
# Rethinking piles in light of current knowledge

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# Outline of the TC212 1st ISSMGE Harry Poulos Honour Lecture

*delivered in the occasion of* PANAMGEO CHILE 2024 — 17TH PAN-AMERICAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING | 2ND LATIN-AMERICAN REGIONALCONFERENCE OF IAEG

- **1943-2024: 81 years of research and practice on piles**
- **Routine approach to pile design**
- **Outcomes from Pile Prediction Events**
- **Back to single pile: shaft and base resistances**
- **From single pile to (sustainable) piled foundation**
- **Concluding remarks and implication for design**

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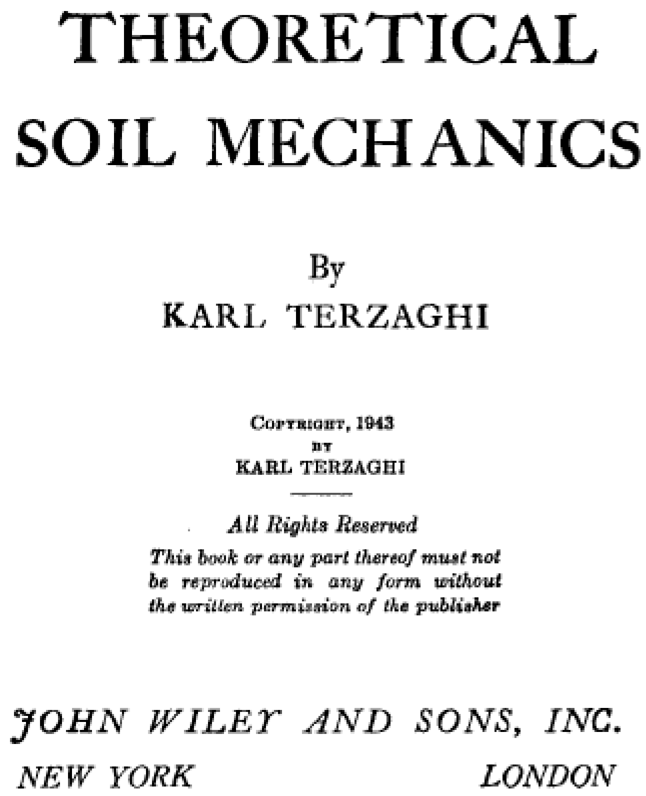
- Outcomes from Pile Prediction Events
- Back to single pile: shaft and base resistances
- From single pile to (sustainable) piled foundation (TODAY MAIN FOCUS)
- Concluding remarks and implication for design

# 1943-2025: 82 years of research and practice on piles

## WHY 1943 ??



THEORETICAL
SOIL MECHANICS

By
KARL TERZAGHI

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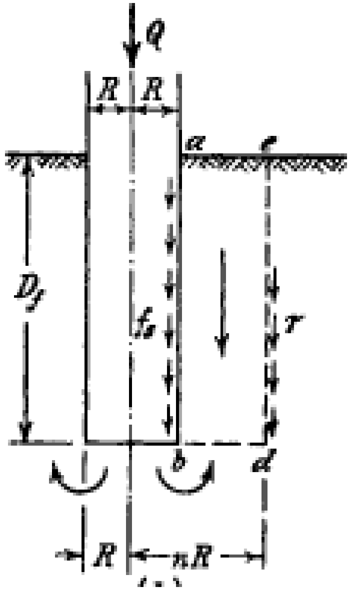
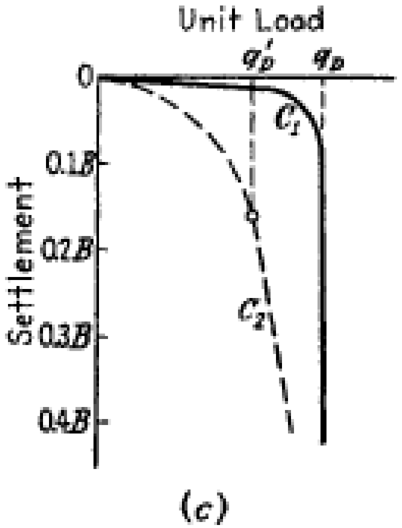
*JOHN WILEY AND SONS, INC.*
*NEW YORK* *LONDON*

**Few pages on pile problems ……**



# 1943-2025: 82 years of research and practice on piles

## SOME WORLD'S RECORDS

**(at my knowledge)**

**The largest diameter bored pile:**
**Jiashao Bridge (China); d = 3.8 m; L = 110 m**

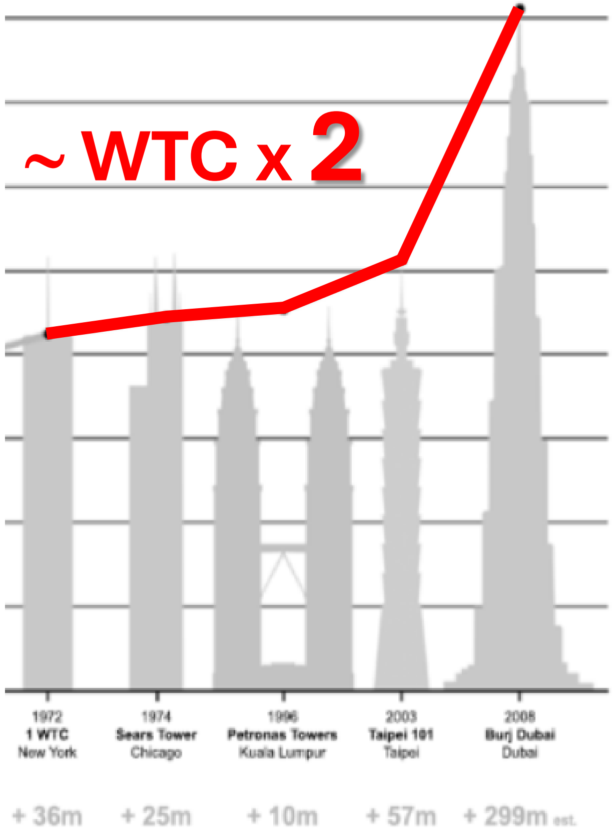
**The largest pile loading test:**
**Ohio River Bridge (USA)**
**Q = 322 MN by 4 x 860 mm O-Cell at 1 single level 1.1 m above pile base**

# 1943-2025: 82 years of research and practice on piles

## SOME WORLD'S RECORDS

(at my knowledge)

415 m




828 m

**The tallest building (H = 828 m):**
**Burj Khalifa (DUBAI)**

**Foundation:**
**3.7 m thick raft supported by**
- **Tower – 194 bored piles d = 1.5 m; L = 47.45 m**
- **Podium – 750 bored piles d = 0.9 m; L = 30 m**

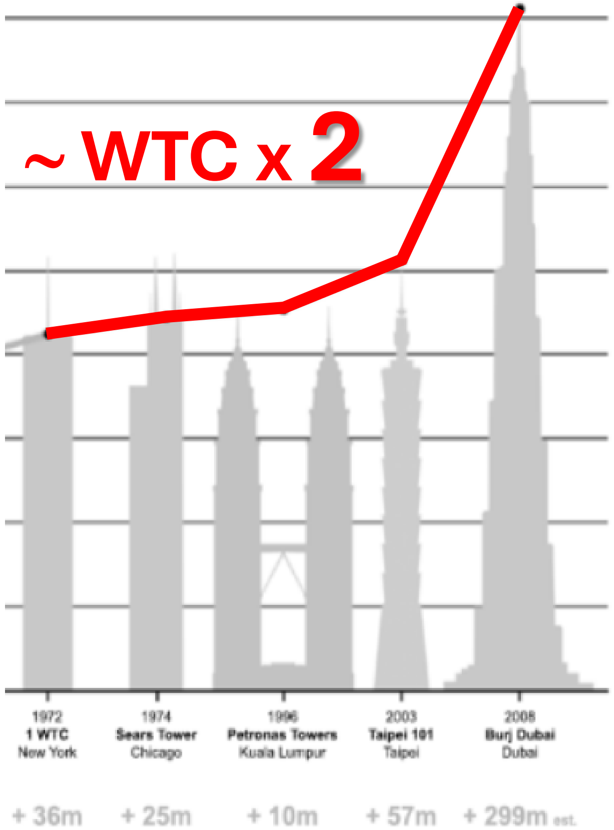
# 1943-2025: 82 years of research and practice on piles

## SOME WORLD'S RECORDS

(at my knowledge)

415 m

~ WTC x 2




828 m

1008 m

~ WTC x 2.5

**Kingdom Tower**
(Jeddah, SA)

Foundation:
5 m thick raft supported by 270 bored piles d = 1.8 m
(72 up to depth 105 m)

# 1943-2025: 82 years of research and practice on piles

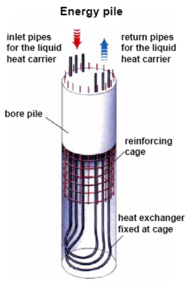
## MULTI-PURPOSE PILES

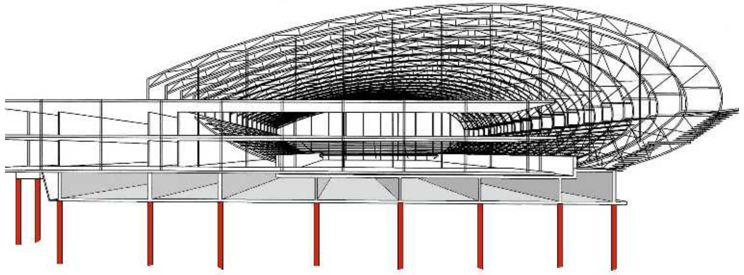
**Conference Hall – Wien (Austria)**
Annual saving of 85,000 $m^3$ of natural gas which is equivalent to an environmental relief of 73 tons $CO_2$.

## ENERGY PILES

### (heat exchange with surrounding soils)

***Energy foundations and other thermo-active ground structures.***
**Brandl, H. (2006). GÉOTECHNIQUE 56, No. 2, 81–122 (41st Rankine Lecture)**



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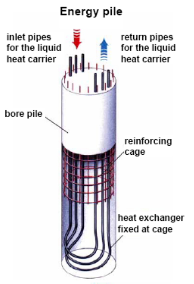


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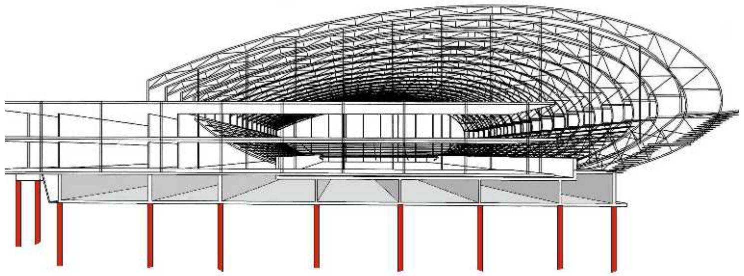
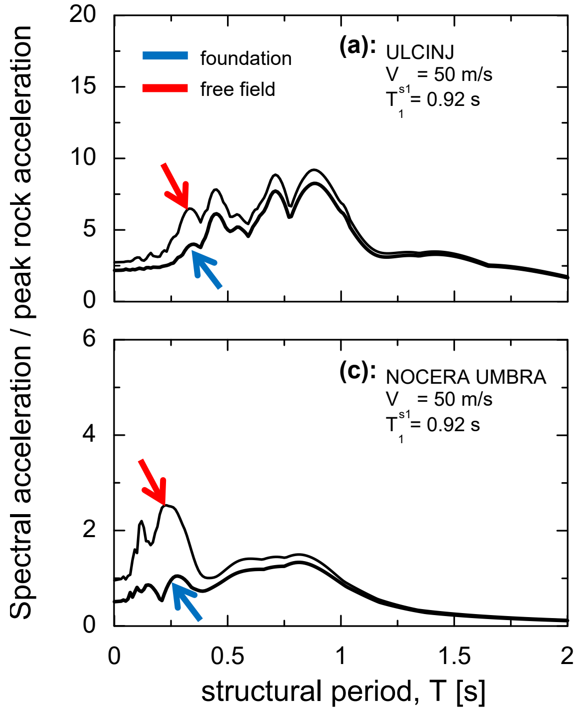


## SEISMIC DEMAND REDUCERS PILES

(Beneficial effect – at least, not detrimental)

***Effects of the filtering action exerted by piles on the seismic response of RC frame buildings.***
**de Sanctis, L.; Di Laora R.; Caterino, N.; Maddaloni, G.; Aversa, S.; Mandolini, A.; Occhiuzzi, A. (2015)**
**BULLETIN OF EARTHQUAKE ENGINEERING 13, No. 11, 3259-3275**

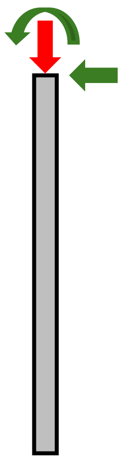


# ROUTINE DESIGN APPROACH

**For given pile material and subsoil conditions, according to local Code:**

- **Minimum cross-sectional area (diameter $d_{min}$ and steel reinforcement) is typically derived from the expected maximum shear force and bending moment on one of the pile belonging to a group**

- **Minimum pile length $L_{min}$ is typically derived from the maximum axial loading condition on one of the pile belonging to a group**



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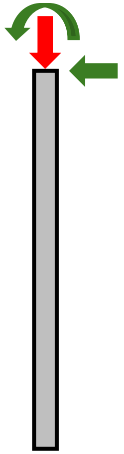

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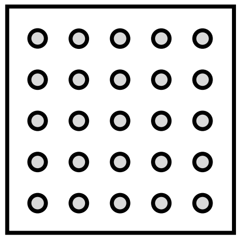
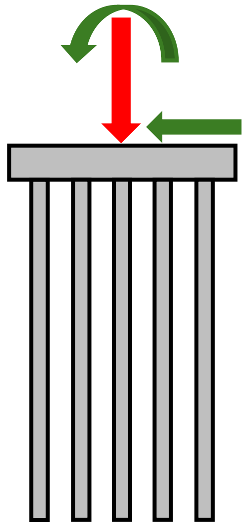
**BUT PILES ARE NOT ISOLATED, THEY BELONG TO A GROUP AND CONNECTED AT PILE HEAD BY SOME STRUCTURAL ELEMENT (CAP, RAFT, ...)**



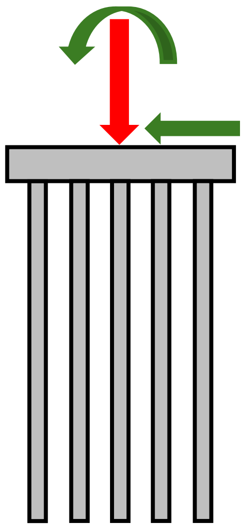


# ROUTINE DESIGN APPROACH

**Looking at vertical load (often conditioning the design):**

- **Cap/raft/... rather <u>flexible</u> → not able to redistribute the load among piles → '<u>local</u>' loading conditions prevail and ULSs are related to <u>single pile collapse</u>**

- **Cap/raft/... rather <u>stiff</u> → able to redistribute the load among piles → '<u>overall</u>' loading conditions prevail and ULSs are related to <u>pile group collapse</u>**



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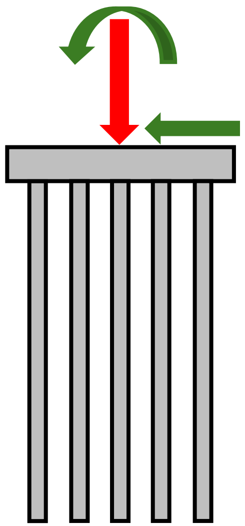
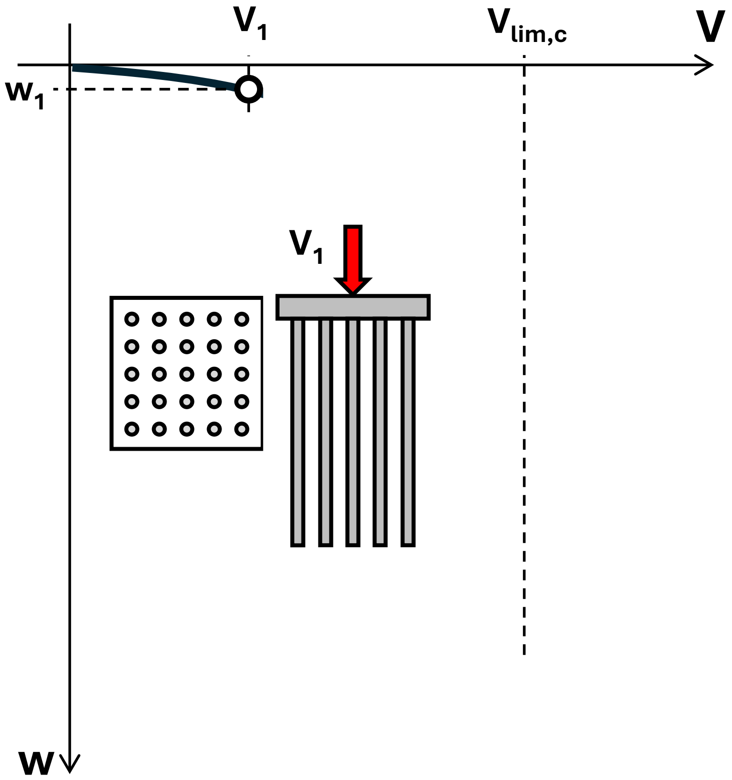
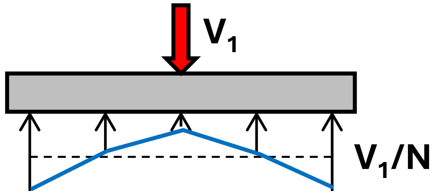


# INTERACTION DOMAIN FOR PILE GROUPS

$$V_{lim,c} = N \cdot V_s$$




(Elastic) interaction among piles yields to more load to peripheral piles

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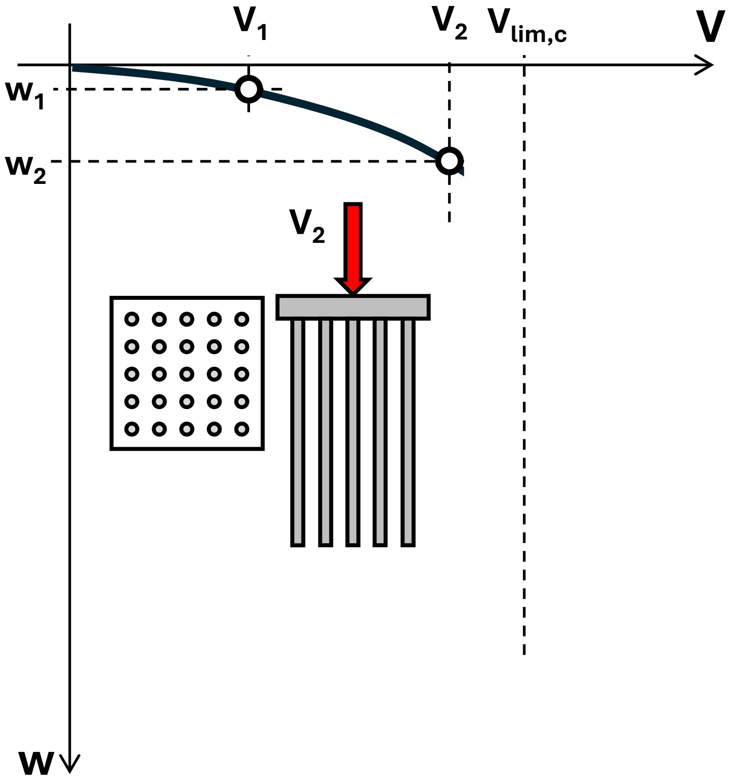


