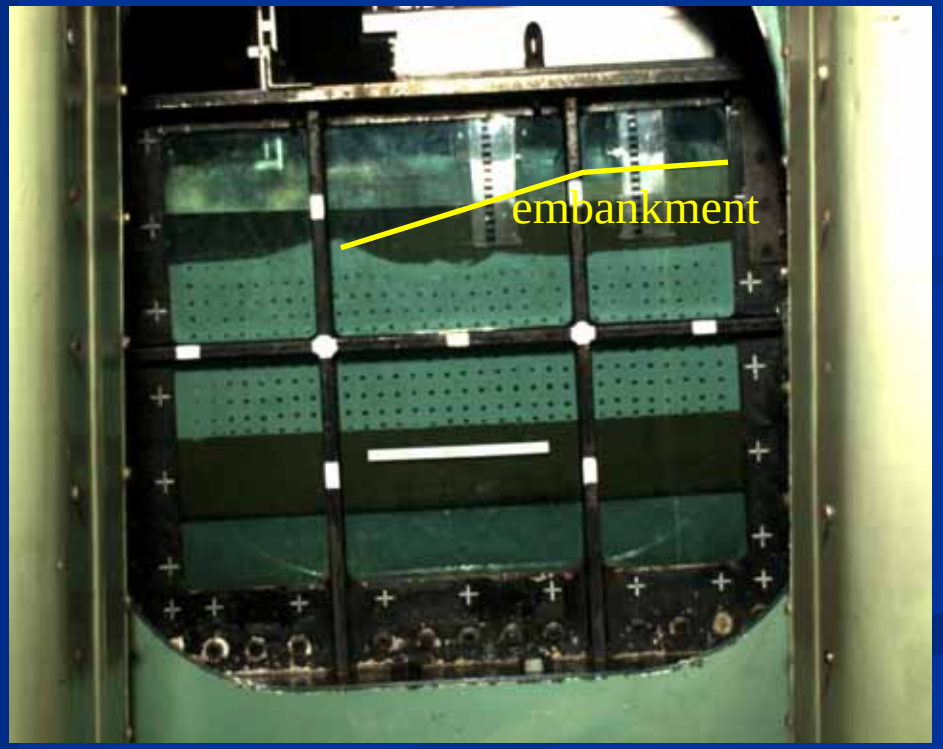
diameter:	
inner	1.6 cm
outer	1.9 cm
length :	20 cm
EI:	9.3 Nm^2
unit weight:	1.43 g/cm^3

Failure mode
- Unimproved ground -

Embankment pressure – disp.

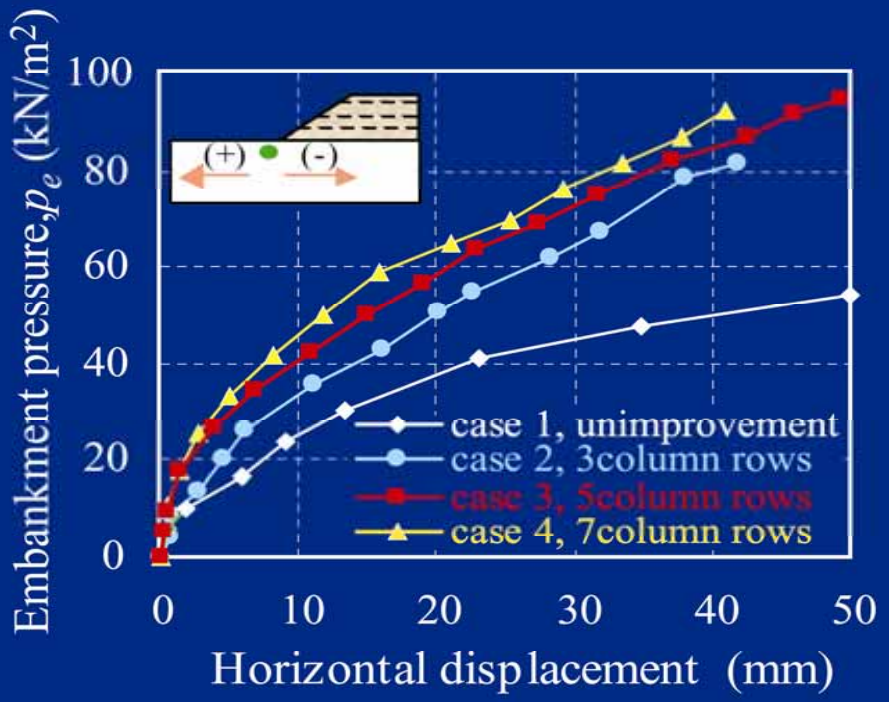


Failure mode

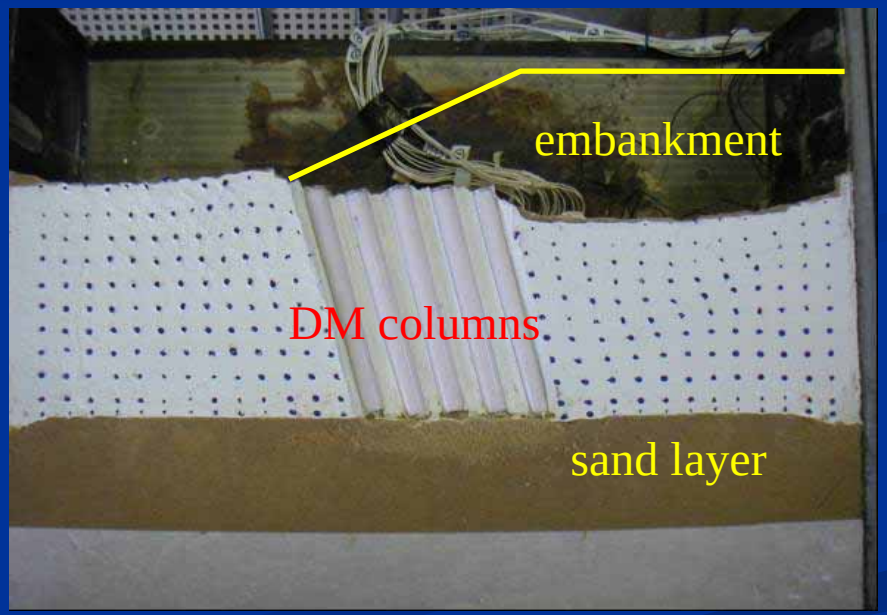


Failure mode
- External stability -

Embankment pressure – disp.

