NON LINEAR SOIL STRUCTURE INTERACTION : IMPACT ON THE SEISMIC RESPONSE OF STRUTURES

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GÉODYNAMIQUE & STRUCTURE

OUTLINE OF PRESENTATION

- Review of existing foundation design practice
  - Required changes in design philosophy
- Examined foundation behavior during cyclic loading
  - Modeling aspects through dynamic macroelement
- Assess the impact of foundation non linearities and variability of seismic motion on structural behavior
- Draw some preliminary conclusions

FOUNDATION DESIGN PHILOSOPHY

- Foundations are designed to remain elastic during earthquakes
  - foundation cannot be easily inspected and repaired after an earthquake
- Ductility demand restricted to superstructure

- Alternative approach
  - Accept permanent (limited and controlled) displacements at foundation
  - Performance based design ⇔ displacement based design

MOTIVATION FOR DISPLACEMENTS EVALUATION

- Soil structure interaction plays a dominant role in seismic response of the structure
  - Beneficial or detrimental ?? Controversial but all linear elastic studies

- Permanent foundation displacements affect the performance of the structure

WHY CONSIDERING FOUNDATION NONLINEARITY / INELASTICITY ?

- Recent records revealed very strong seismic shaking
  - 1994 Northridge : 0.98 g , 1.40 m/s
  - 1995 Kobe : 0.85 g , 1.50 m/s

  and SA values reaching 2 g

- Retrofitting of existing/damaged structures impossible to accomplish elastically

MOSS LANDING
(Loma Prieta, 1989)

MEXICO
(Michoacan, 1985)


FOTOCLINICA
TRANSPARENCIAS
MEDICA
MINOLTA XD-5
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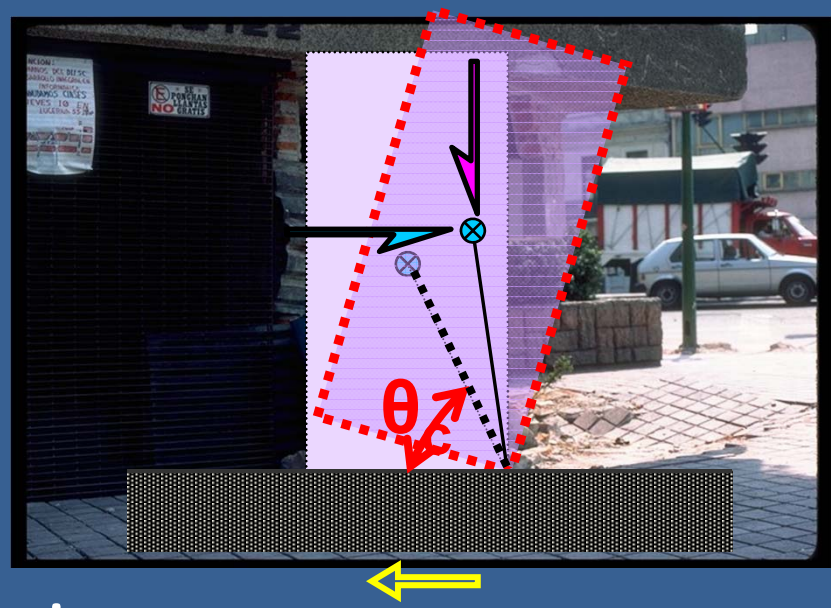
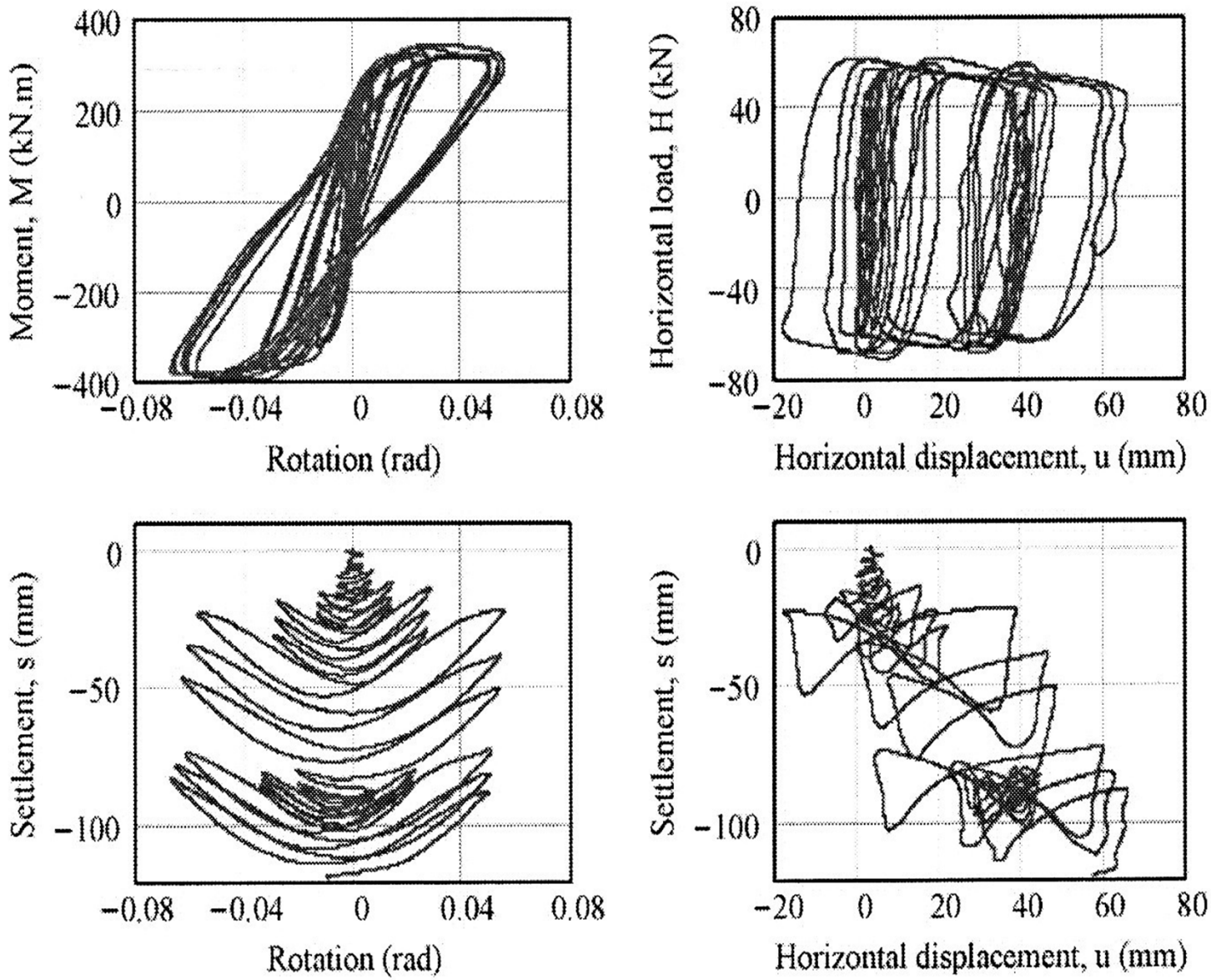
IMPLICATIONS OF NON LINEARITIES GEOTECHNICAL EARTHQUAKE ENGINEERING