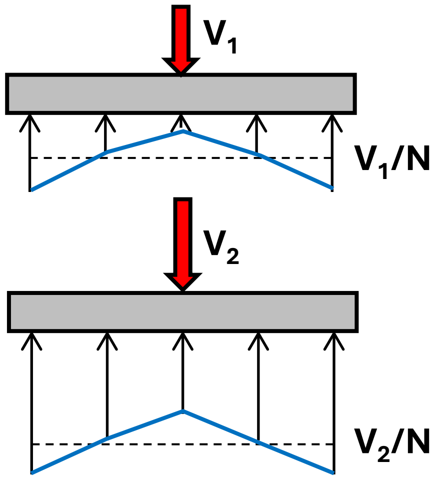


(Elastic) interaction among piles yields to more load to peripheral piles

Due to nonlinearity, additional load are taken more by the central piles (stiffer) and less by the peripheral piles (softer) → loads on piles tend to be more uniform

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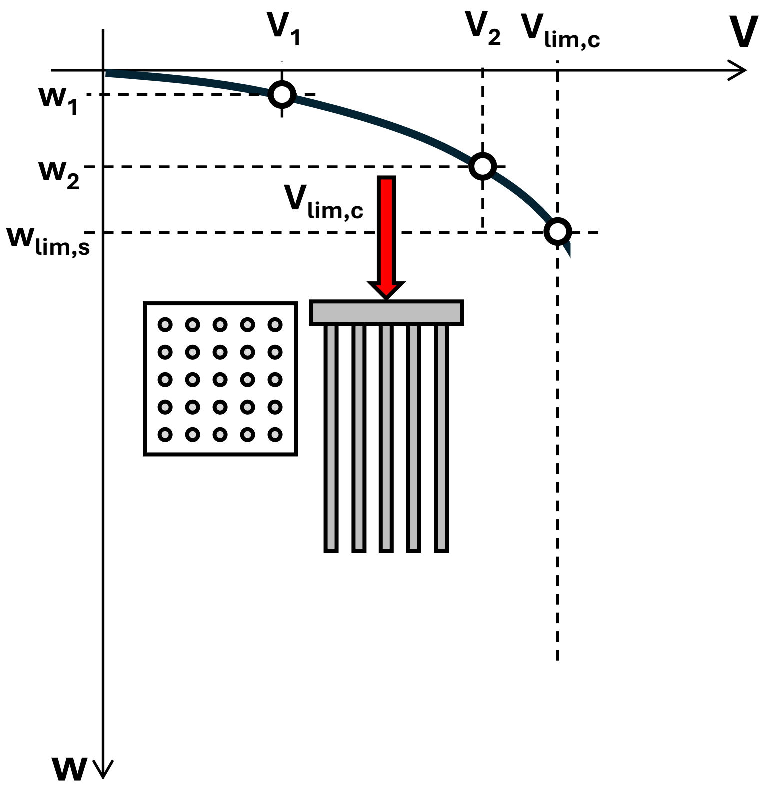


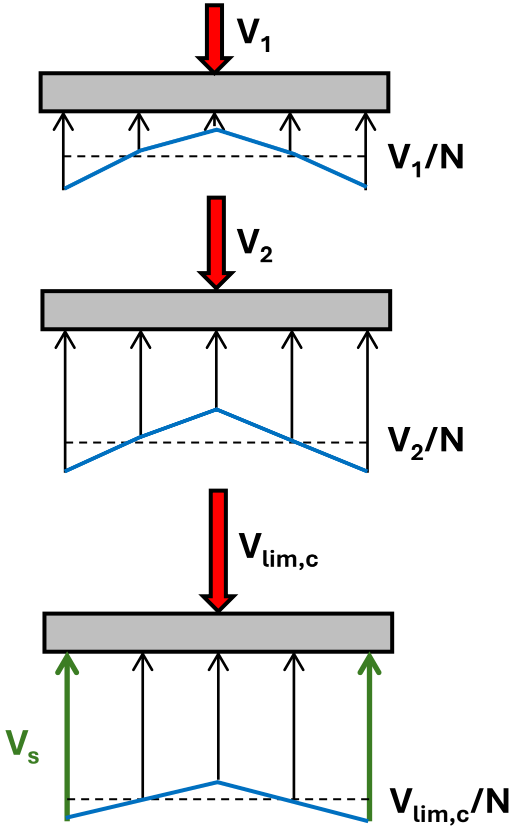


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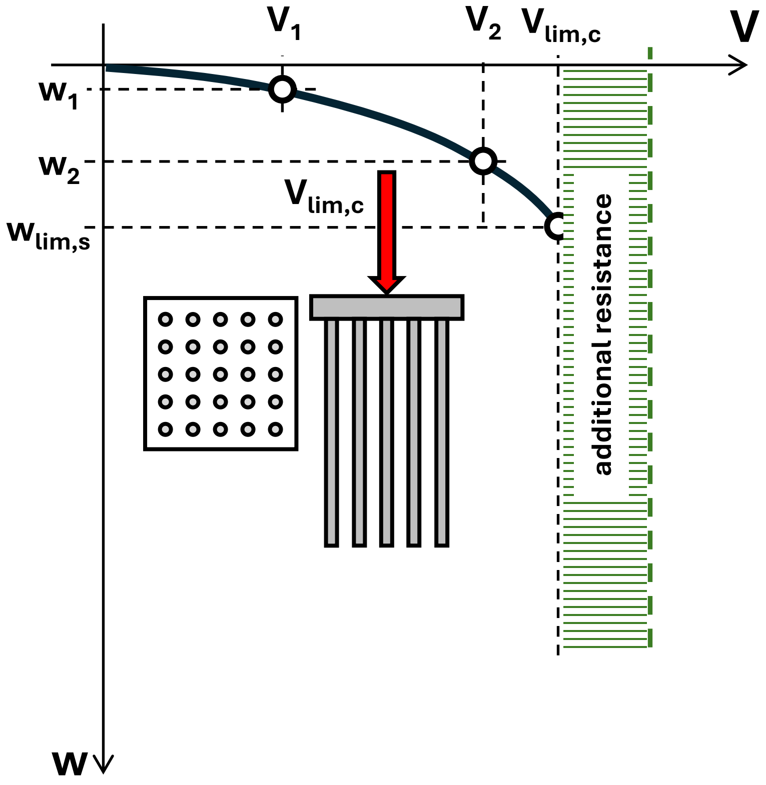


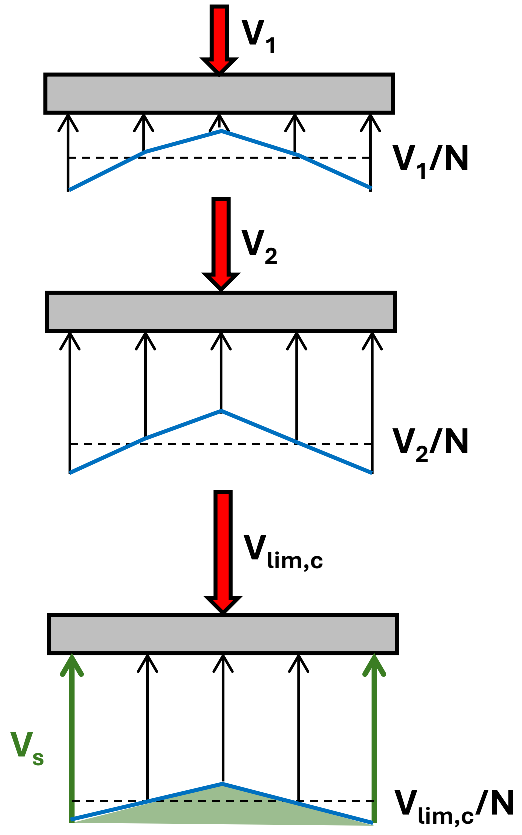


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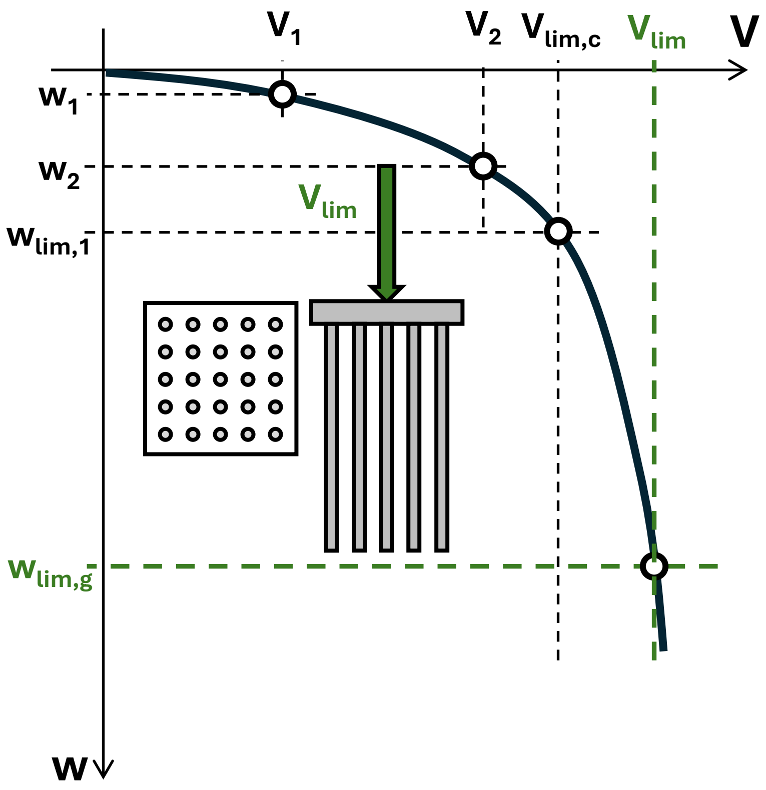


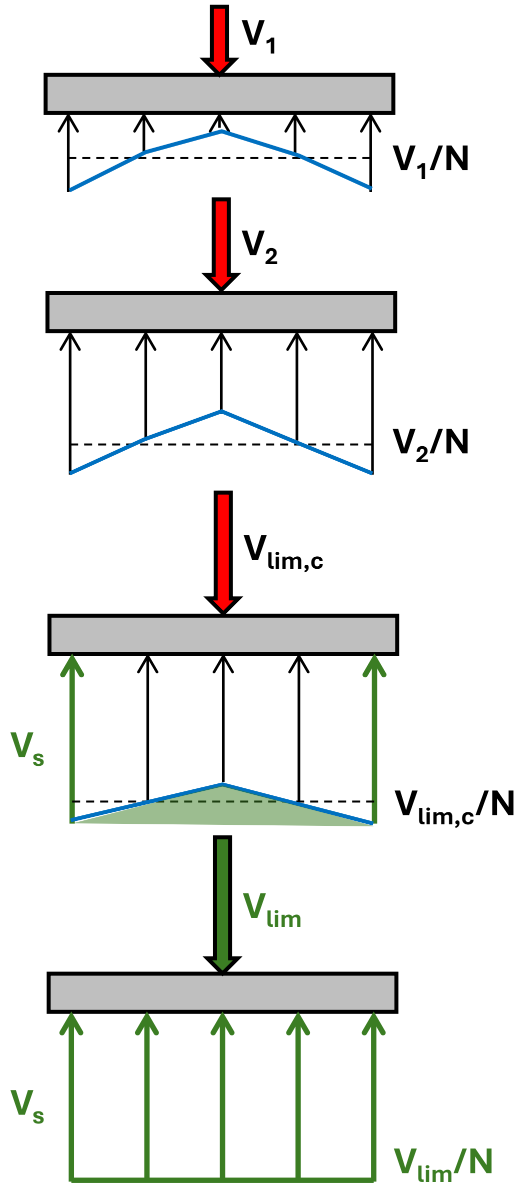


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**COLLAPSE !!!**

# ROUTINE DESIGN APPROACH

**Looking at vertical load (often conditioning the design):**

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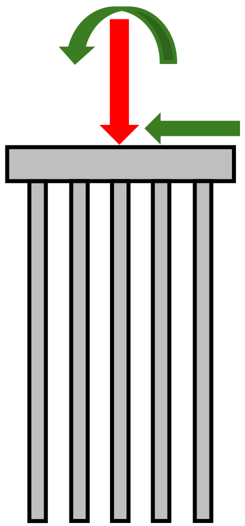


**2004 – Eurocode 7 – Part 1: Geotechnical design**

If the piles support a <u>stiff</u> structure, advantage may be taken of the ability of the structure to redistribute load between the piles. A limit state will occur only if a significant number of piles fail together; therefore, <u>a failure mode involving only one pile need not be considered</u>.

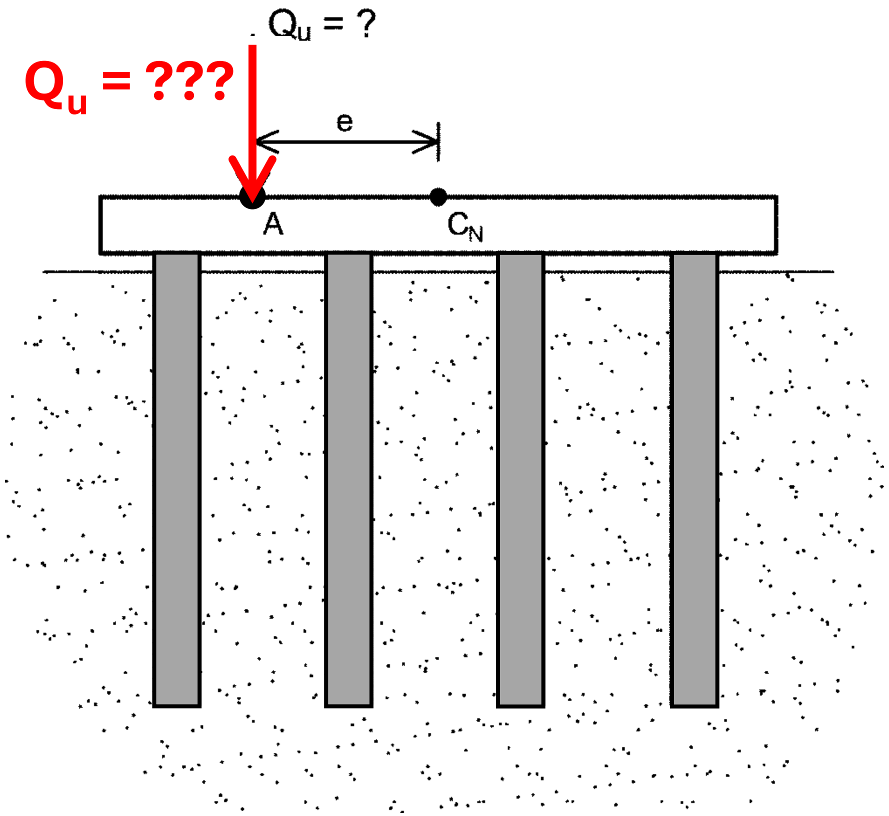
**2024 – Eurocode 7 – Part 3: Geotechnical structures**

The verification of geotechnical ultimate and serviceability limit states <u>for individual piles may be omitted provided is verified that the</u> **pile cap is able to redistribute loads** without itself exceeding an ultimate or serviceability limit state.

# BASIC CONCEPT FOR CB INTERACTION DOMAIN APPROACH (N-M)

**PROBLEM:**

**Which is the ultimate load of a pile group subjected to a vertical eccentric load?**




**Traditional approach:** **consider the achievement of the axial capacity on the outermost pile as the ultimate limit state of the pile group**

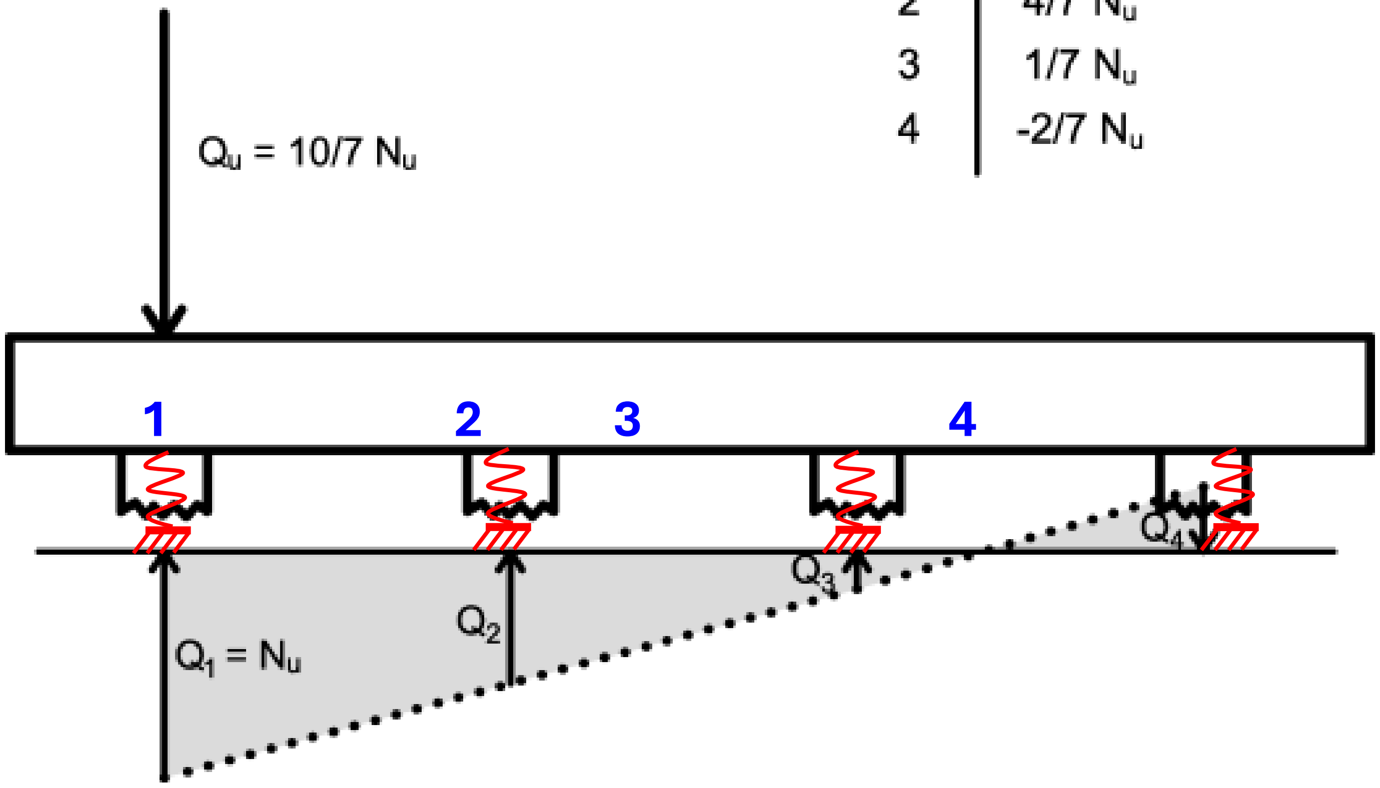
***Recommended for example by AASHTO Bridge Design Specifications (AASHTO, 2012)***