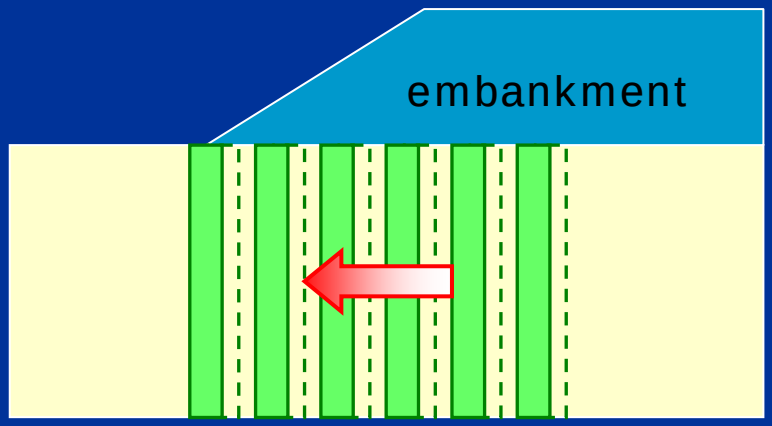


Failure mode



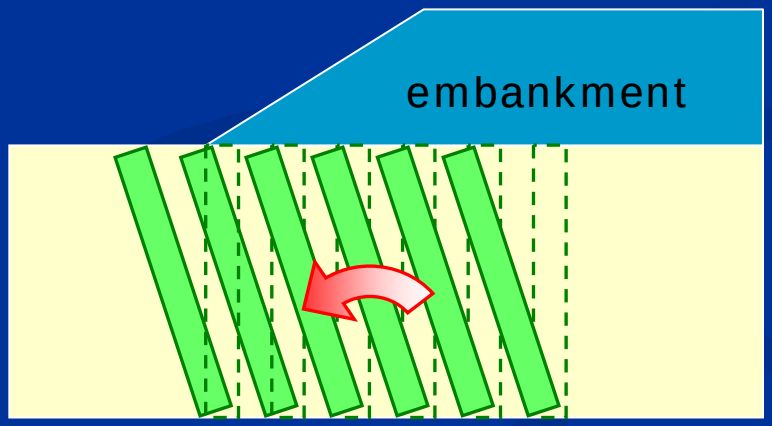
Failure mode in external stability

- **external stability**
  - **sliding failure mode**
  - **collapse failure mode**