- Sliding of foundation
- Foundation uplift
- Partial loss of bearing capacity



CENTRIFUGE TESTS

(*Gajan et al.*, 2005)

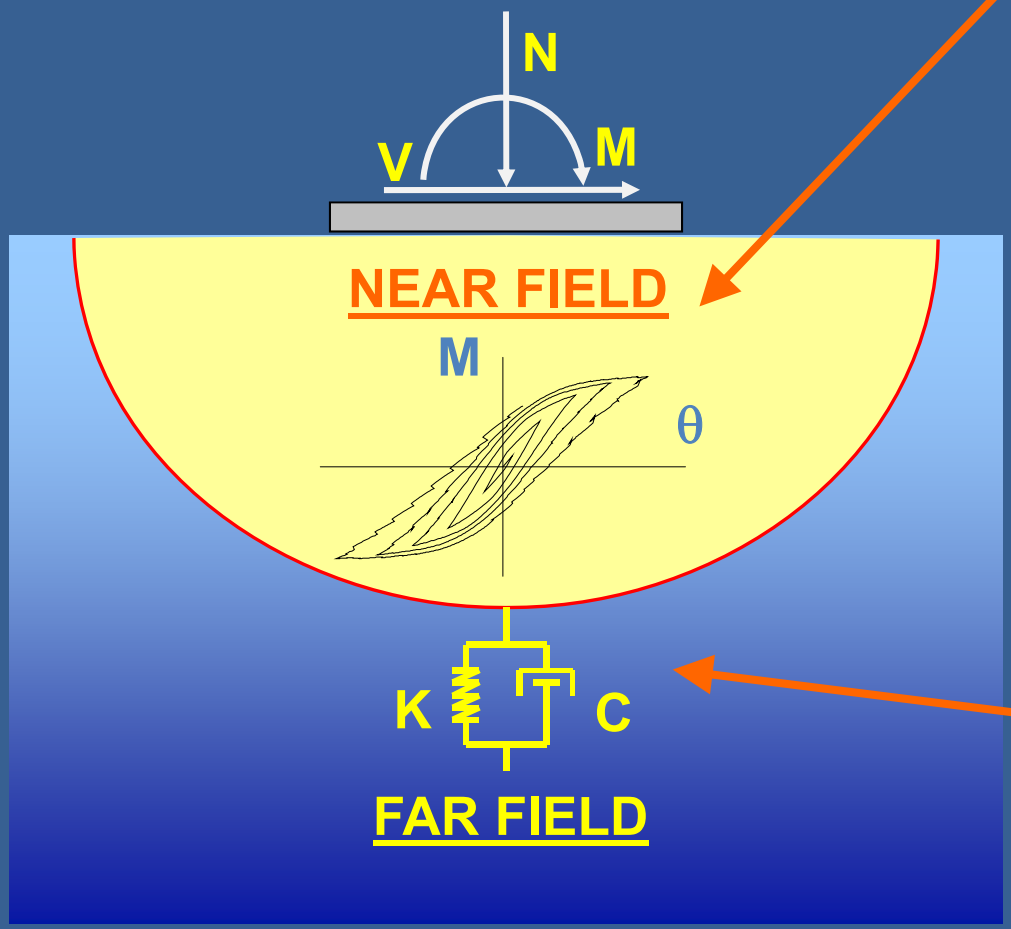


DIFFICULTIES OF NON LINEAR DYNAMIC ANALYSES

- Analyses are time consuming & expensive to run
  - Especially if soil is modeled (3D continuum)

- Results are very sensitive to small changes in input data
  - Input motion
  - Structural characteristics
  - Soil characteristics

DYNAMIC MACRO ELEMENT



Nonlinearities :

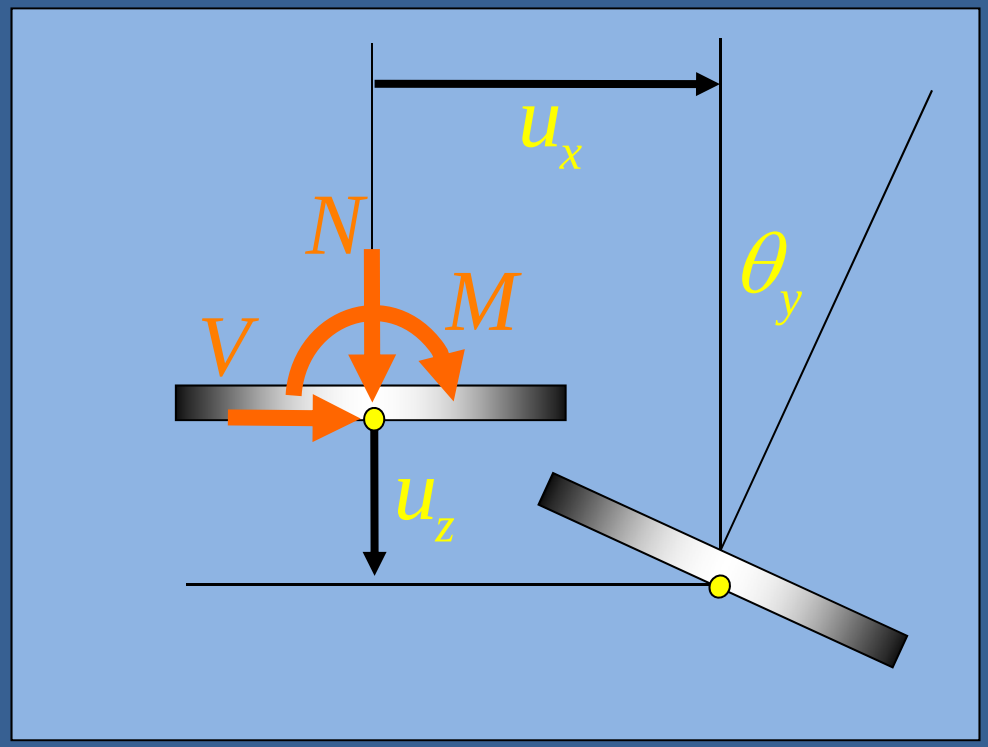
- Geometrical (interface behavior) →Uplift model
- Material (elasto-plastic soil behavior) →Plasticity model

Wave propagation :