# BASIC CONCEPT FOR CB INTERACTION DOMAIN APPROACH (N-M)

## TRADITIONAL APPROACH:

**distribution of loads on piles (neglecting pile-to-pile interaction) when pile n. 1 reaches failure**

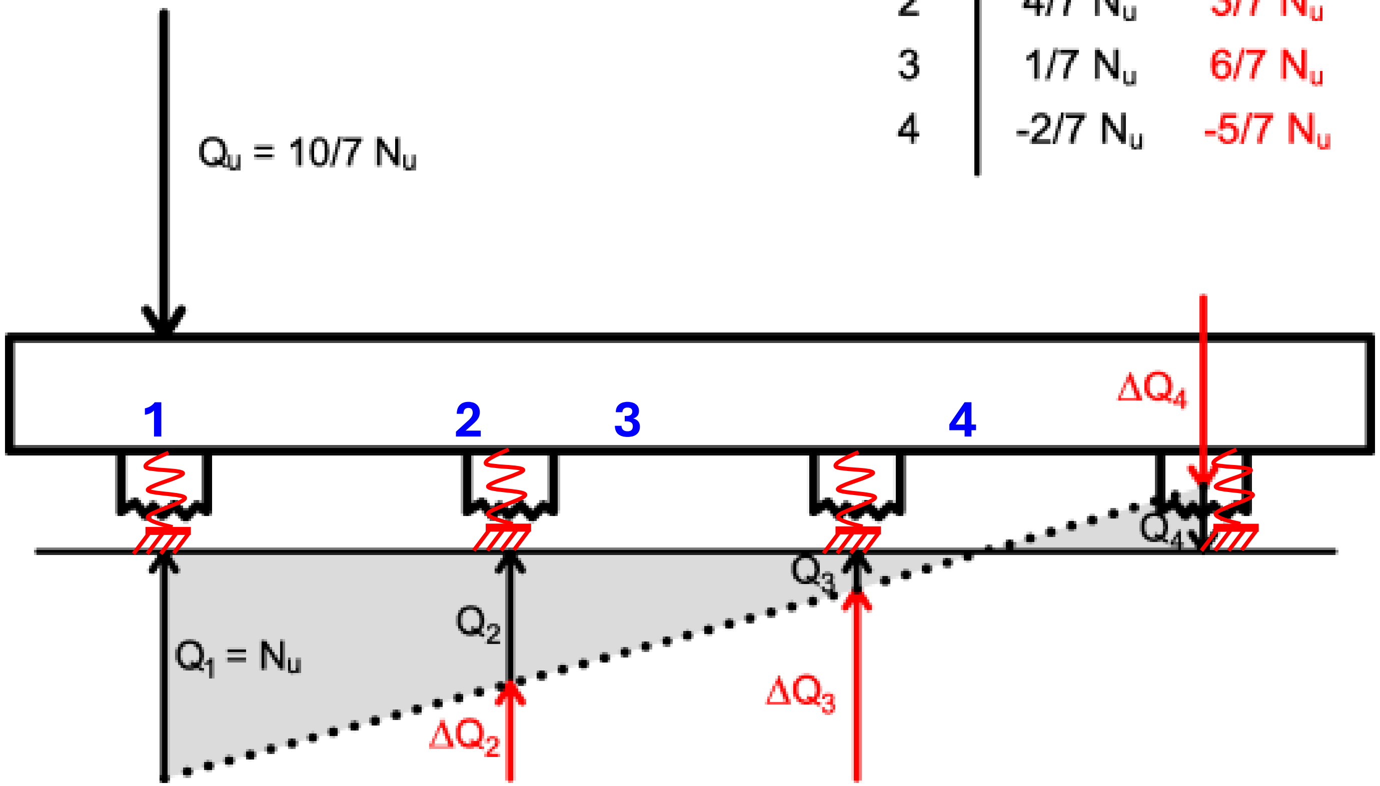
| pile n. | $Q_i$ |
|---|---|
| 1 | $N_u$ |
| 2 | $4/7\ N_u$ |
| 3 | $1/7\ N_u$ |
| 4 | $-2/7\ N_u$ |



# BASIC CONCEPT FOR CB INTERACTION DOMAIN APPROACH (N-M)

**However, some piles can still carry a further amount of axial load before reaching failure**

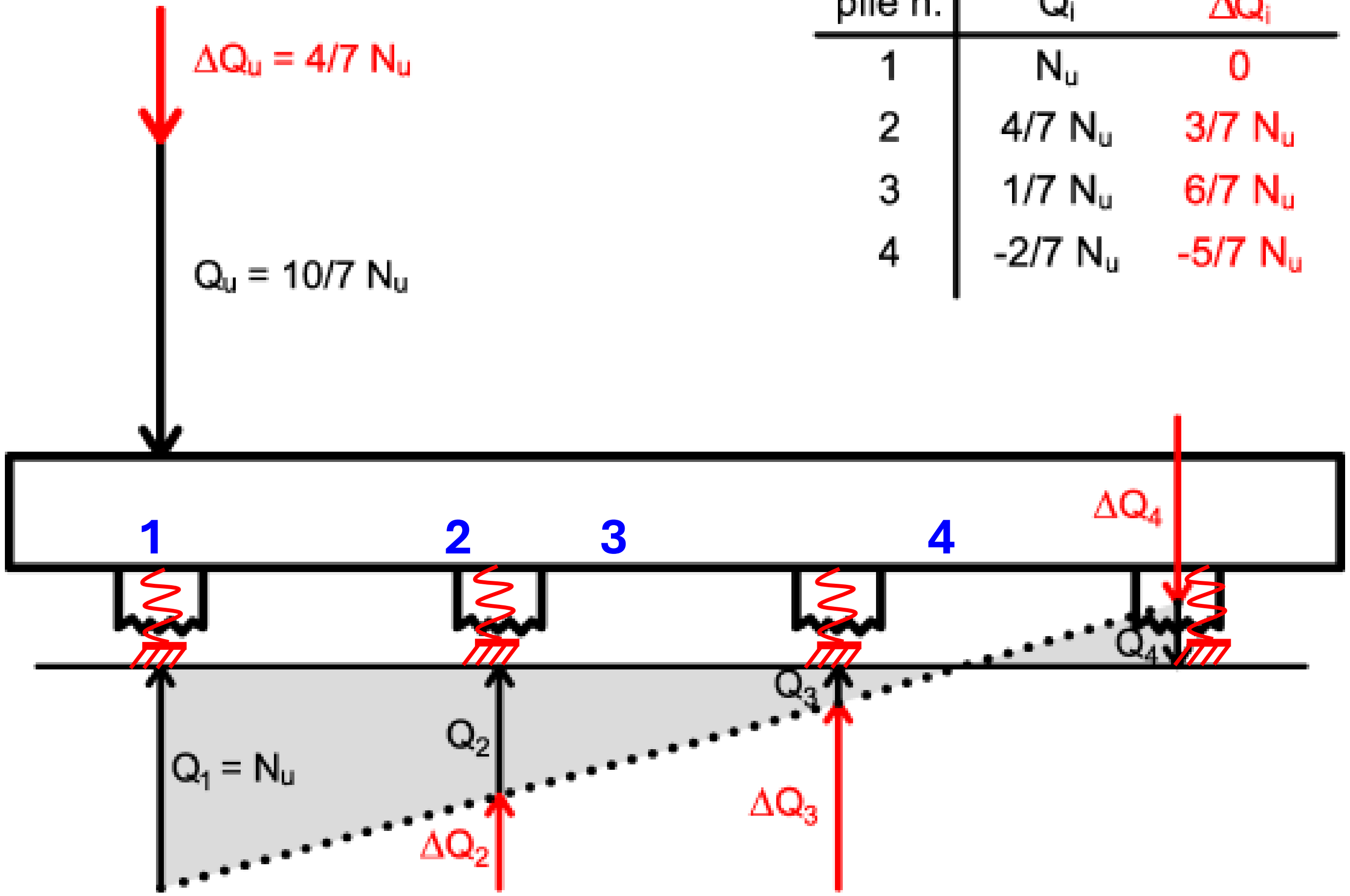
| pile n. | $Q_i$ | $\Delta Q_i$ |
|---|---|---|
| 1 | $N_u$ | 0 |
| 2 | $4/7\ N_u$ | $3/7\ N_u$ |
| 3 | $1/7\ N_u$ | $6/7\ N_u$ |
| 4 | $-2/7\ N_u$ | $-5/7\ N_u$ |



# BASIC CONCEPT FOR CB INTERACTION DOMAIN APPROACH (N-M)

## When all piles reach failure, the external axial load increases of 40%!!!!

| pile n. | $Q_i$ | $\Delta Q_i$ |
|---|---|---|
| 1 | $N_u$ | 0 |
| 2 | 4/7 $N_u$ | 3/7 $N_u$ |
| 3 | 1/7 $N_u$ | 6/7 $N_u$ |
| 4 | -2/7 $N_u$ | -5/7 $N_u$ |

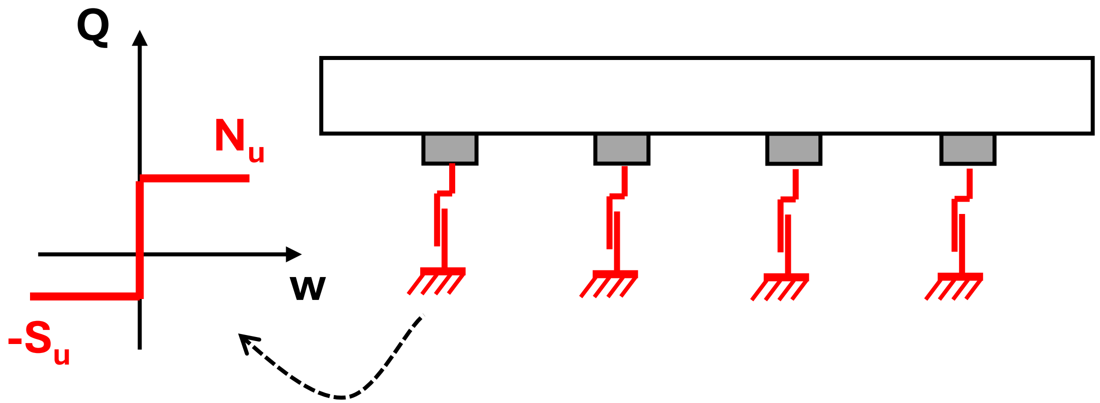


# BASIC CONCEPT FOR CB INTERACTION DOMAIN APPROACH (N-M)

## ALTERNATIVE APPROACH (Di Laora et al, 2019)

**HYPOTHESES:**

- **Rigid cap connecting piles' heads**
- **Piles behaving as rigid-plastic elements**



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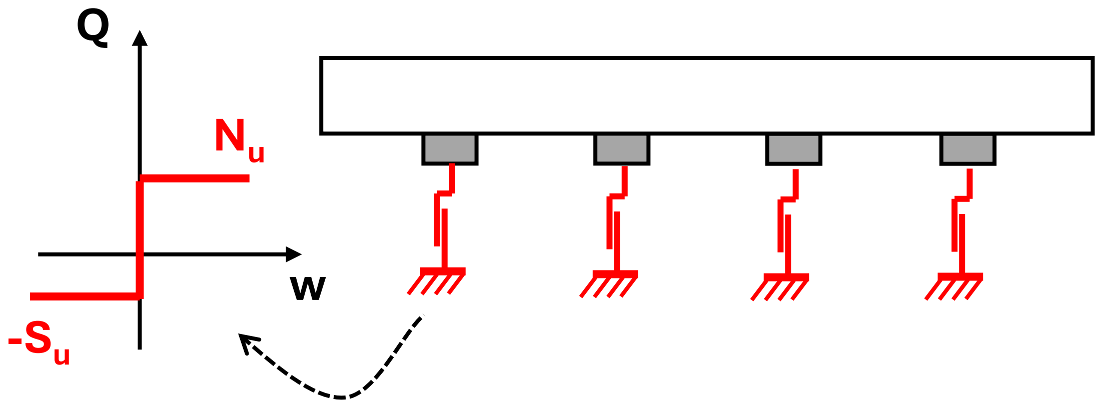


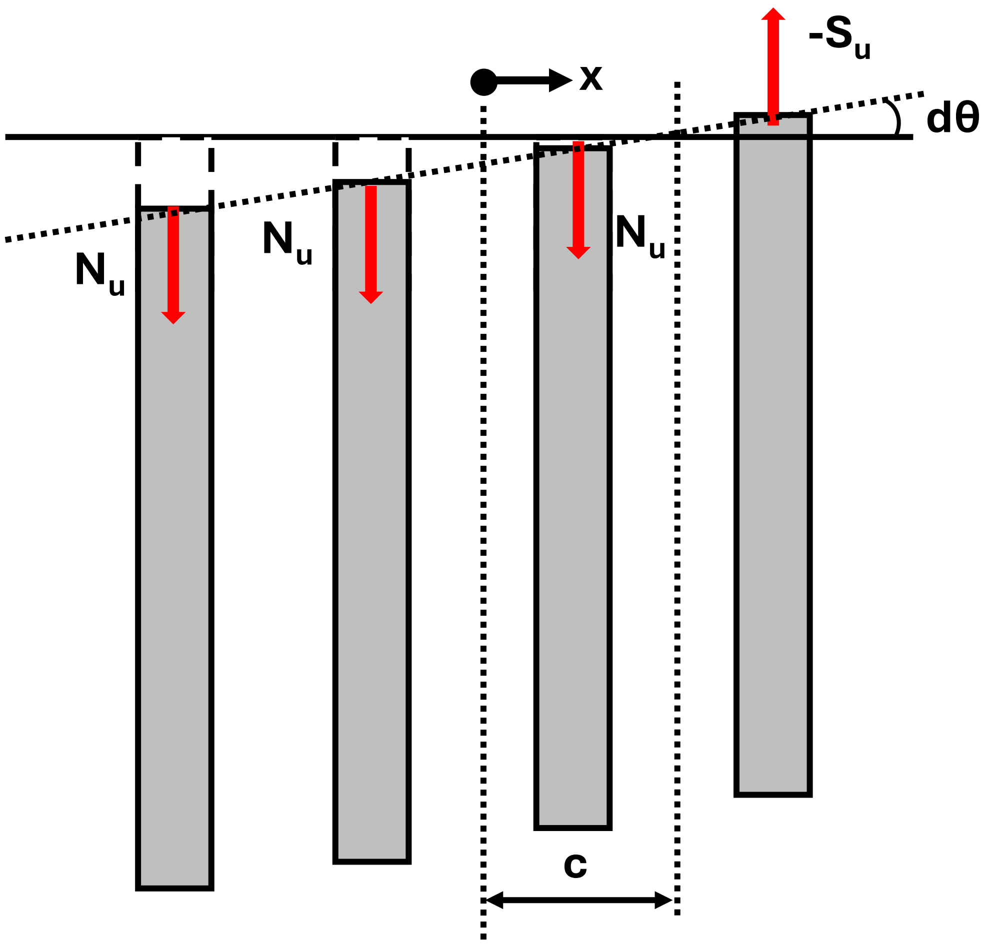

**CONSEQUENCES:**

- If the displacement of a pile is not zero, then this pile is subjected to his failure load, in compression or in uplift
- If a pile does not displace, then is subjected to a load ranging between its tensile and its compressive failure load

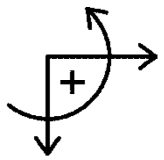
# BASIC CONCEPT FOR CB INTERACTION DOMAIN APPROACH (N-M)