sliding failure mode

Stable



collapse failure mode

Less stable

collapse – sliding failure mode found in daily life

collapse failure

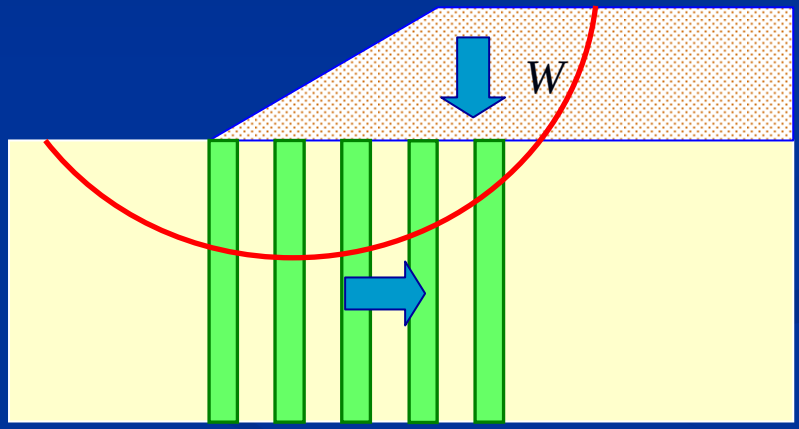
Domino Taoshi

sliding failure

Dharma Otoshi

Internal Stability

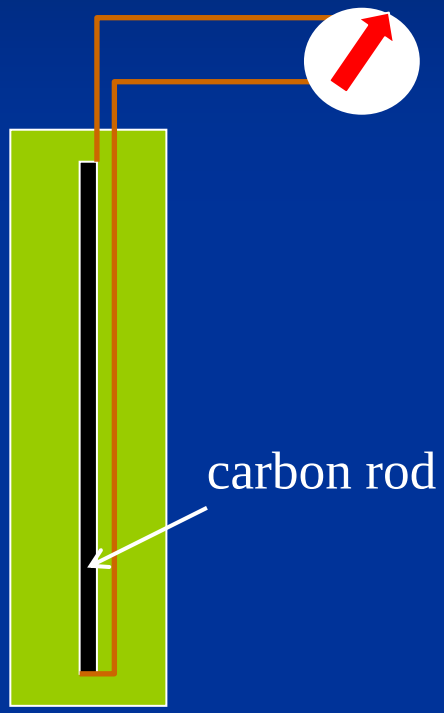
shear failure

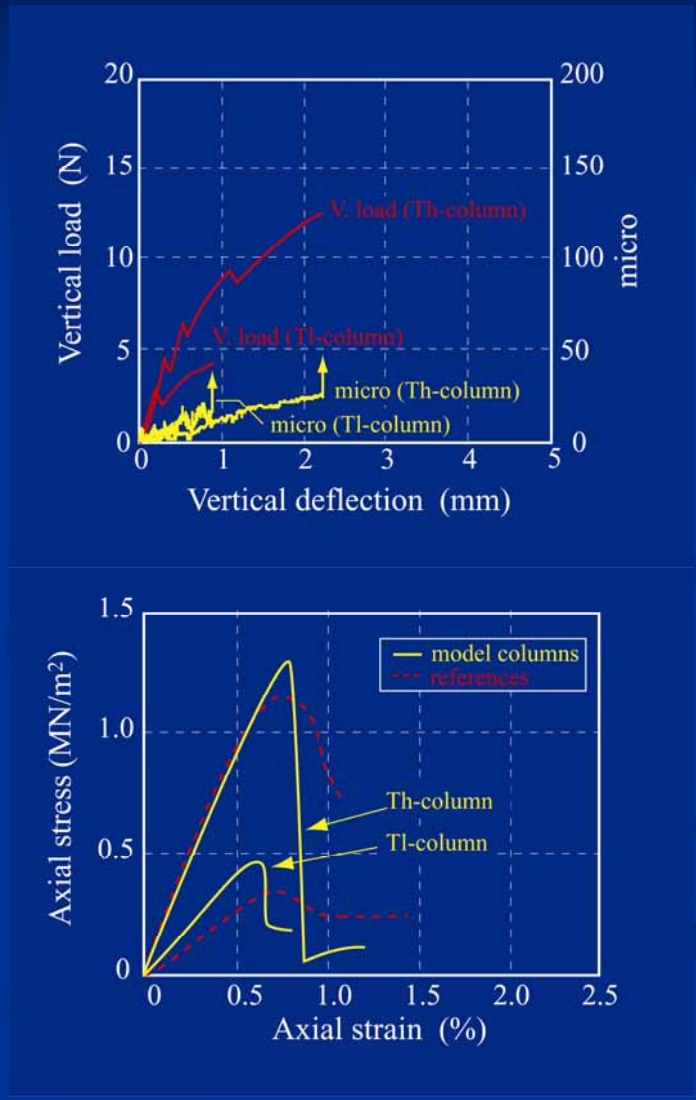


Model treated column for internal stability

Test series	mixing condition		size		strength		carbon rod
	w_i (%)	a_s (%)	diameter	length	q_u (kPa)	σ_b (kPa)	diameter
Th	160	10.0	2cm	20cm	1300	320	3mm
Tl	160	12.5	2cm	20cm	400	120	2mm