- Dissipation of radiation energy
- Dynamic elastic impedances

GENERALIZED FORCES AND DISPLACEMENTS

Rigid circular footing under planar loading



$$\underline{Q} = \begin{bmatrix} Q_N \\ Q_V \\ Q_M \end{bmatrix} = \frac{1}{DN_{\max}} \begin{bmatrix} DN \\ DV \\ M \end{bmatrix}$$

$$\underline{q} = \begin{bmatrix} q_N \\ q_V \\ q_M \end{bmatrix} = \frac{1}{D} \begin{bmatrix} u_z \\ u_x \\ D\theta_y \end{bmatrix}$$

$$\underline{\dot{Q}} \overset{?}{\longleftrightarrow} \underline{\dot{q}}$$

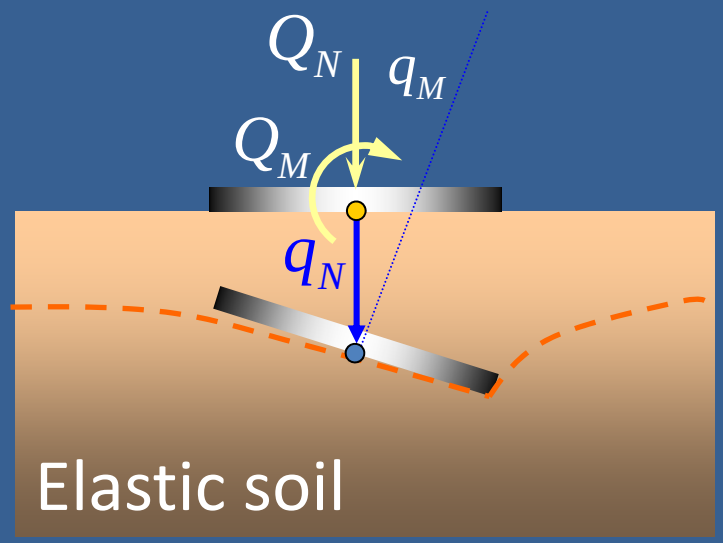
$$\underline{\dot{q}} = \underline{\dot{q}}^{el} + \underline{\dot{q}}^{up} + \underline{\dot{q}}^{pl}$$

MODEL COMPONENTS

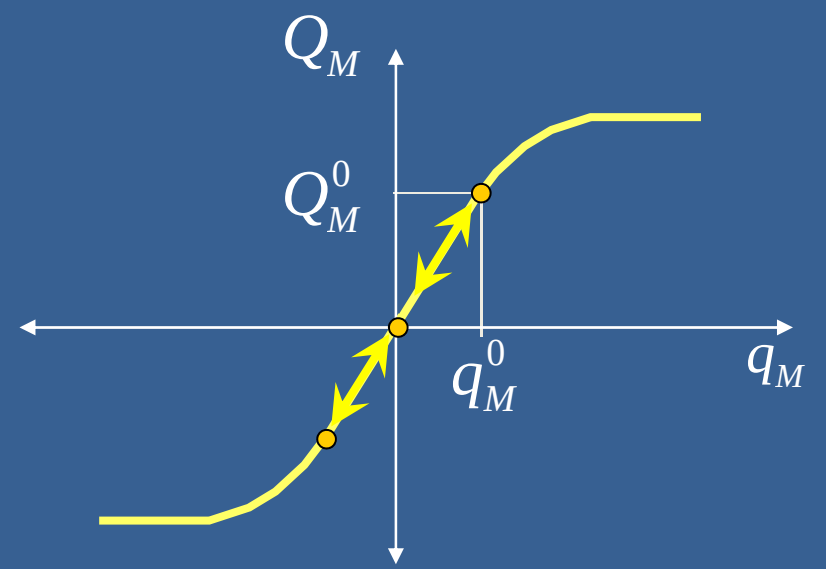
MECHANISM	DISSIPATION	REVERSIBILITY	NON-LINEARITY	MACROELEMENT
Elasticity	No	Reversible	No	Elasticity
Uplift	Non – dissipative	Reversible	Geometric	Non-linear elastic model
Soil Yielding	Dissipative	Irreversible	Material	Associated Plasticity model