## MECHANISM (a)

**Rotation around a point in between two piles**

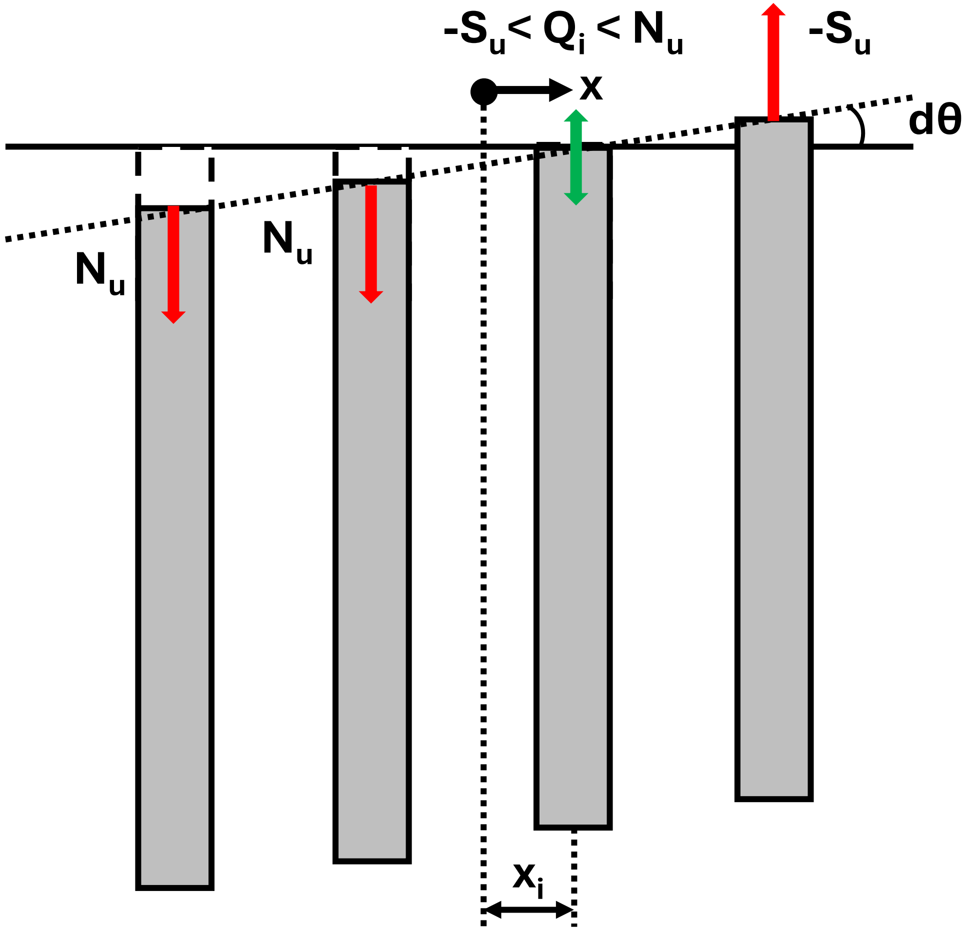



**All piles fail**




## MECHANISM (b)

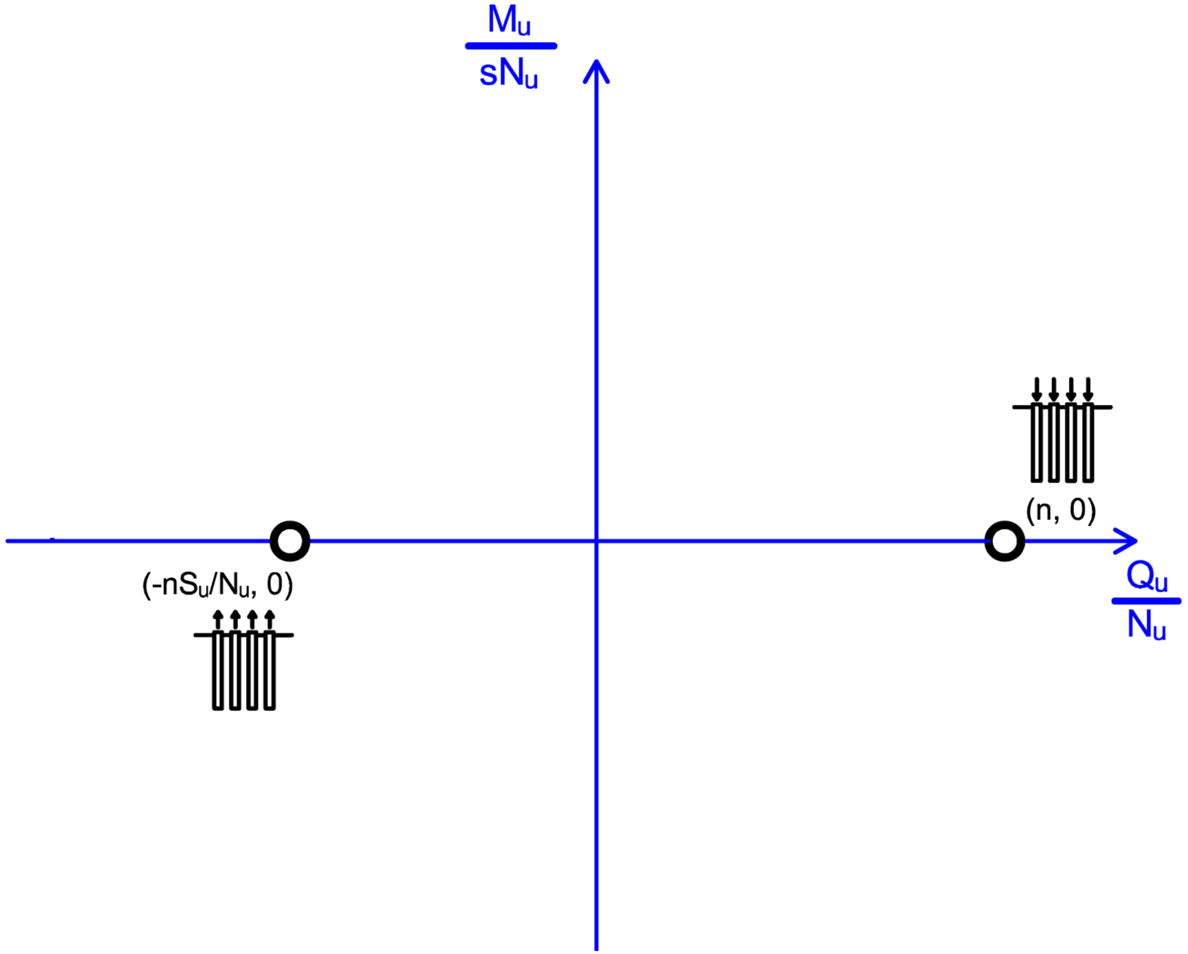
**Rotation around the head of a pile**




**All piles fail, except one**

# BASIC CONCEPT FOR CB INTERACTION DOMAIN APPROACH (N-M)

**Construction of $M_u$ - $Q_u$ interaction diagram for a row of identical, equally-spaced piles**



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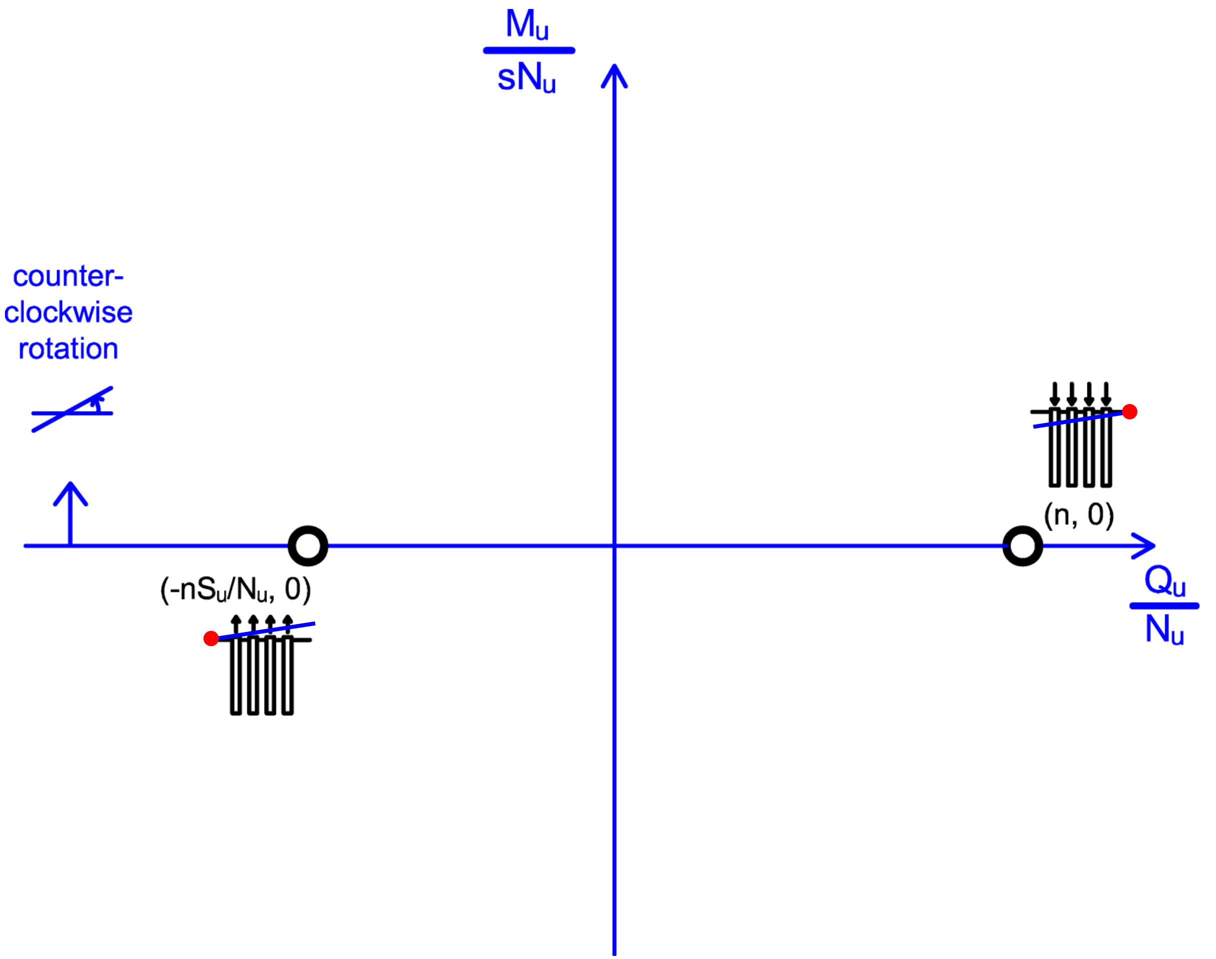

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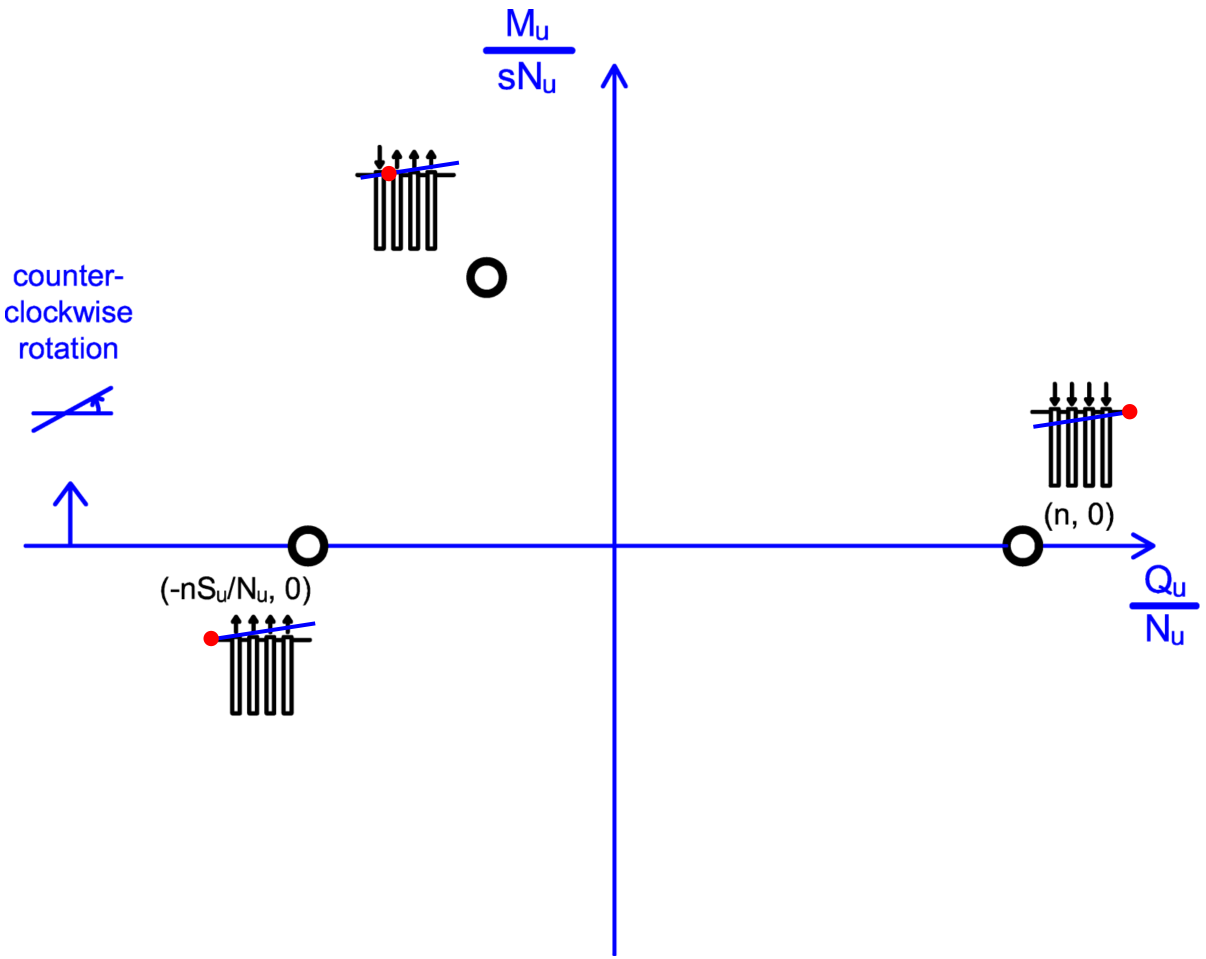

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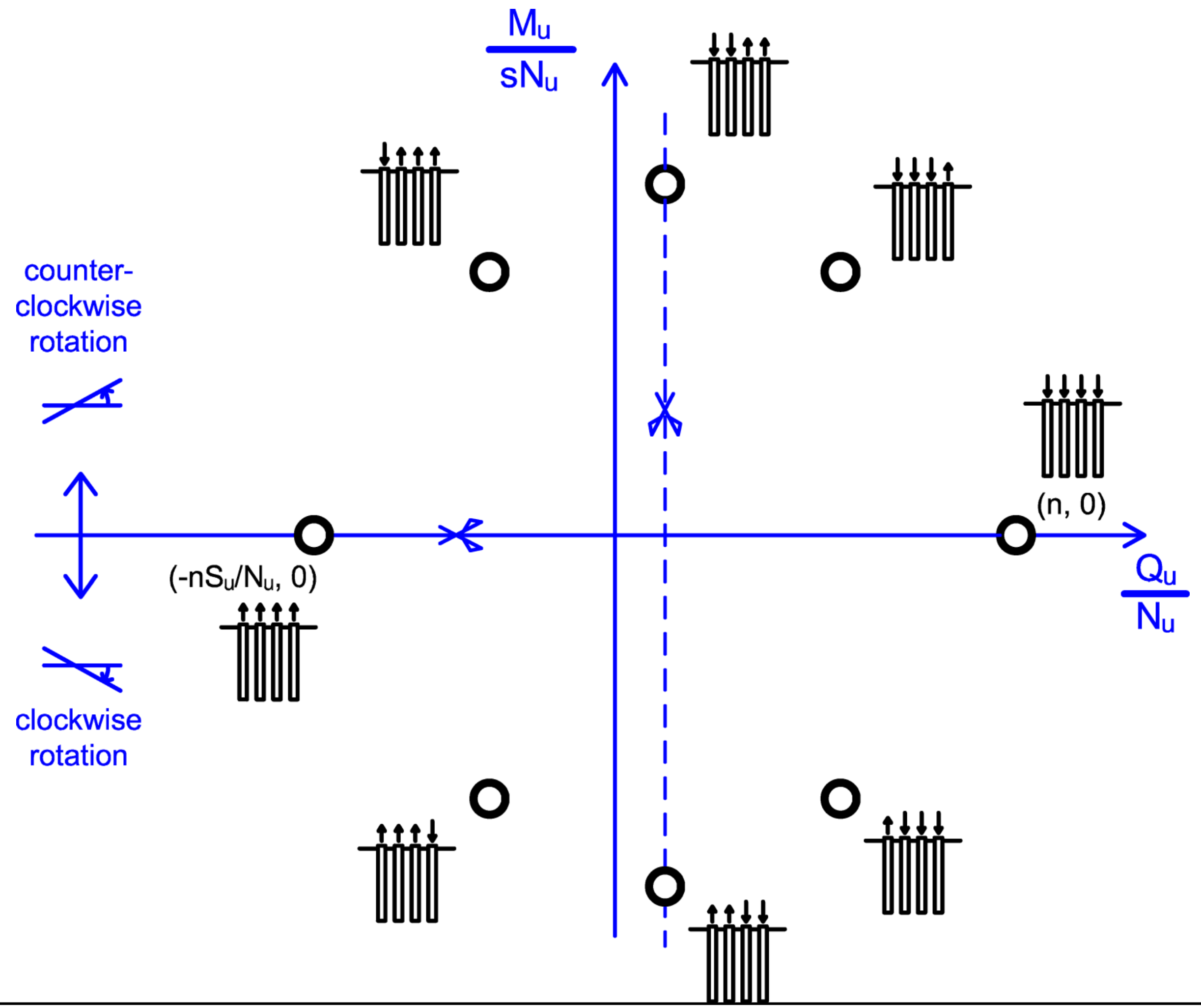

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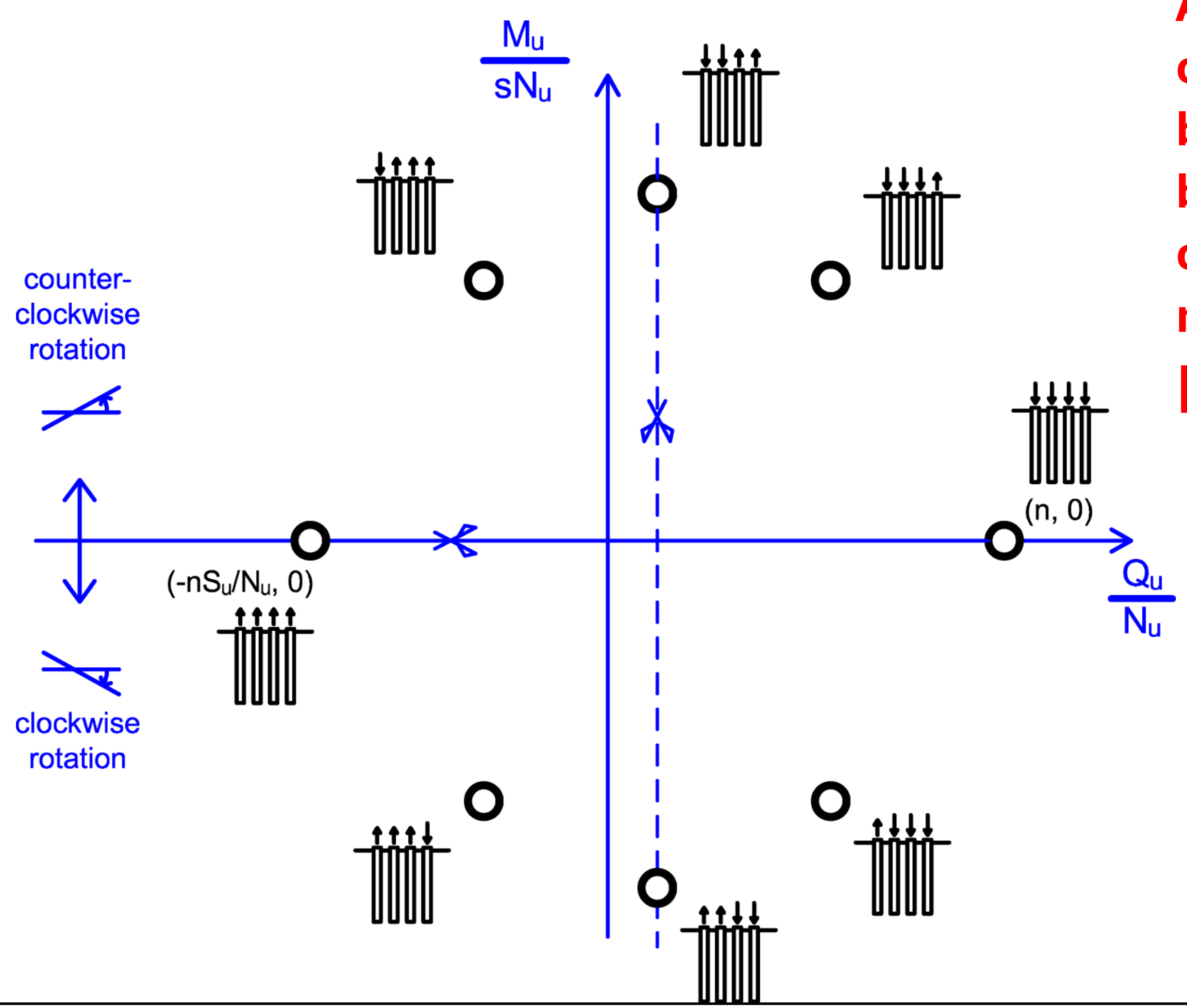


**All points represent configurations respeting both the lower- and upper-bound theorems of plastic collapse, and thereby they represent**

**EXACT SOLUTIONS!**

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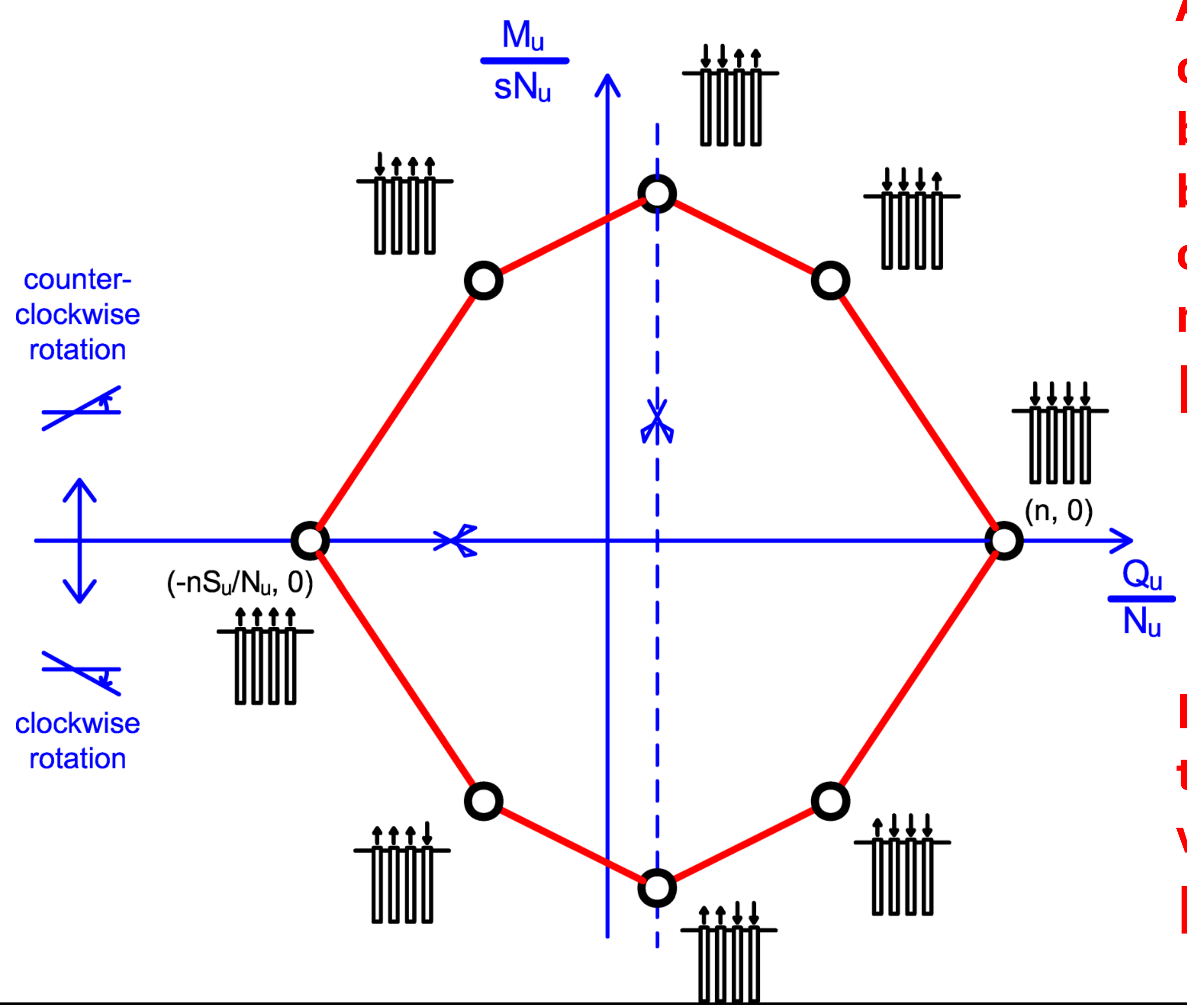



**All points represent configurations respeting both the lower- and upper-bound theorems of plastic collapse, and thereby they represent**