Model treated column

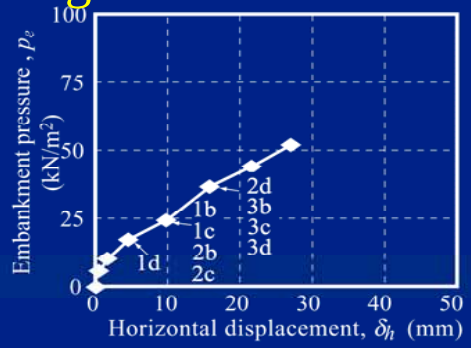




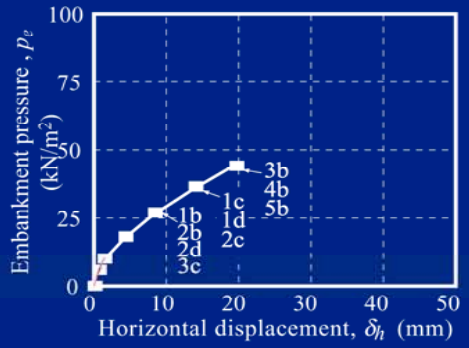
Internal stability

Embankment pressure – displacement

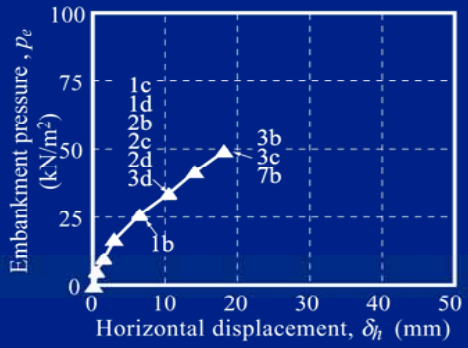
low strength



(a) Case 6

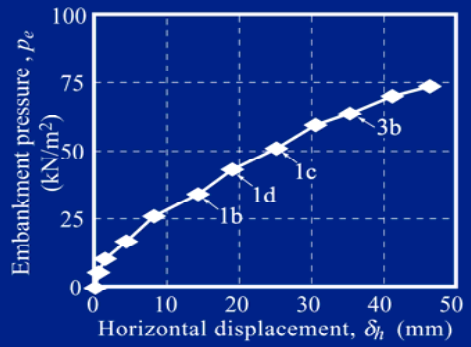


(b) Case 7

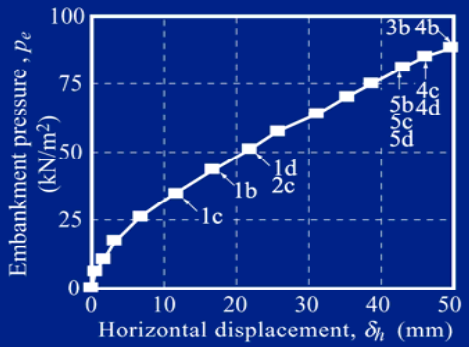


(c) Case 8

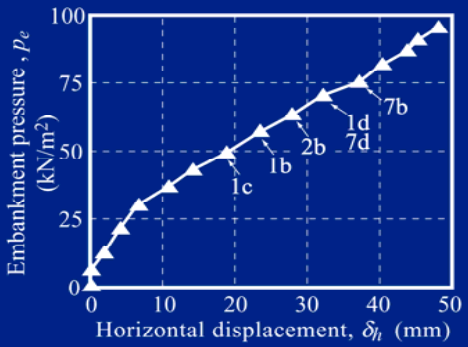