**EXACT SOLUTIONS!**

**It could be demonstrated that straight lines connecting vertices also represent**

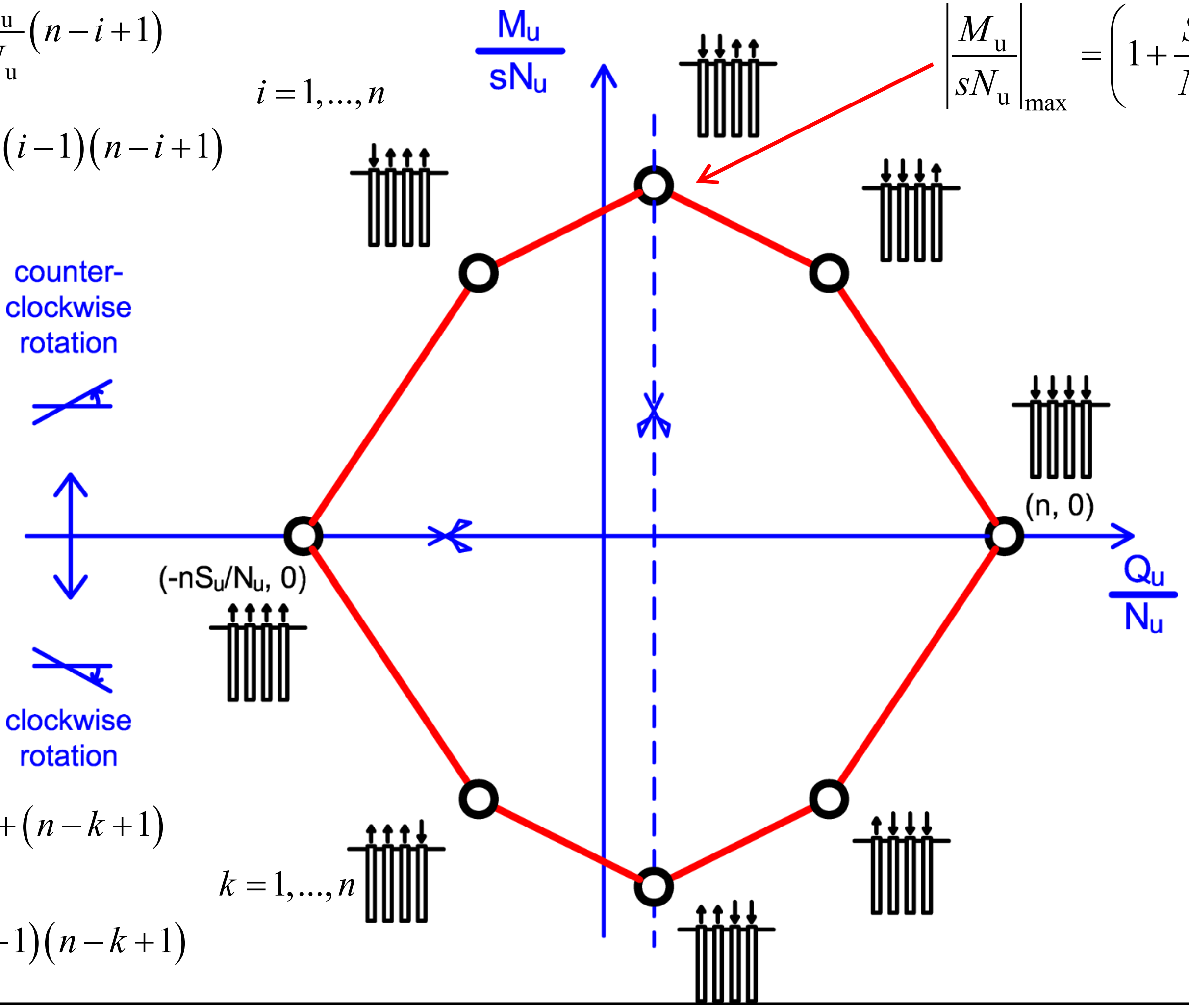
**EXACT SOLUTIONS!**

# BASIC CONCEPT FOR CB INTERACTION DOMAIN APPROACH (N-M)

## Construction of $M_u$ - $Q_u$ interaction diagram for a row of identical, equally-spaced piles

$$\begin{cases} \dfrac{Q_{ui}}{N_u} = i - 1 - \dfrac{S_u}{N_u}(n - i + 1) \\ \dfrac{M_{ui}}{sN_u} = \dfrac{1}{2}\left(1 + \dfrac{S_u}{N_u}\right)(i-1)(n-i+1) \end{cases} \quad i = 1, \ldots, n$$

$$\left|\frac{M_u}{sN_u}\right|_{max} = \left(1 + \frac{S_u}{N_u}\right)\frac{n^2 - \delta}{8}$$

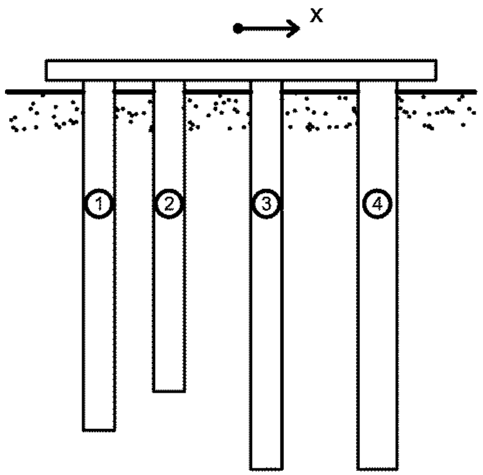



$$\begin{cases} \dfrac{Q_{u(k+n)}}{N_u} = -\dfrac{S_u}{N_u}(k-1) + (n - k + 1) \\ \dfrac{M_{ui}}{sN_u} = -\dfrac{1}{2}\left(1 + \dfrac{S_u}{N_u}\right)(k-1)(n-k+1) \end{cases} \quad k = 1, \ldots, n$$

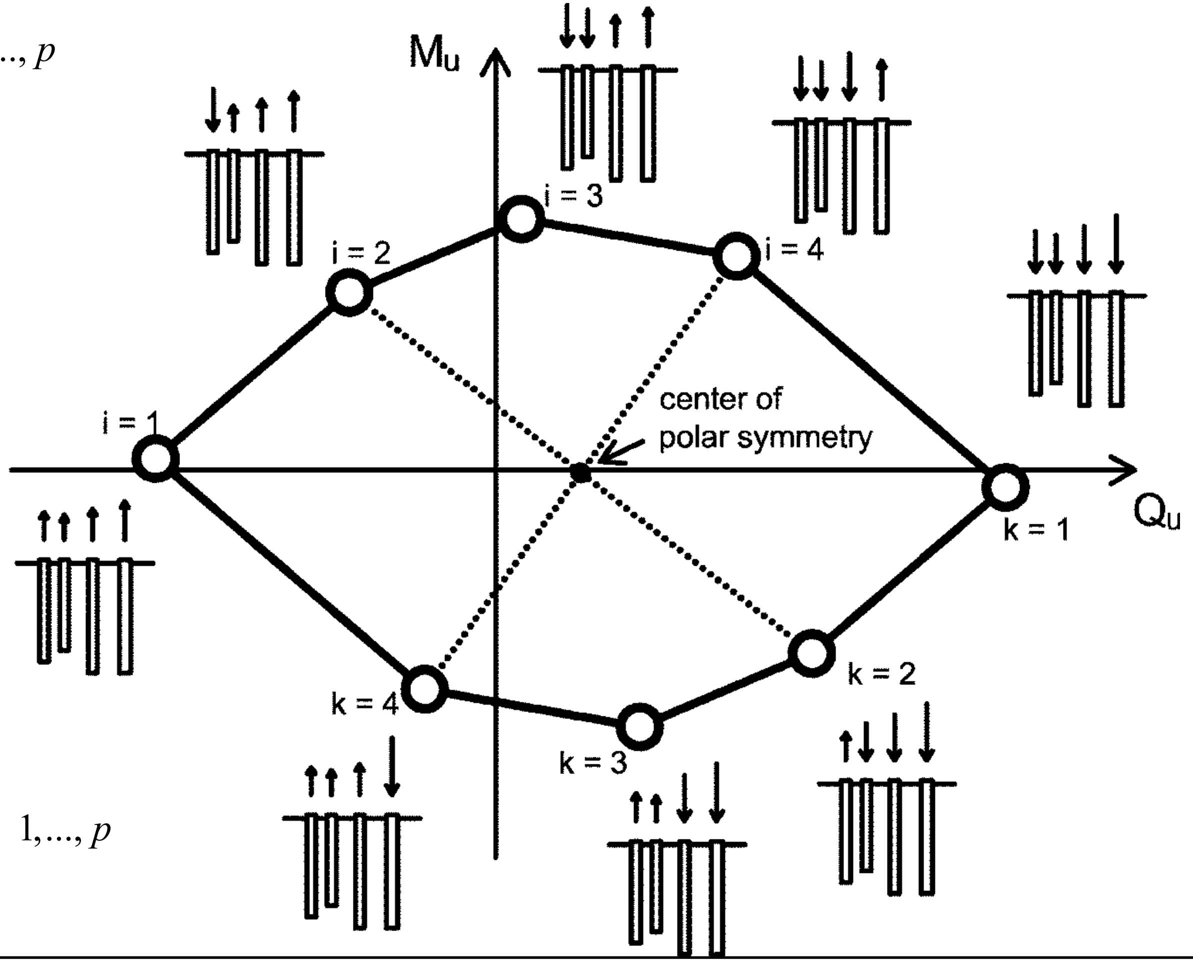
# EXTENSION TO CONSIDER DISSIMILAR PILES

**$M_u$ - $Q_u$ interaction diagram for a group of different, unevenly distributed piles**

$$\begin{cases} Q_{ui} = \sum_{j=1}^{i-1} N_{uj} - \sum_{j=i}^{p} S_{uj} \\ M_{ui} = -\sum_{j=1}^{i-1} N_{uj}\xi_j + \sum_{j=i}^{p} S_{uj}\xi_j \end{cases} \qquad i = 1,\dots,p$$




$$\begin{cases} Q_{u(k+p)} = \sum_{j=k}^{p} N_{uj} - \sum_{j=1}^{k-1} S_{uj} \\ M_{u(k+p)} = \sum_{j=1}^{k-1} S_{uj}\xi_j - \sum_{j=k}^{p} N_{uj}\xi_j \end{cases} \qquad k = 1,\dots,p$$



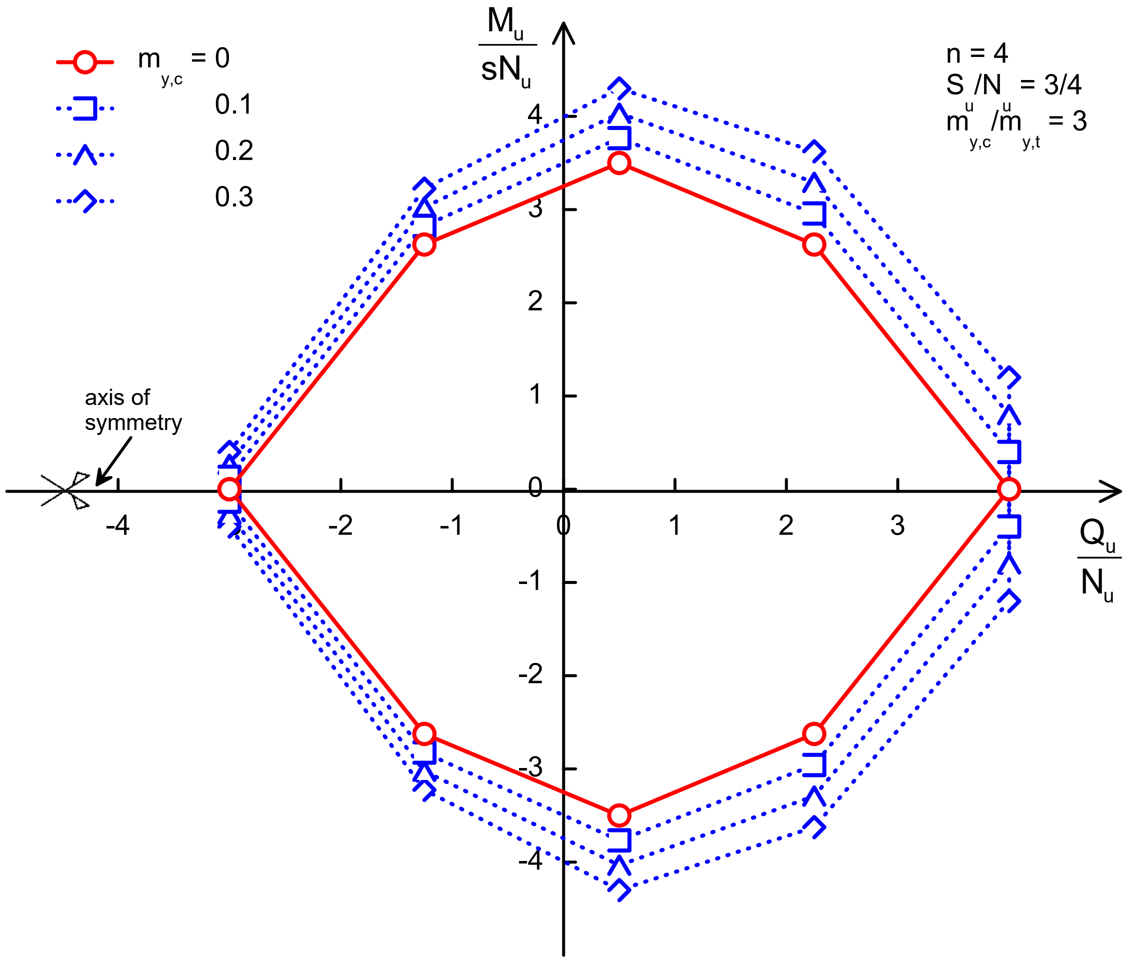

**Exact solution if moment vector is parallel to an axis of (mechanical) simmetry of the pile group**

**Otherwise, this simplified procedure of change in the coordinate system leads to an upper bound solution**

## Consideration of pile sectional yielding moments

$$m_{yt} = \frac{M_{yt}}{sN_u}$$

$$m_{yc} = \frac{M_{yc}}{sN_u}$$

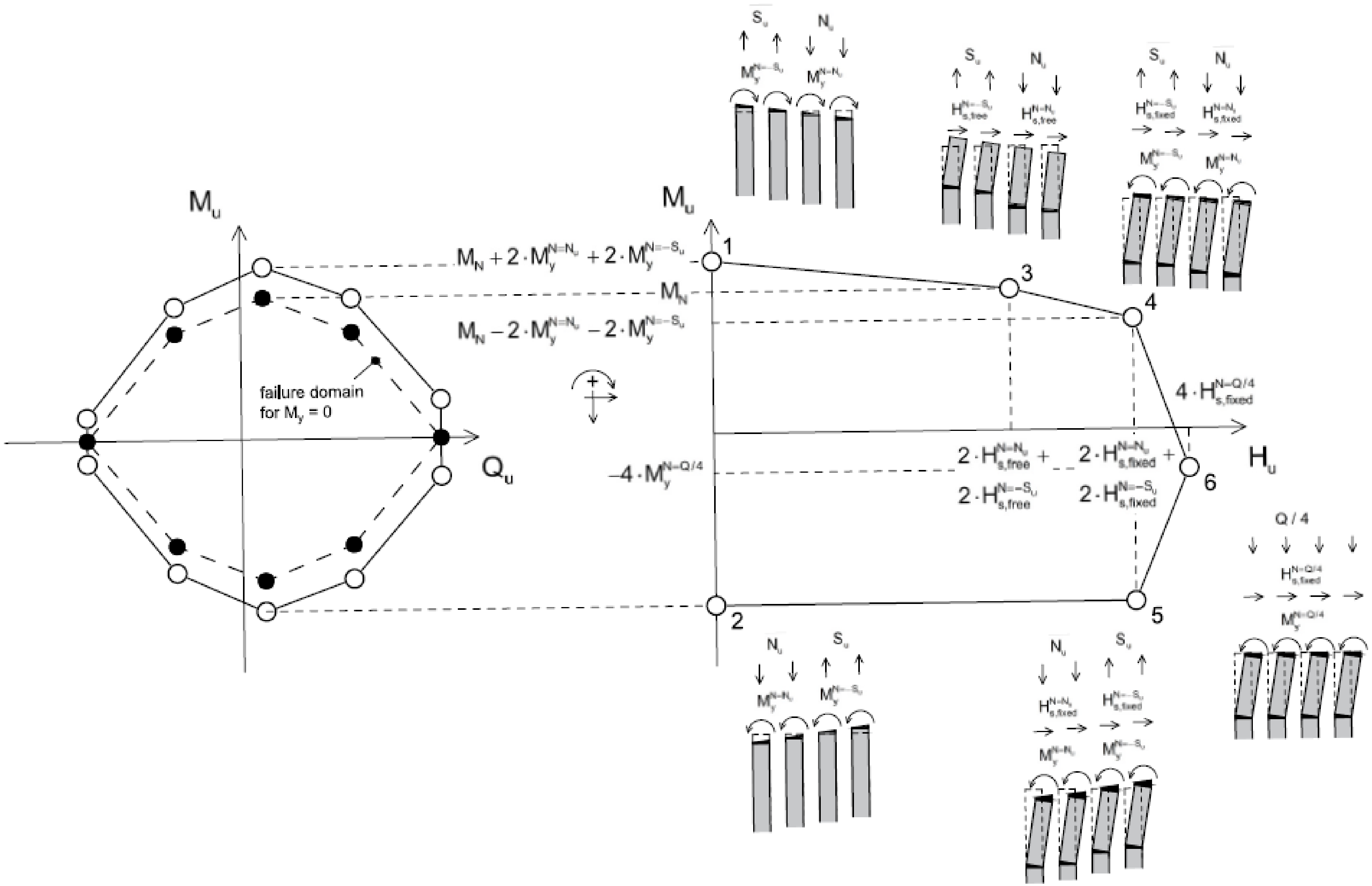



**Points are exact.**

**Lines are conservative approximations.**

**The symmetry of the interaction diagram is LOST!!!**

# EXTENSION TO CONSIDER HORIZONTAL ACTIONS (N-M-H)

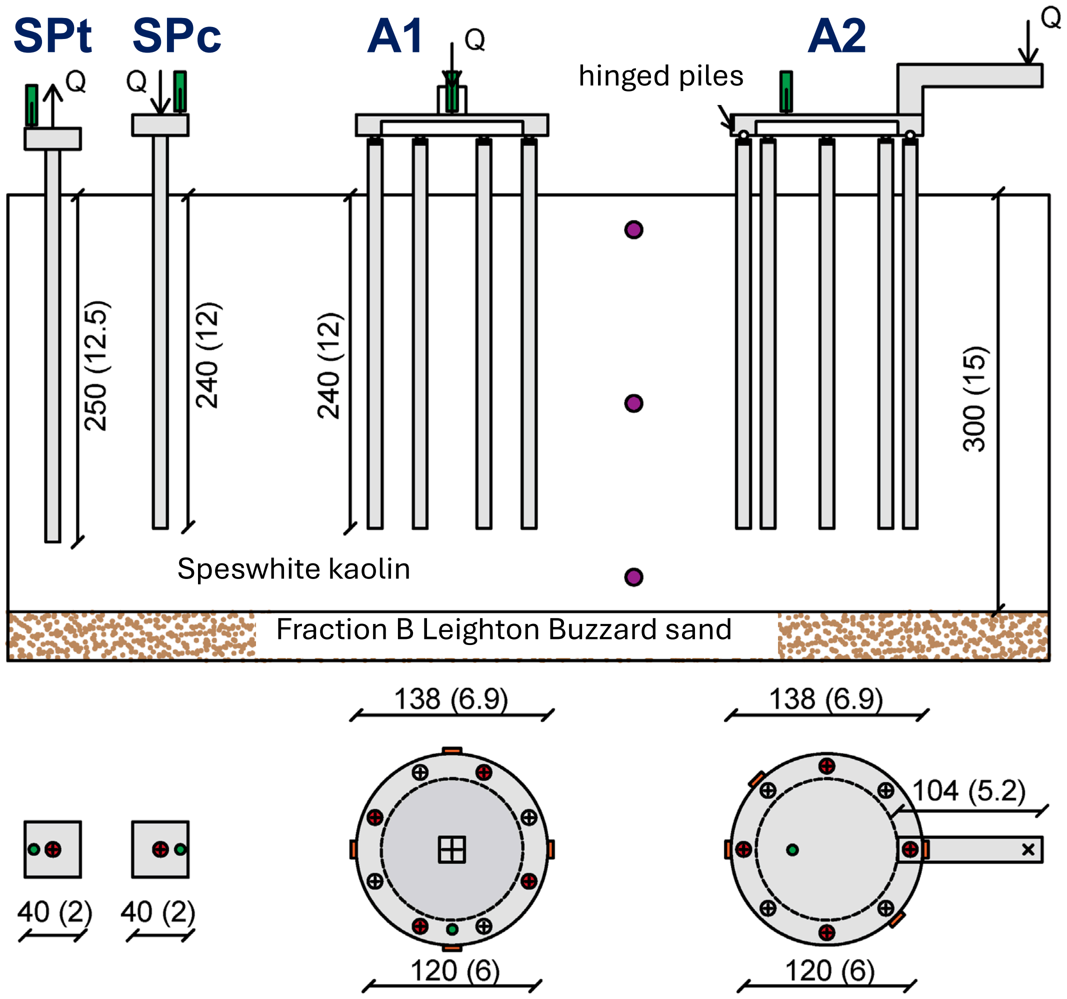


# SCIENTIFIC PAPERS ON INTERNATIONAL JOURNALS

1) **Di Laora, R.,** de Sanctis, L., Aversa, S. (2019). Bearing capacity of pile groups under vertical eccentric load. Acta Geotechnica
2) Iovino, M., Maiorano, R. M. S., de Sanctis, L., Aversa, S. (2021). Failure envelopes of pile groups under inclined and eccentric load. Géotechnique Letters
3) **Di Laora, R., Iodice, C., Mandolini, A.** (2022). A closed–form solution for the failure interaction diagrams of pile groups subjected to inclined eccentric load. Acta Geotechnica
4) Gorini, D. N., Callisto, L. (2022). Generalised ultimate loads for pile groups. Acta Geotechnica
5) Sakellariadis, L., Anastasopoulos, I. (2022). On the mechanisms governing the response of pile groups under combined VHM loading. Géotechnique
6) Potini, F., Gorini, D.N., Conti, R. (2023). Rigorous lower and upper bounds for the generalised failure loads of pile groups. Géotechnique Letters
7) **Cesaro, R., Di Laora, R., Iodice, C., Mandolini, A.** (2024). Interaction domains for capacity– and performance–based design of pile groups. Acta Geotechnica
8) Sakellariadis, L., Anastasopoulos, I. (2024). Analytical 3D failure envelopes for RC pile groups under combined loading: A generalised design approach. Soil Dynamics and Earthquake Engineering
9) **Di Laora, R., Cesaro, R., Iodice, C.,** Iovino, M., de Sanctis, L. (2025). A closed form solution for the generalised failure envelope of a pile group. Soil Dynamics and Earthquake Engineering.

**In bold: research group at Università della Campania**

# IN LAB EXPERIMENTAL VALIDATION BY CENTRIFUGE TESTS (N-M)




displacement transducers (LVDT)

MEMS accelerometers

pressure transducers

load cells

**dimensions in mm (m) at the model (prototype) scale**

**hinges**

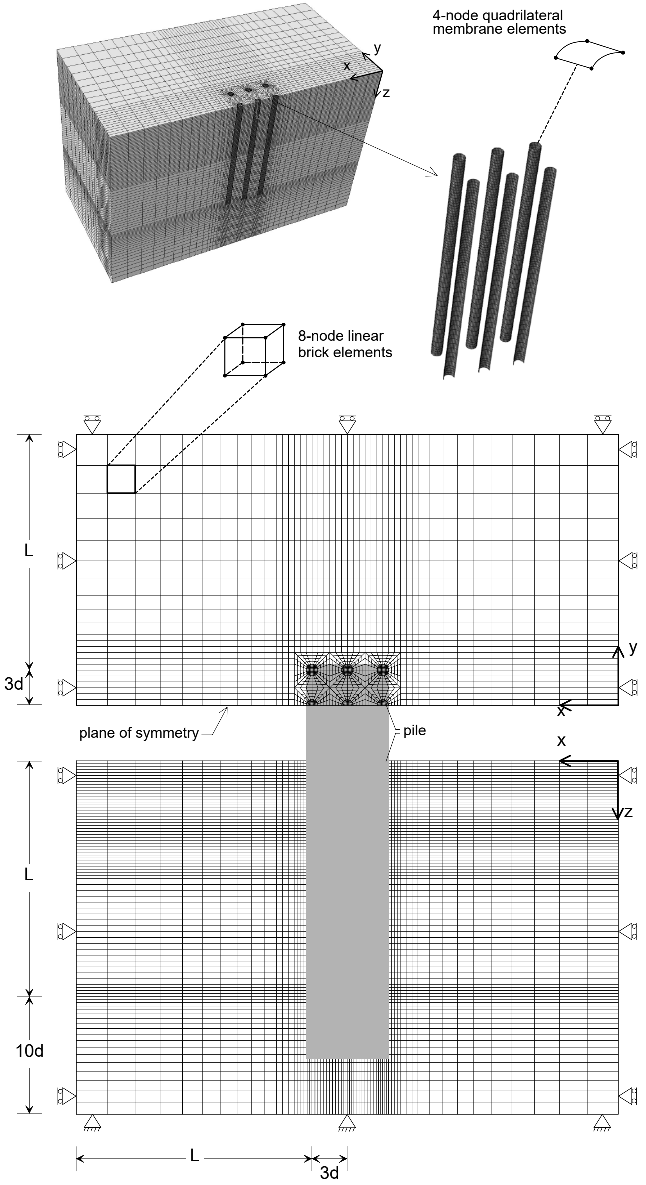
**Group A2**

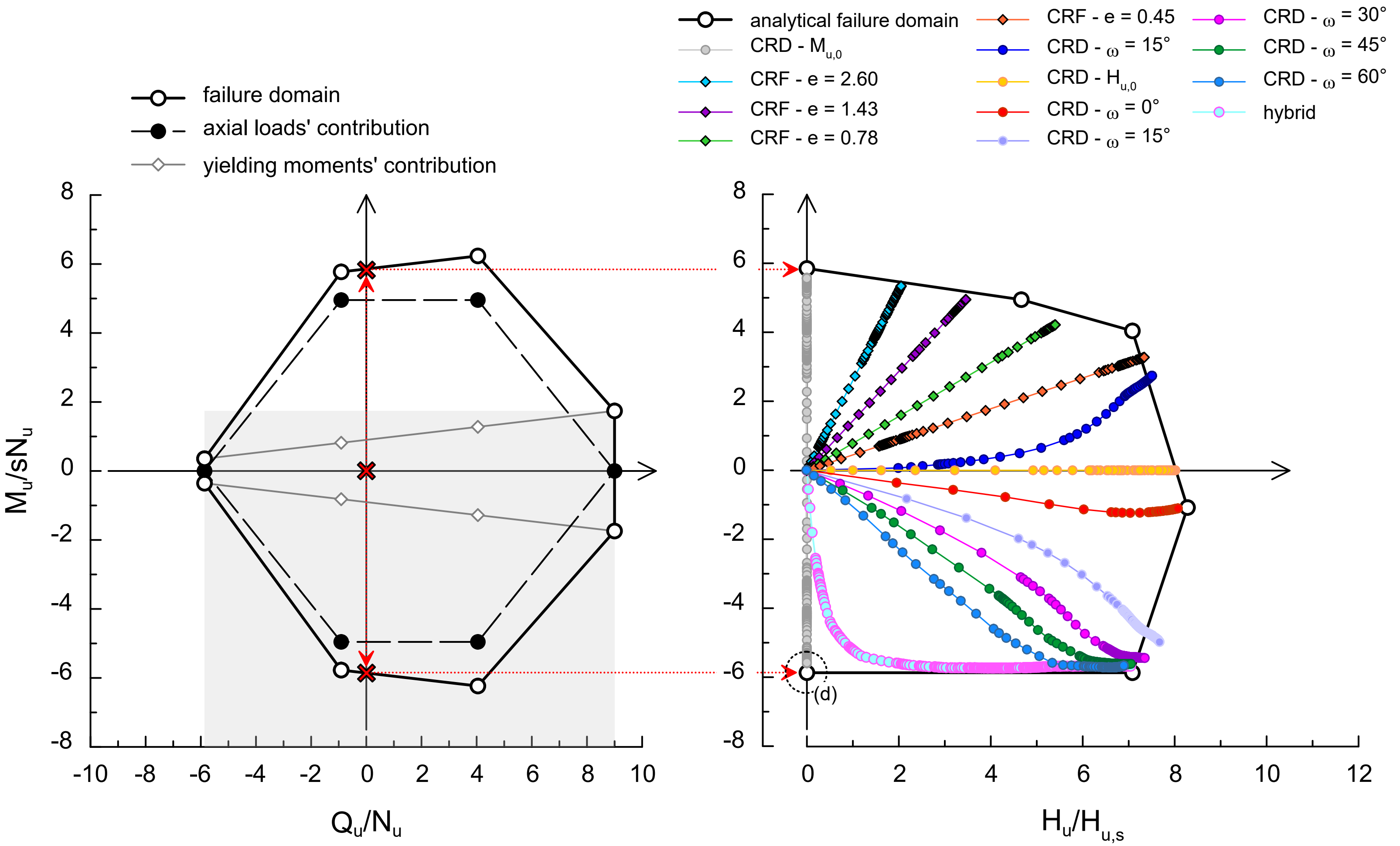
**circular caps**

**hollow cap**

**Schofield Centre, Cambridge, UK**

# NUMERICAL VALIDATION BY COMPLEX ABAQUS 3D-FE (N-M-H)



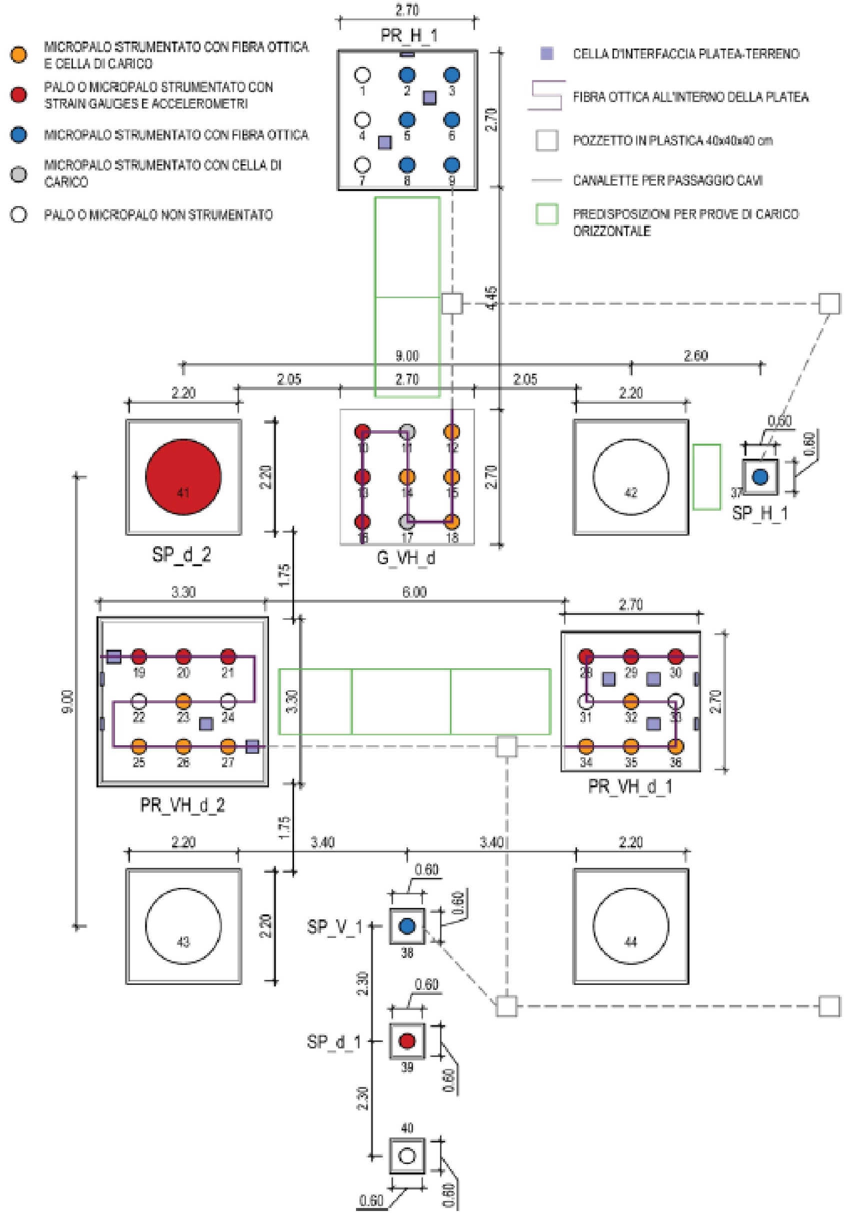




Di Laora, R., Cesaro, R., Iodice, C., Iovino, M., de Sanctis, L. (2025). A closed form solution for the generalised failure envelope of a pile group. Soil Dynamics and Earthquake Engineering.

# MEANWHILE ……


FORTEZZA
TRENTO
VICENZA
VERONA
PADOVA
Roma
FOGGIA
BARI
NAPOLI
SALERNO
MESSINA
PALERMO
REGGIO CALABRIA
ENNA
CALTANISSETTA
CATANIA
ITALFERR
GRUPPO FERROVIE DELLO STATO ITALIANE
webuild
Università
degli Studi
della Campania
Luigi Vanvitelli
Dipartimento di Ingegneria

# IN SITU EXPERIMENTAL VALIDATION BY FULL SCALE TESTS (N-M-H)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Università degli Studi della Campania Luigi Vanvitelli
Dipartimento di Ingegneria

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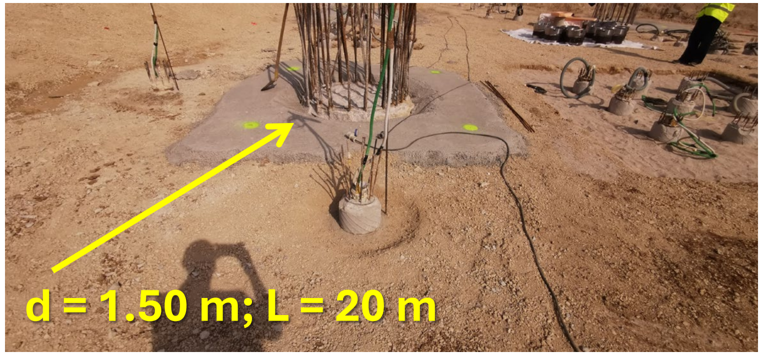
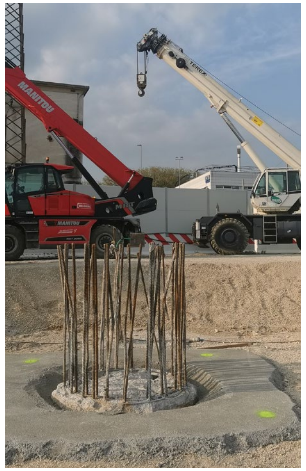


**Ready to start !!!!!**

**September → December 2025**

**1.7 millions $**

# REMEDIAL MEASURES


CSL tests and PITs revealed some defected piles for relatively large numbers of piers

# REMEDIAL MEASURES


Università degli Studi della Campania *Luigi Vanvitelli*

Dipartimento di Ingegneria

*LINEA FERROVIARIA NAPOLI–BARI*
*TRATTA NAPOLI–CANCELLO*

*CONSULENZA SCIENTIFICA IN CAMPO GEOTECNICO*
*(Convenzione con NACAV s.c.a.r.l.)*


***Nota metodologica per l'approccio alla risoluzione delle non conformità riscontrate per le palificate di fondazione***

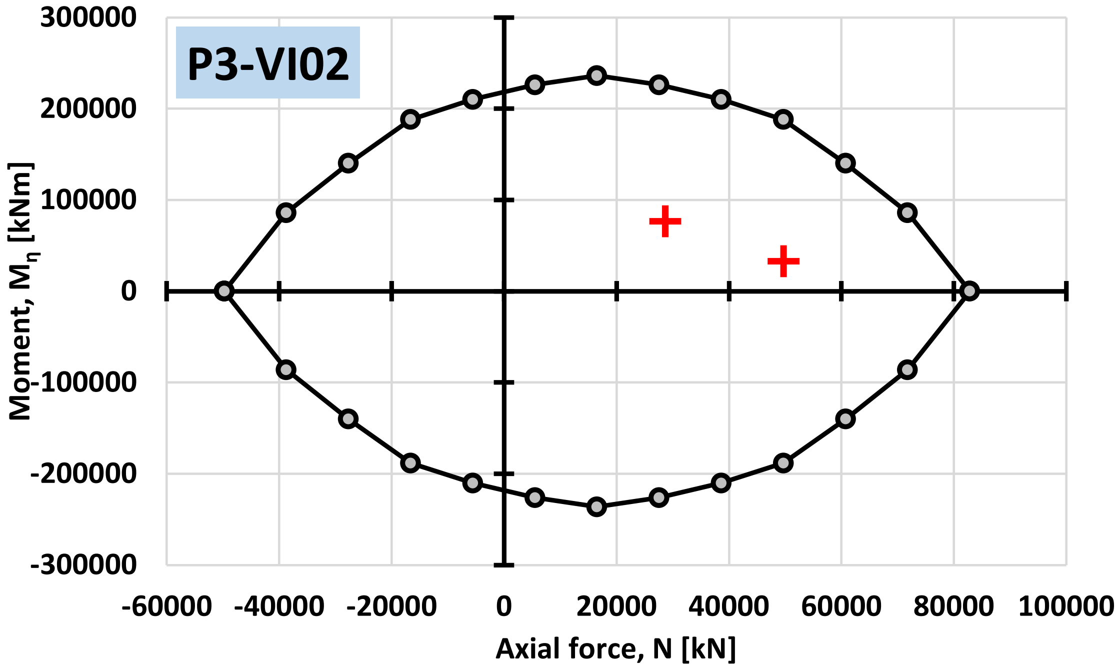
*Responsabile Scientifico: prof. ing. Alessandro Mandolini*