high strength



(d) Case 9



(e) Case 10



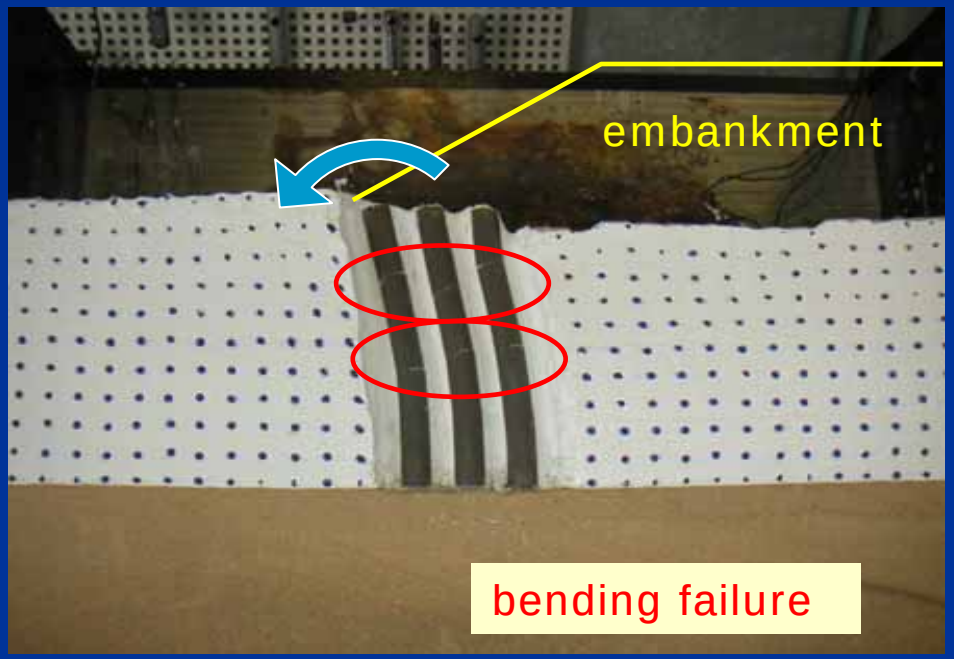
(f) Case 11

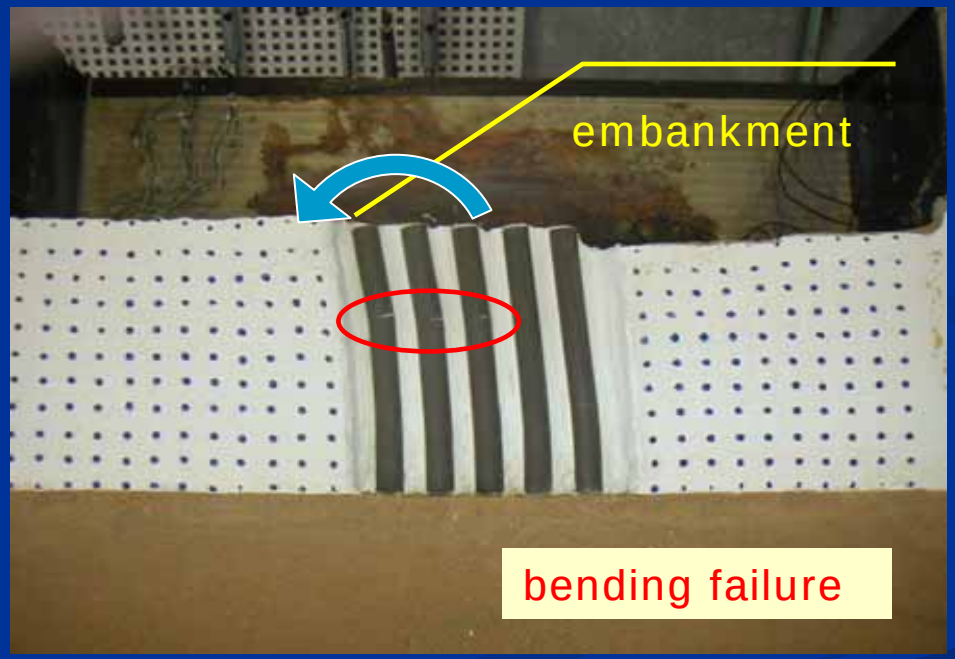
3 piles

5 piles

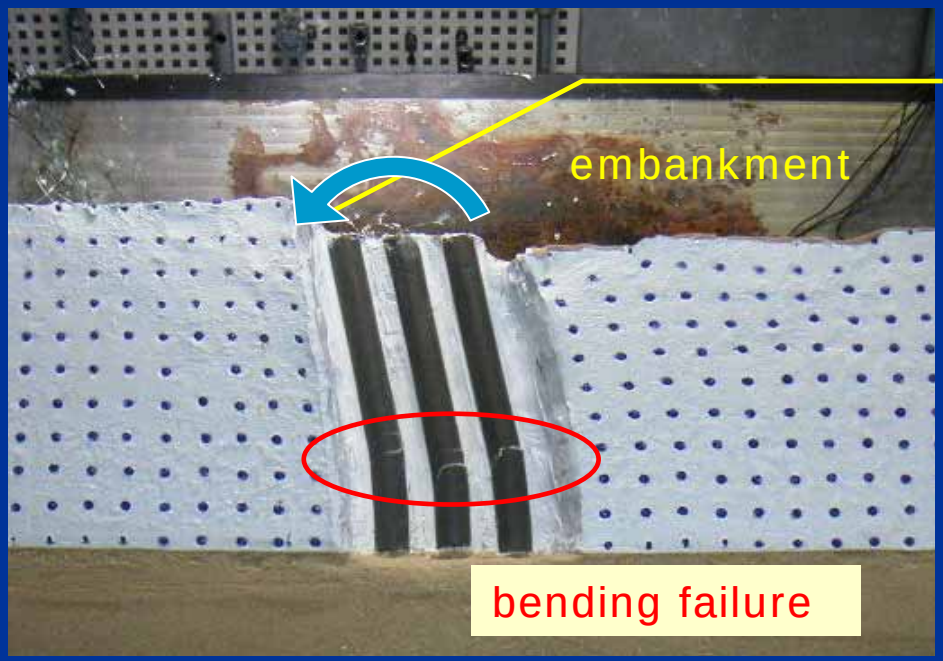
7 piles

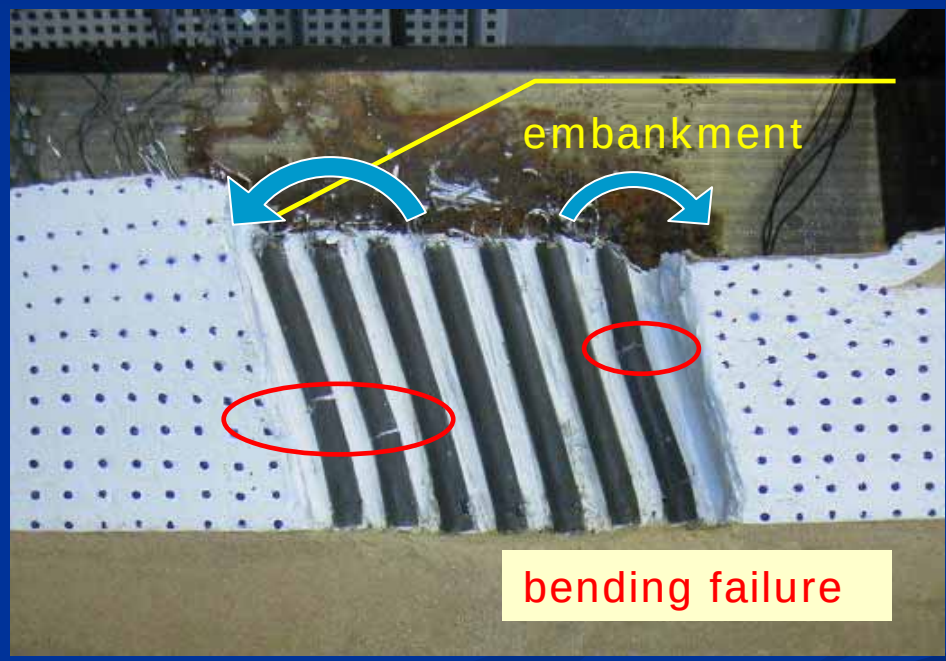
column failure mode
- low strength column -





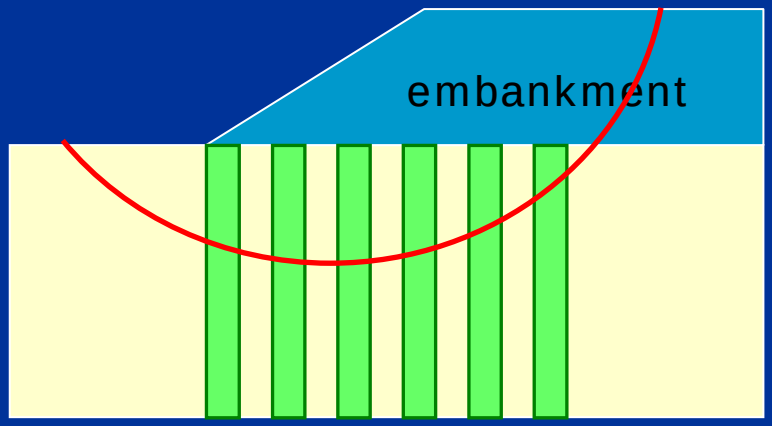
column failure mode
- high strength column -