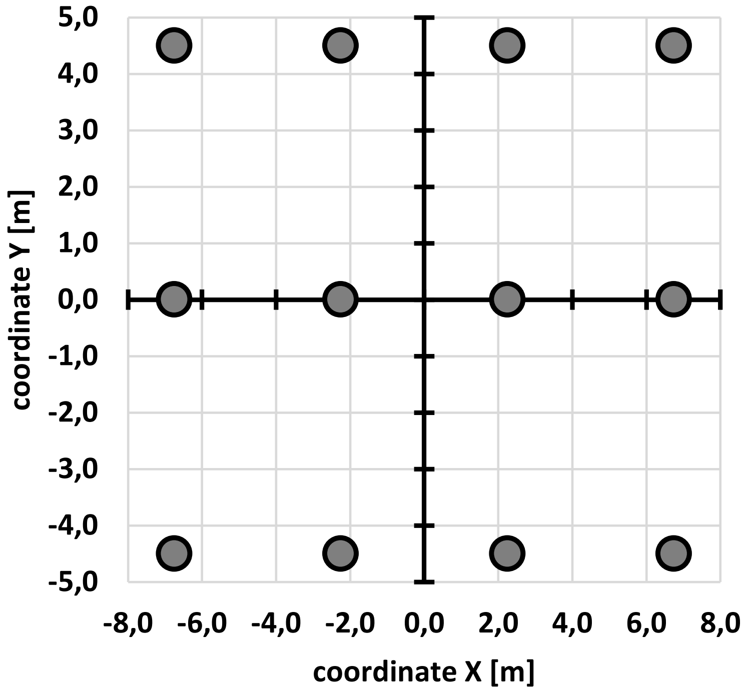
*Giugno 2020*

RAPP NOTA METODOLOGICA RNC 2020-06-26

# REMEDIAL MEASURES ?

**Solution from conventional design: L = 27 m**

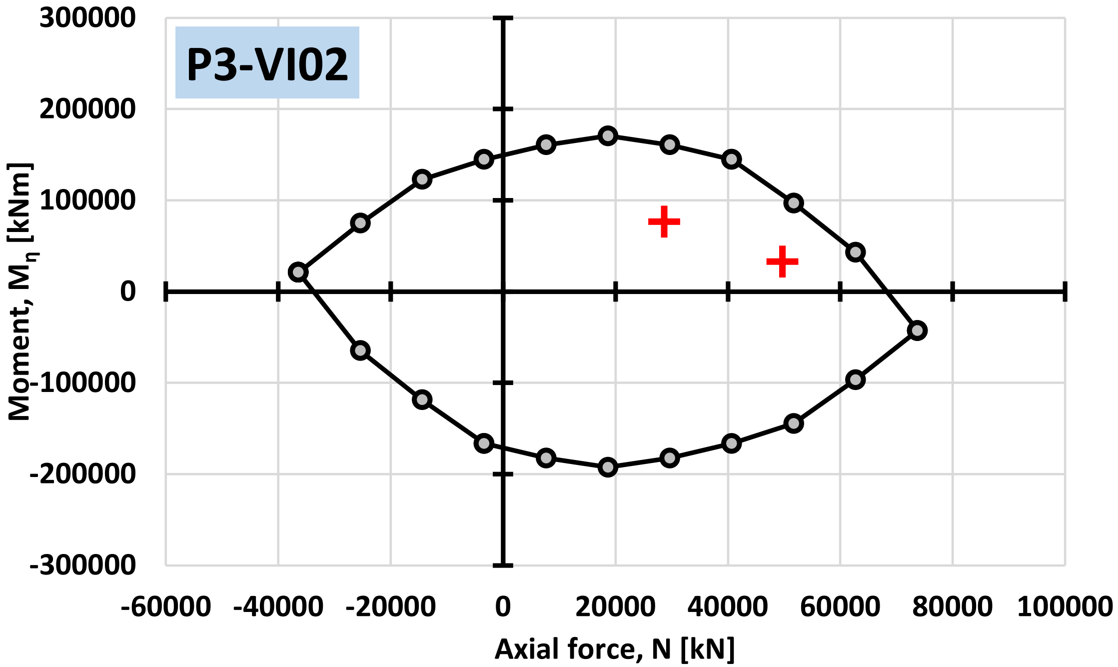


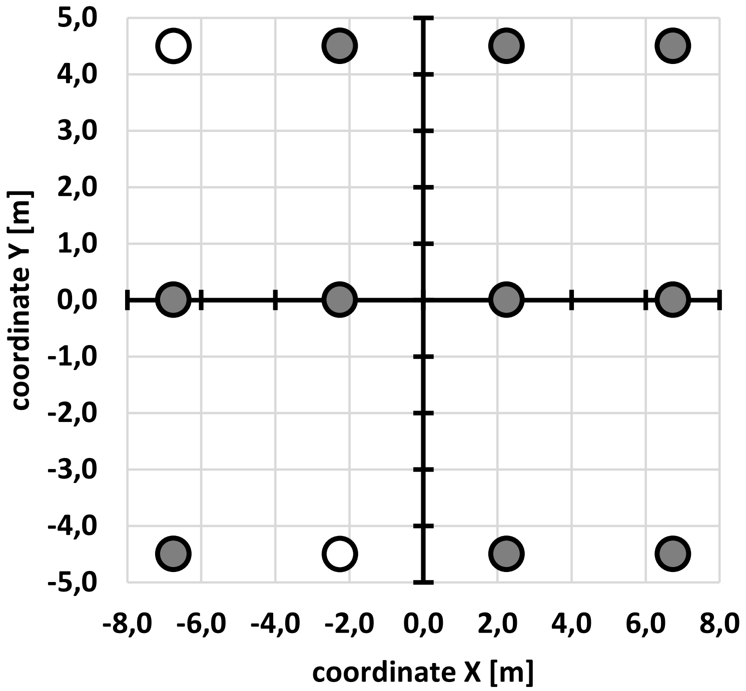




**As expected, clearly conservative !!!**

# REMEDIAL MEASURES ? NO

**CSL and PIT revealed that actual pile length was L = 24 m and two piles were poorly constructed**




**Design actions still internal to the resistance domain which considers only 10 over 12 piles of reduced length (24 m instead of 27 m)**

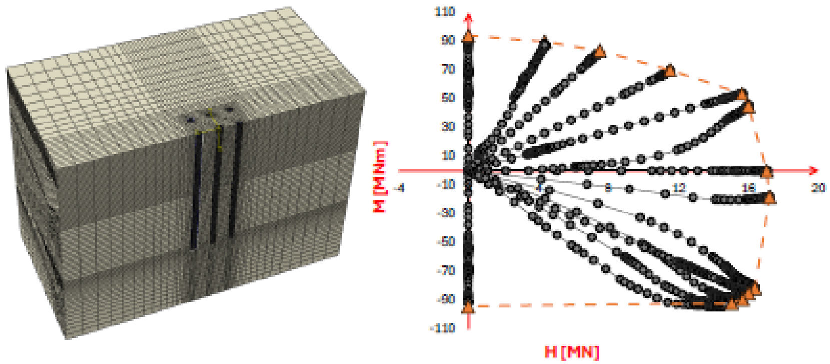
# ON GOING UPDATED DESIGN APPROACH


Università degli Studi della Campania *Luigi Vanvitelli*

Dipartimento di Ingegneria

**UTILIZZO DEI DOMINI DI INTERAZIONE**

**PER LE VERIFICHE DELLE FONDAZIONI SU PALI**




***Nota Metodologica***

***Maggio 2025***

**Responsabile Scientifico:** Prof. ing. Alessandro Mandolini

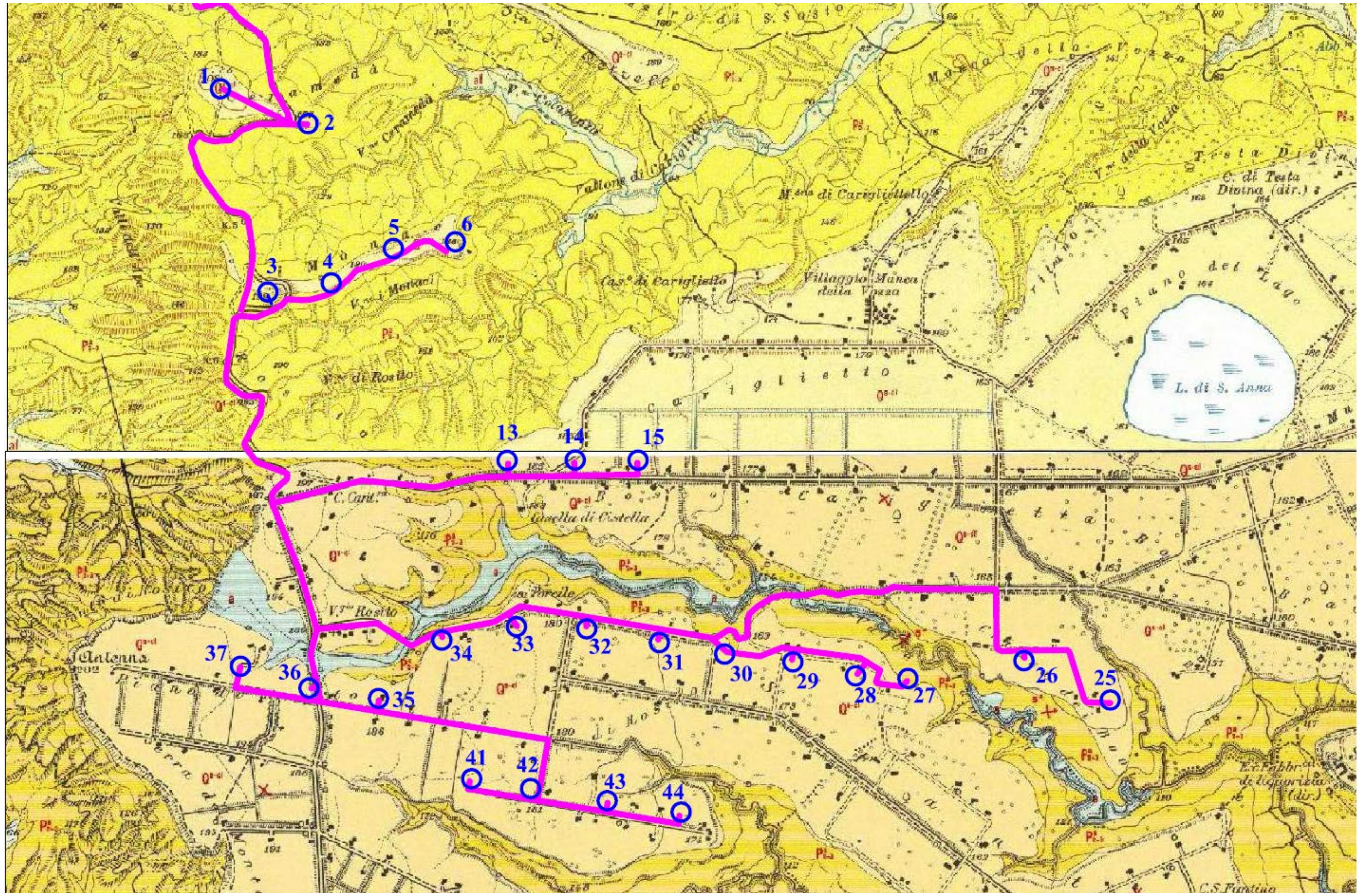
**Gruppo di lavoro:** Prof. ing. Raffaele Di Laora

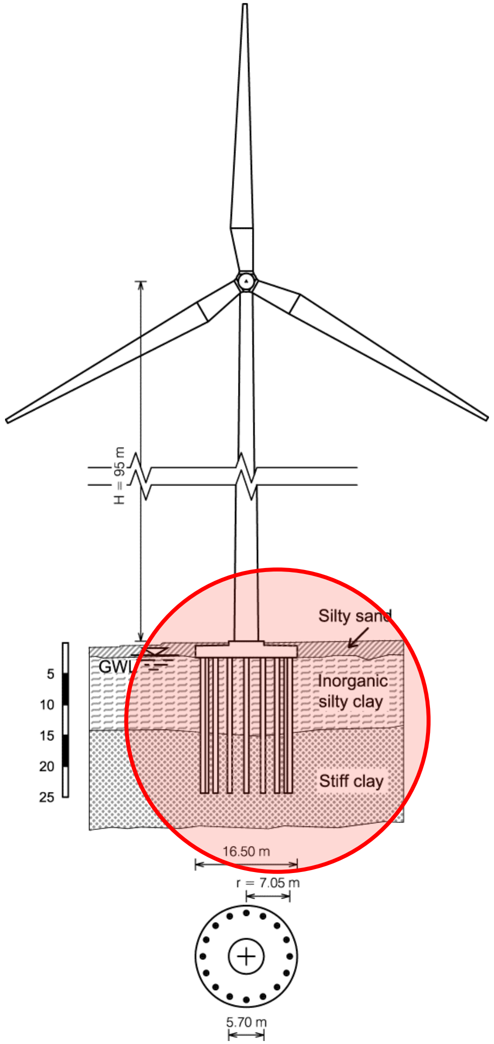
Dott. ing. Chiara Iodice

Dott. ing. Raffaele Cesaro

# MEANWHILE ……

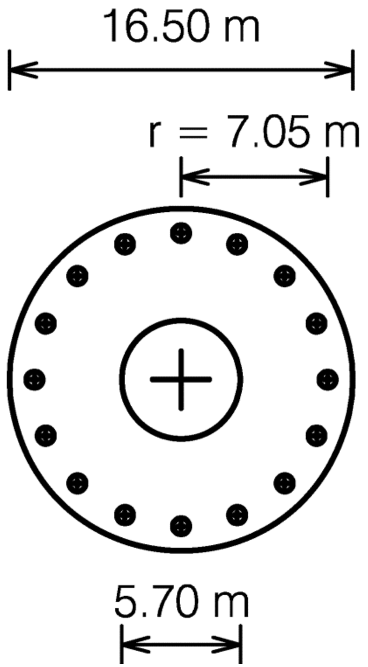
## Wind farm in Italy
## (23 turbines)

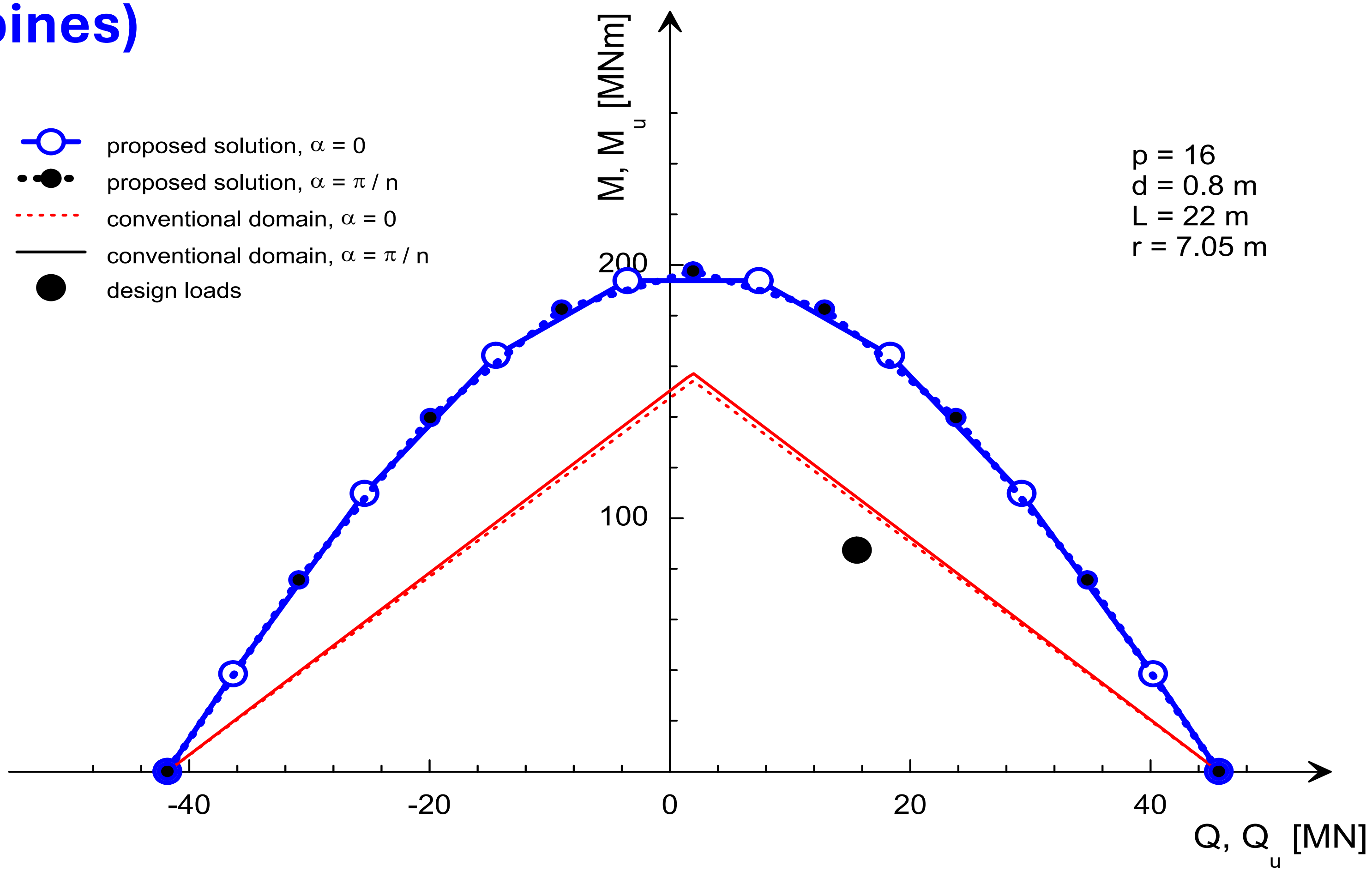


# MEANWHILE ……

## Wind farm in Italy
## (23 turbines)



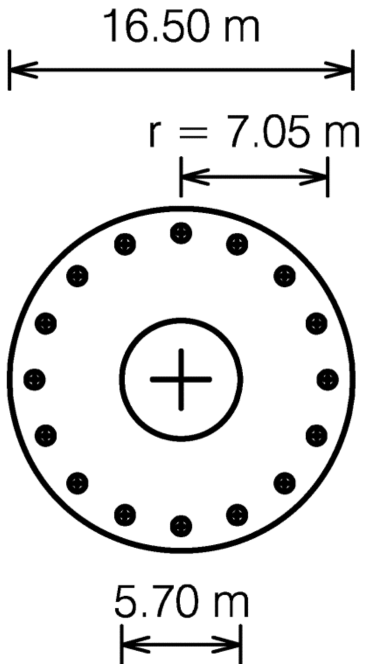



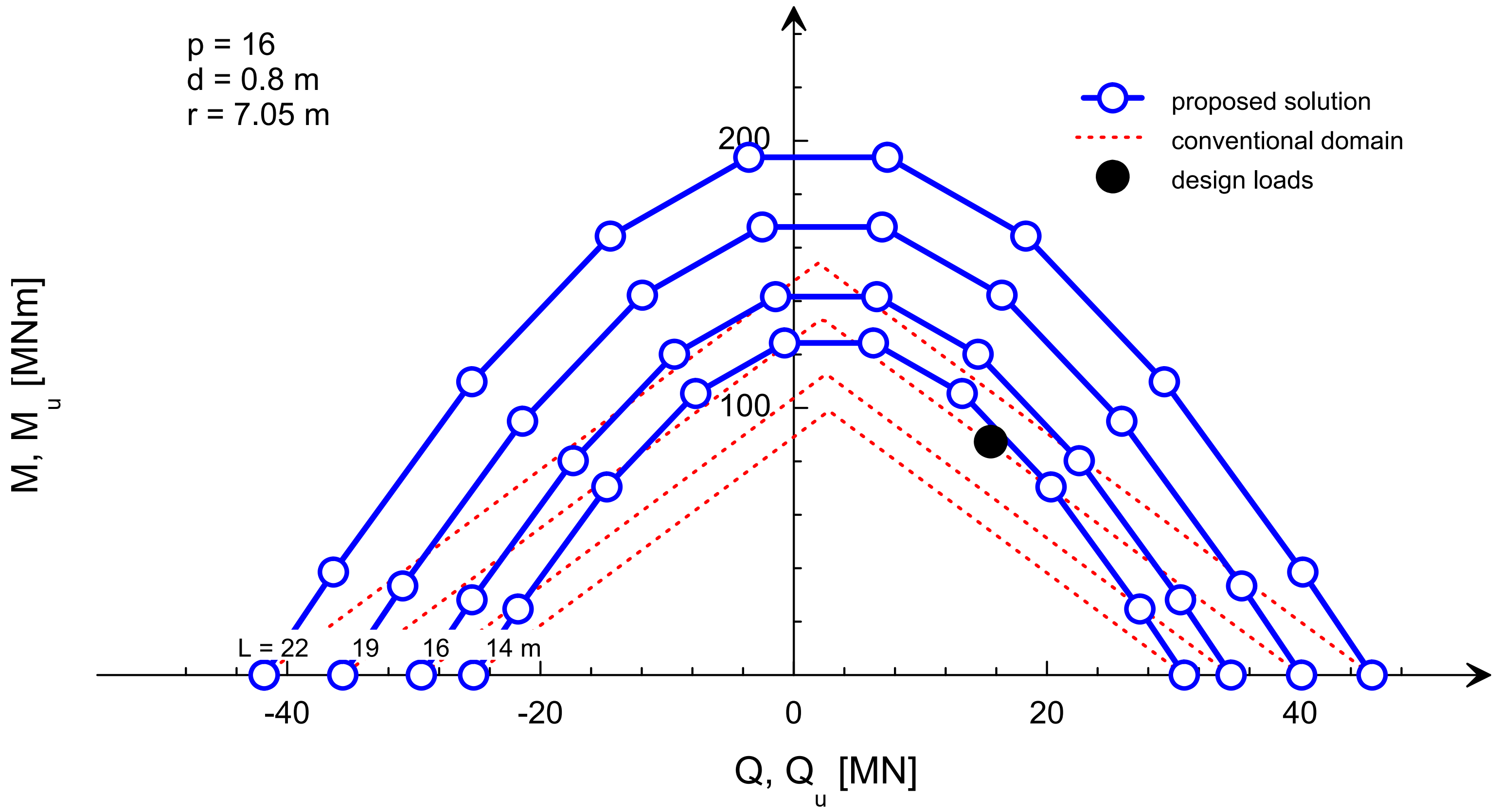

**Design solution based on the traditional approach:**

**16 piles with diameter d = 0.8 m and length L = 22 m → (nL) = 8096 m**

# MEANWHILE ......

## Wind farm in Italy (23 turbines)




**New solution:**

**16 piles with L = 14 m, (nL) = 5152 m, Reduction: 2944 m**

# CONCLUDING REMARKS

- **Interaction domains represent a simple yet reliable method for assessing the performance of pile groups under generalized loading conditions, also in relation to the design checks required by regulations**