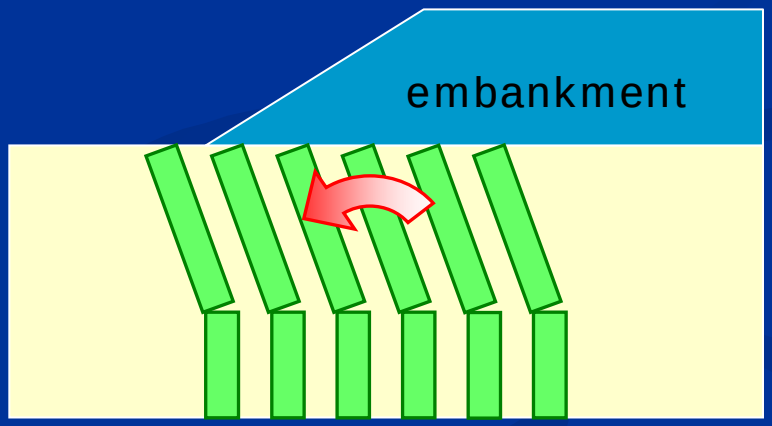
What we found about internal stability

- internal stability
  - shear failure mode
  - bending failure mode



shear failure mode

Stable

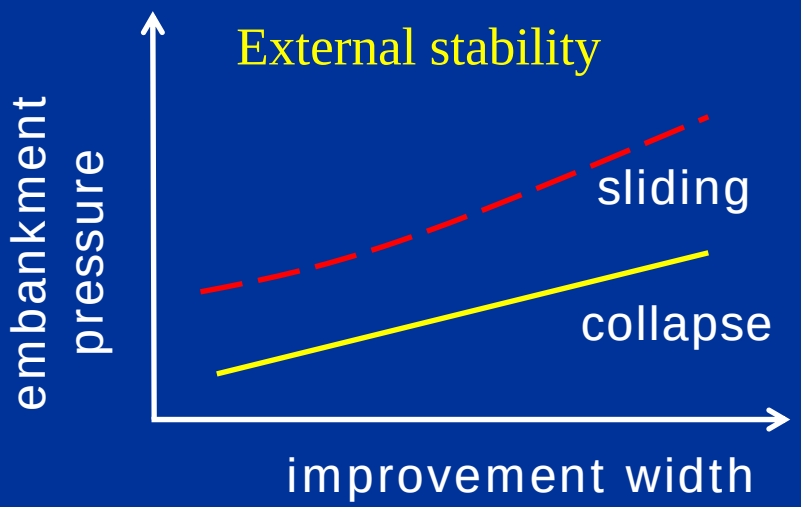


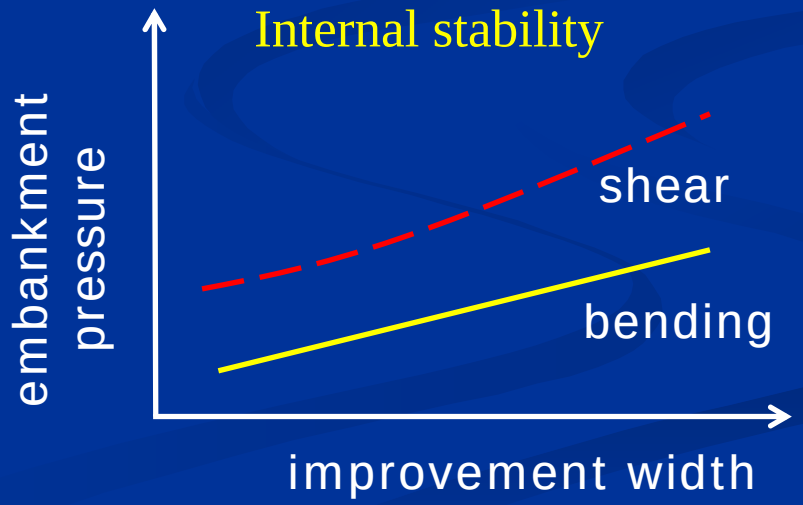
bending failure mode

Less stable

What we found

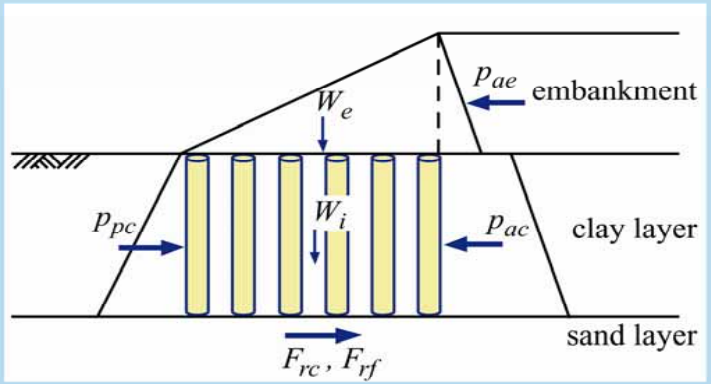
- Failure modes assumed in the current design, sliding and slip circle failure, are not observed in the tests.
- Collapse failure and bending failure modes are observed.
- The current design may overestimates the stability.





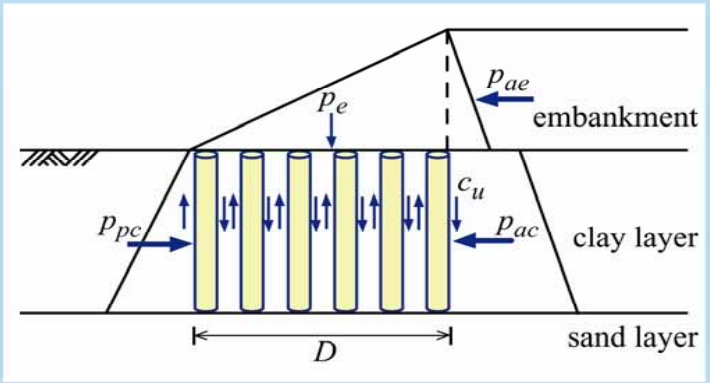
Evaluation
- External stability -

sliding failure



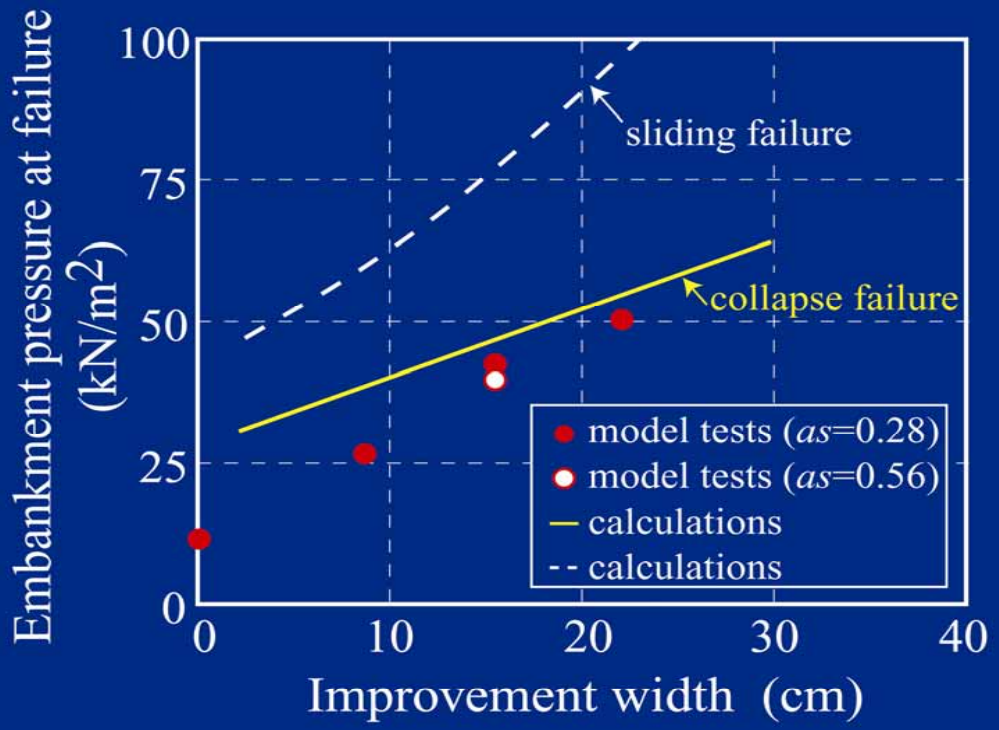
$$Fs = \frac{P_{pc} + F_{rf} + F_{rc}}{P_{ae} + P_{ac}}$$

collapse failure



$$Fs = \frac{M_{sc} + M_{rc} + M_{rt} + M_{re} + M_{pc}}{M_{ae} + M_{ac}}$$

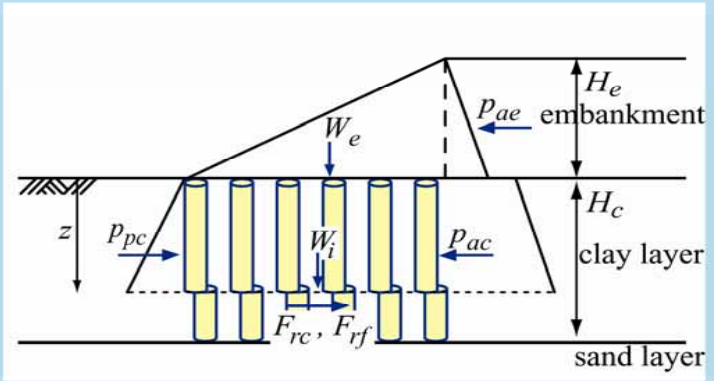
Evaluation
- External stability -



The calculation incorporating collapse failure gives reasonable estimation of the model tests.

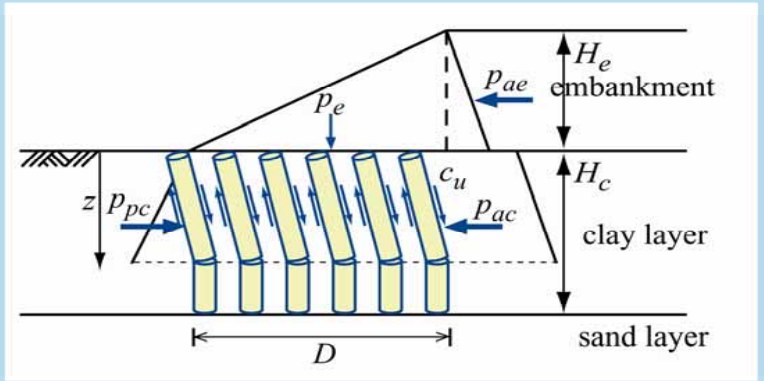
Evaluation
- Internal stability -

shear failure



$$Fs = \frac{P_{pc} + F_{rf} + F_{rc}}{P_{ae} + P_{ac}}$$

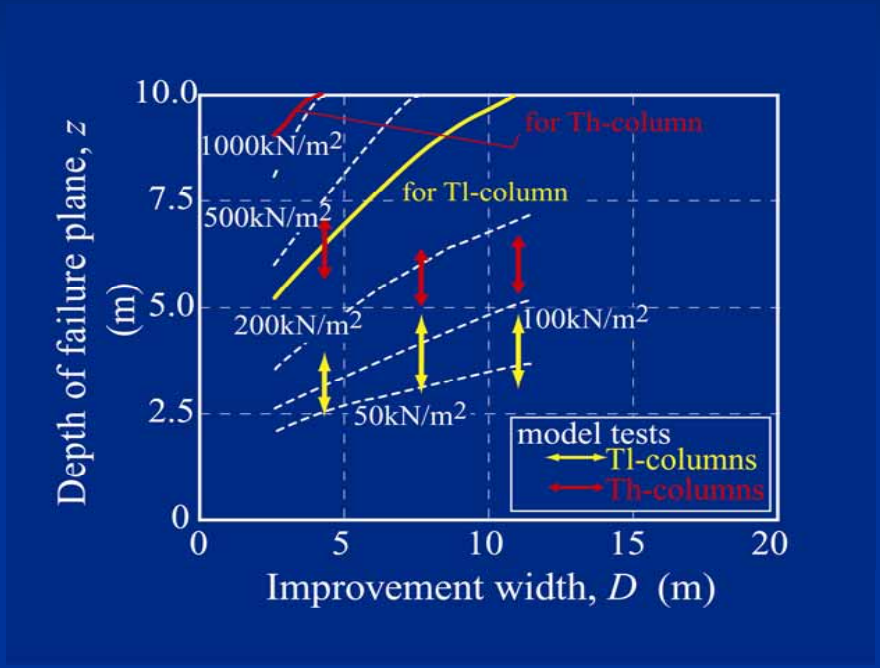
bending failure

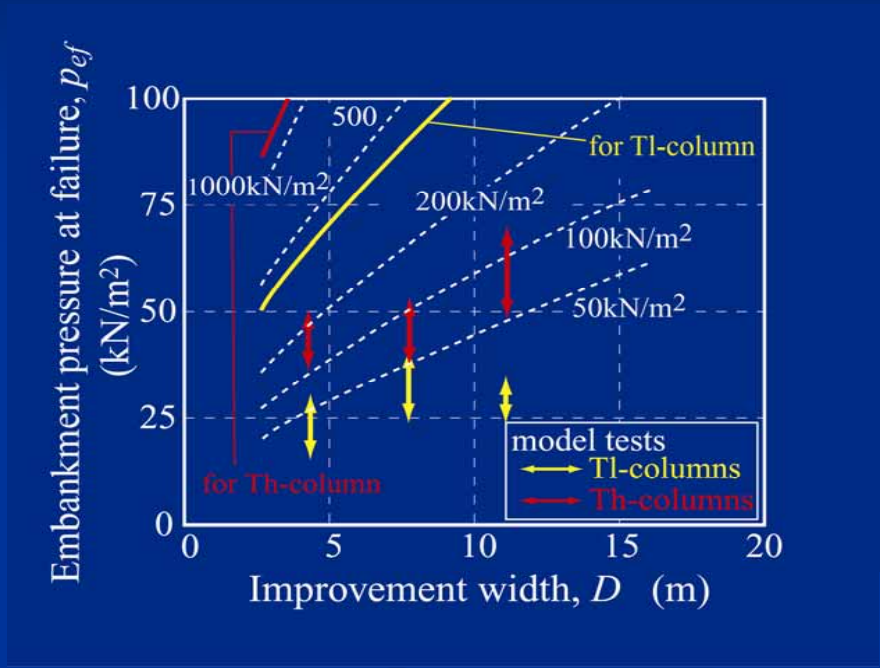


$$Fs = \frac{M_{sc} + M_{rc} + M_{rt} + M_{re} + M_{pc} + M_{pb}}{M_{ae} + M_{ac}}$$