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- **There is still room for eliminating some overconservatism in the pile group design, e.g. accounting for the contribution of raft (WORK IN PROGRESS….)**

# CONCLUDING REMARKS

- **Interaction domains represent a simple yet reliable method for assessing the performance of pile groups under generalized loading conditions, also in relation to the design checks required by regulations**
- **There is still room for eliminating some overconservatism in the pile group design, e.g. accounting for the contribution of raft (WORK IN PROGRESS….)**
- **We must be aware that in this way we are also eliminating some hidden safety margins**

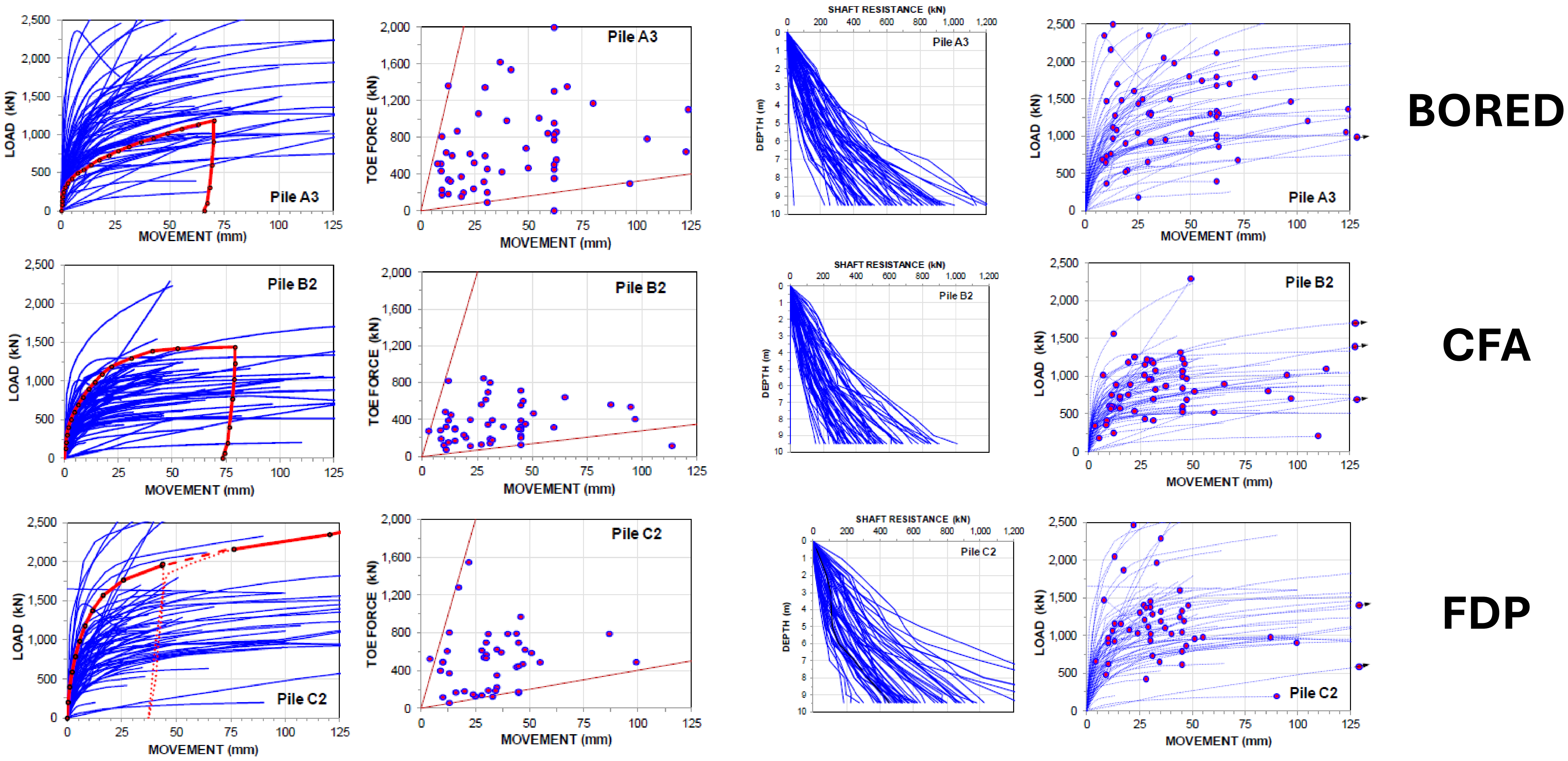
## CONCLUDING REMARKS

- Interaction domains represent a simple yet reliable method for assessing the performance of pile groups under generalized loading conditions, also in relation to the design checks required by regulations
- There is still room for eliminating some overconservatism in the pile group design, e.g. accounting for the contribution of raft (WORK IN PROGRESS….)
- We must be aware that in this way we are also eliminating some hidden safety margins
- **However, the overall reliability of the pile group design depends on how accurate is the assessment of the single pile behaviour**

# CONCLUDING REMARKS

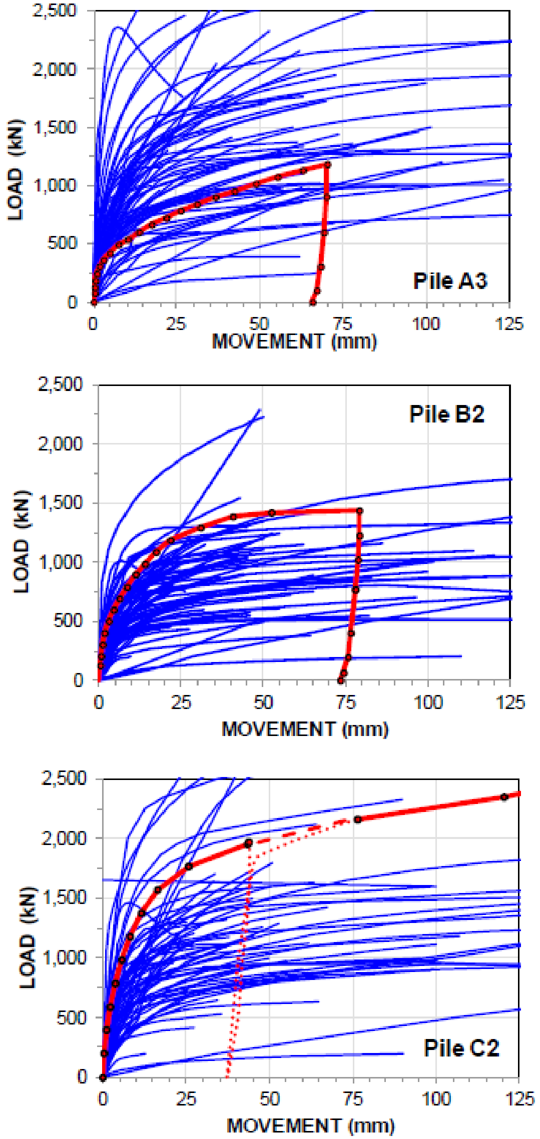
incotec SIMSG ISSMGE

**International Pile Prediction Event**
**BEST for Piles**



# CONCLUDING REMARKS

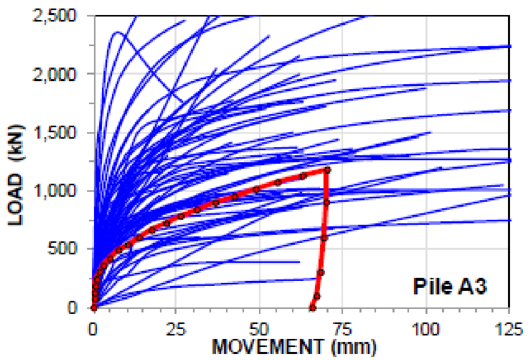
International Pile Prediction Event
BEST for Piles (72 predictions)

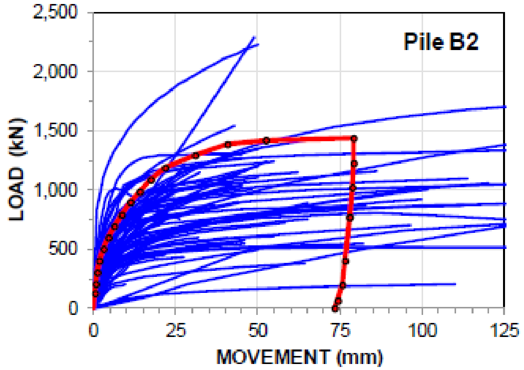


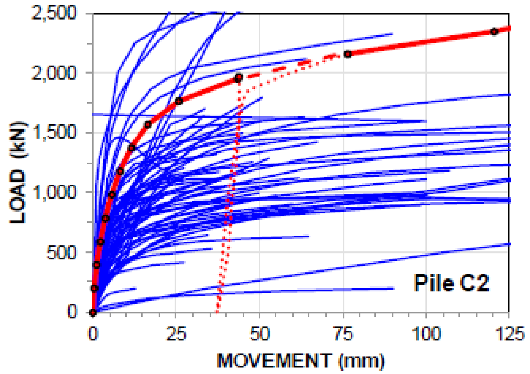

**Very different load-movement curves as results of very different shaft and base curves, ........**

# CONCLUDING REMARKS





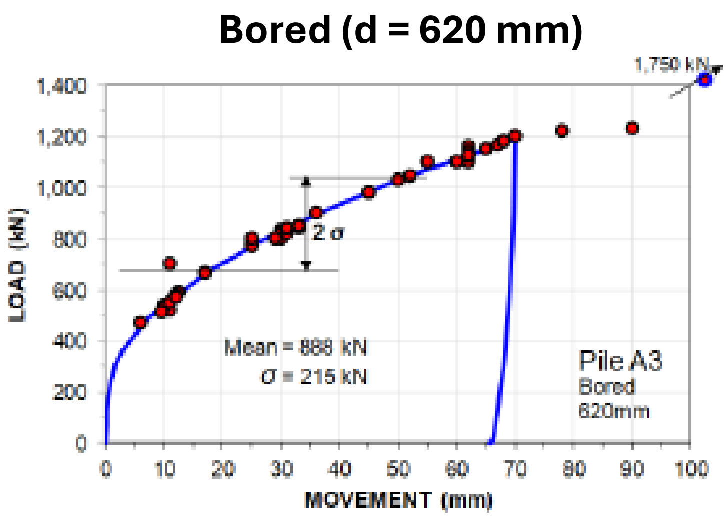

## NEW GAME

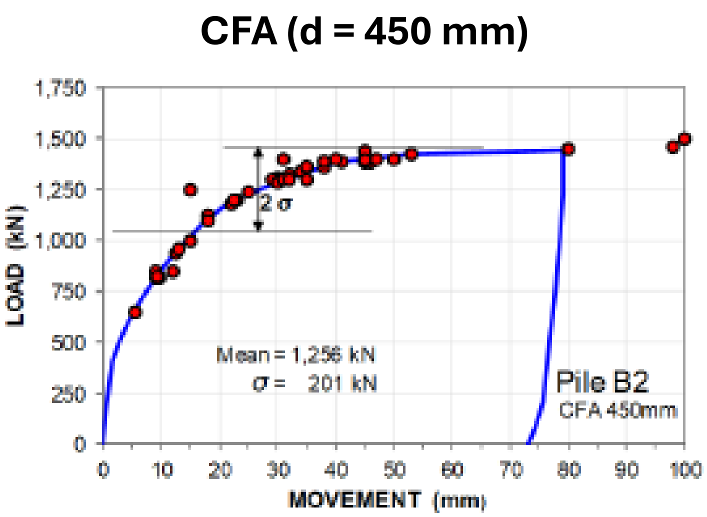
**After loading tests were completed, the results were sent to all the predictors to get their best assessment of the pile capacity simply selecting a point on the available experimental curves. 54 assessed capacities (for each pile) by 94 participants were collected.**

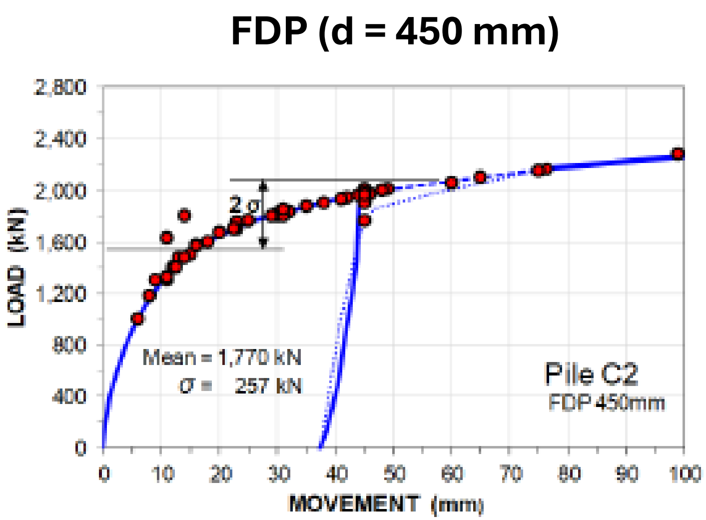
**Very different load-movement curves as results of very different shaft and base curves, ……..**

# CONCLUDING REMARKS

International Pile Prediction Event
BEST for Piles (72 predictions)



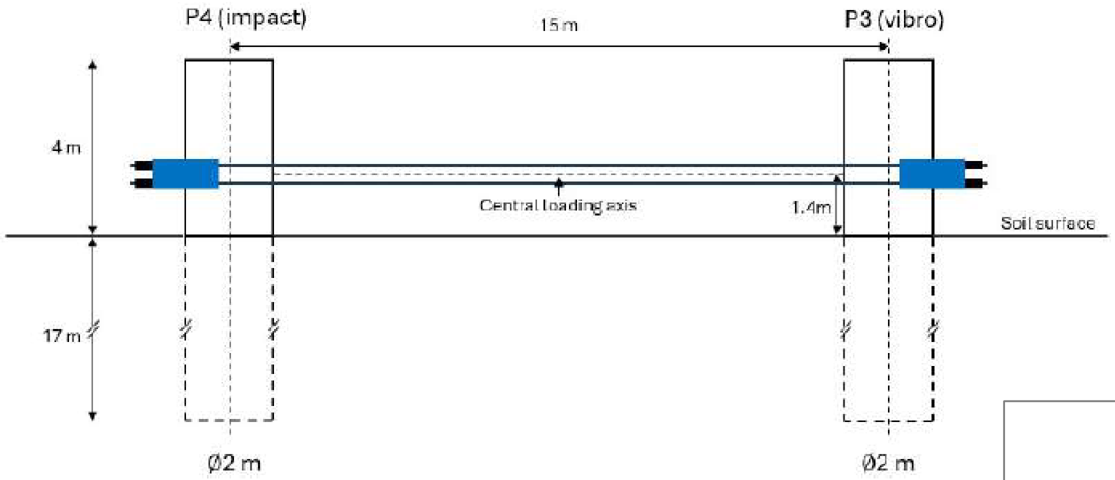



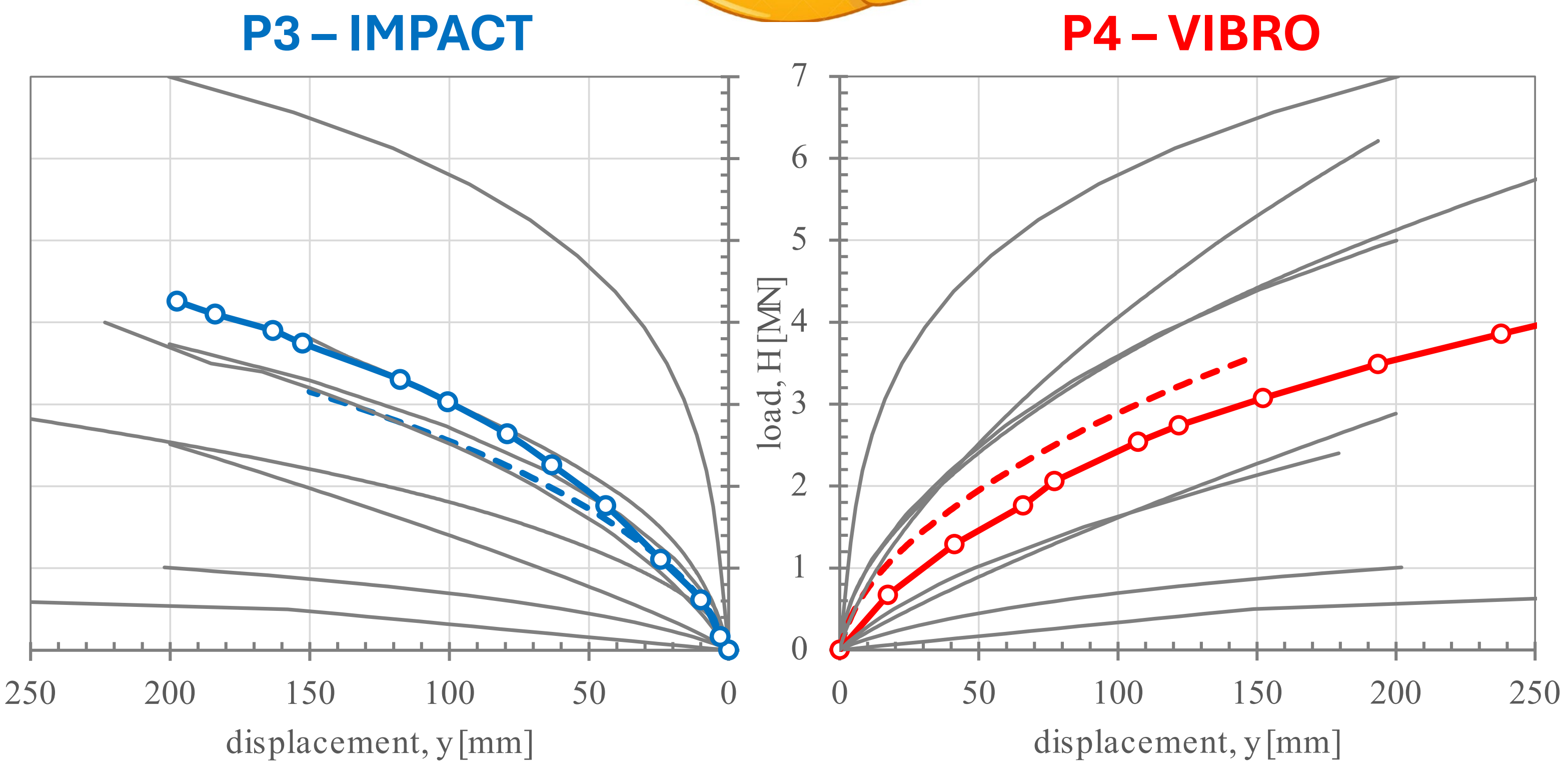

**Very different load-movement curves as results of very different shaft and base curves, with different relative settlement w/d at which the 'failure' load is assessed !!!!!**

# CONCLUDING REMARKS

**Lateral Load**
**Blind Prediction Competition**
**SAGESAND project**

TC212



***Invest in research to save***

***(time, money, $CO_2$ emission, …)***

***through research***