Evaluation

- shear failure mode -

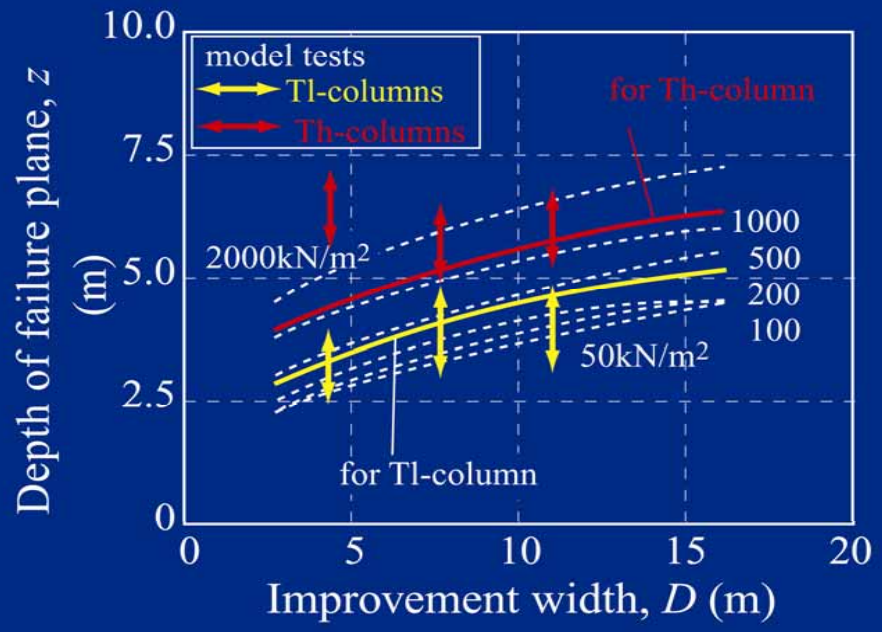


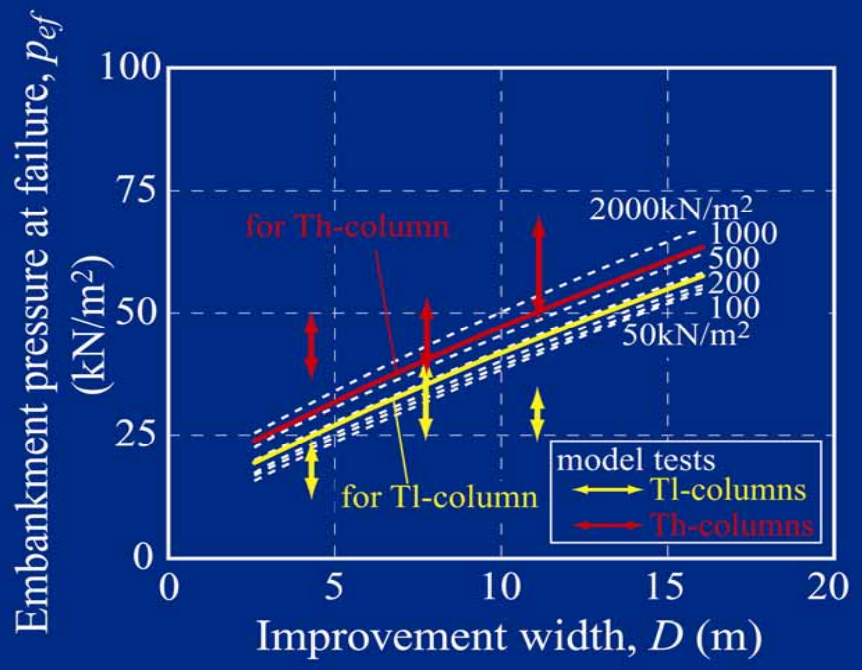


The calculation based on shear failure mode overestimates the depth of failure plane and failure pressure.

Evaluation

- bending failure mode -

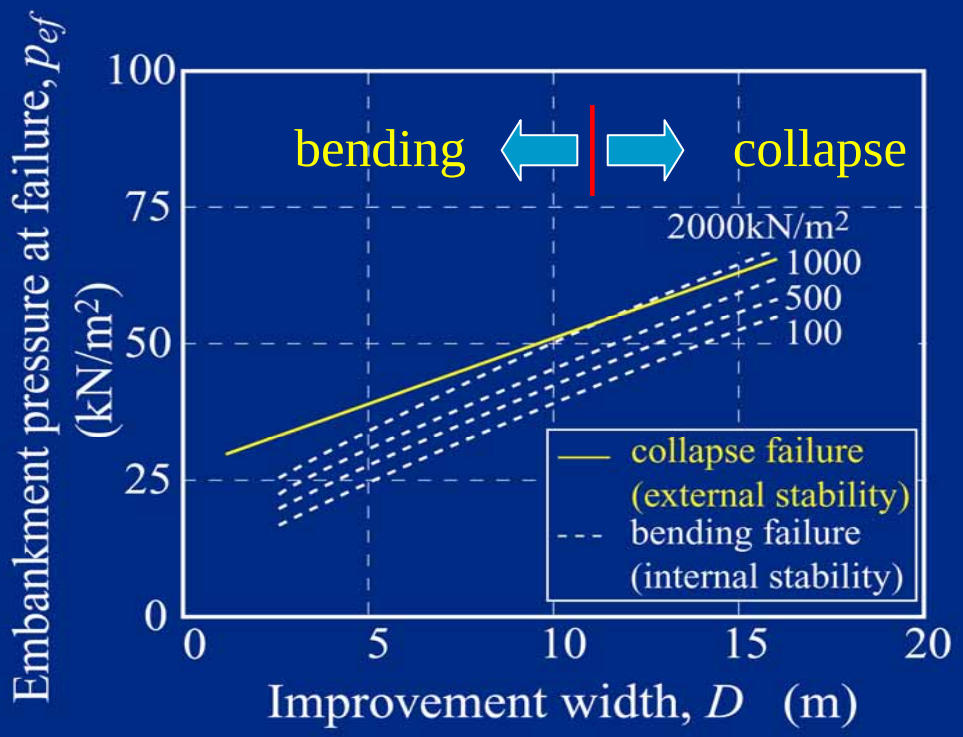




The calculation based on bending failure mode gives reasonable estimation of the depth of failure plane and failure pressure.

Combined failure criteria

improved ground should fail by one of the failure modes that gives a minimum capacity.



Concluding remarks

- **for external stability**
  - **The collapse failure mode instead of the sliding failure mode is observed in the model tests.**
  - **The calculation based on the collapse failure mode can gives reasonable evaluation for the external stability.**
- **for internal stability**
  - **The DM columns do not fail simultaneously but one by one with bending failure mode.**
  - **The calculation based on the bending failure mode of column can gives reasonable evaluation for the internal stability.**

Thank you for your attention

- Physical Experiment is the best teacher
- Physical Experience is also the best teacher