Possible load states are limited by ultimate bearing Capacity of foundation

UPLIFT ON AN ELASTIC SOIL

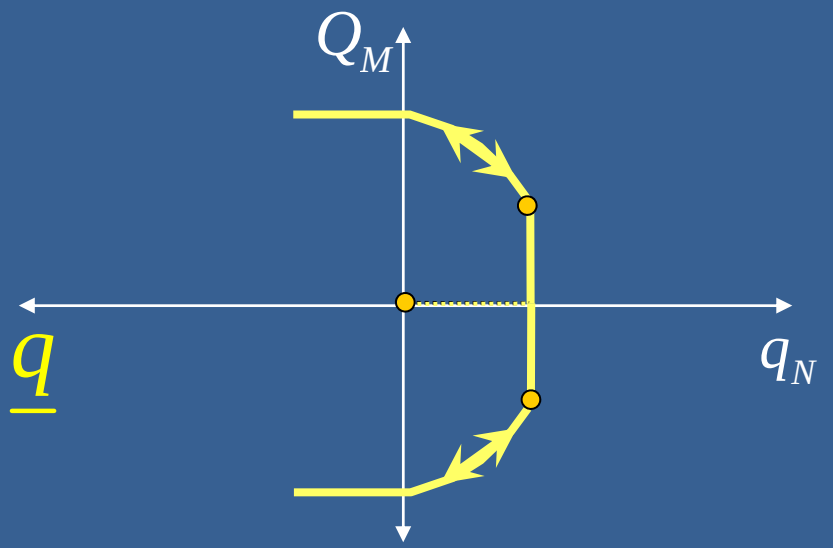


[*Crémer et al* (2001)]
[*Wolf* (1985)]



Phenomenological
non-linear elastic model

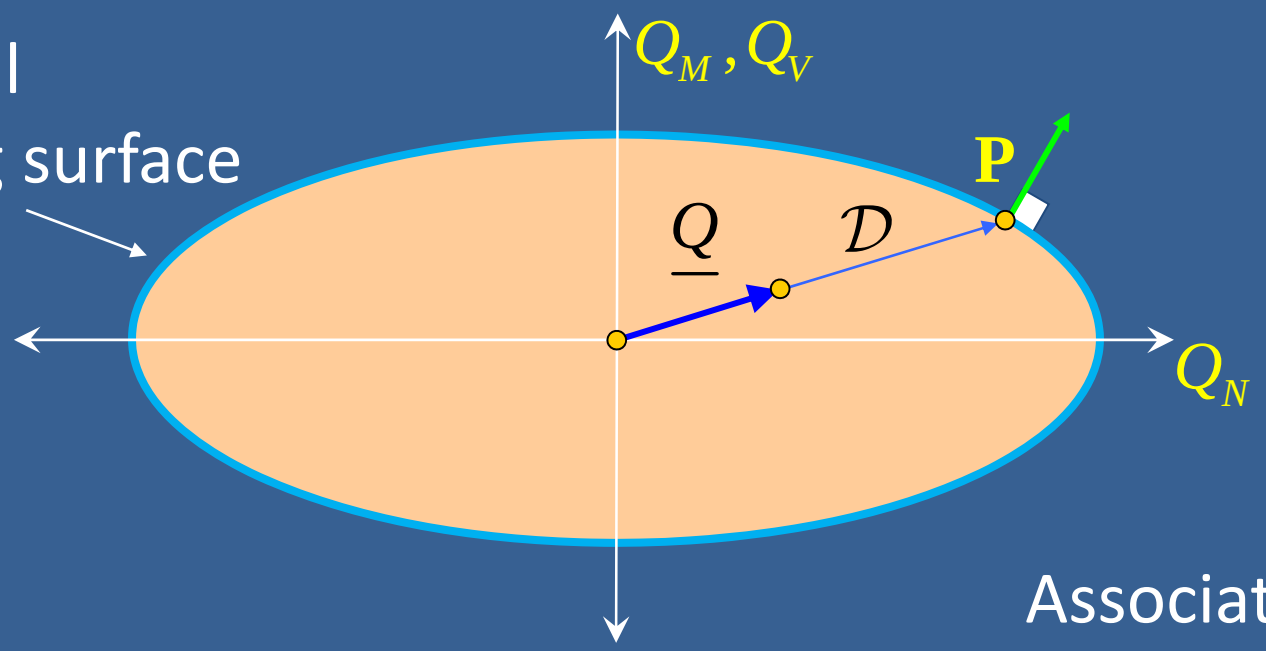
$$\underline{\dot{Q}} = \underline{\underline{K}}\left(\underline{q}\right)\underline{\dot{q}}$$



1. Matrix $\underline{\underline{K}}$ depends explicitly on $\underline{q}$
2. No influence of Q_V on uplift

FOOTING BONDED ON A COHESIVE SOIL
No uplift allowed

Ellipsoidal bounding surface

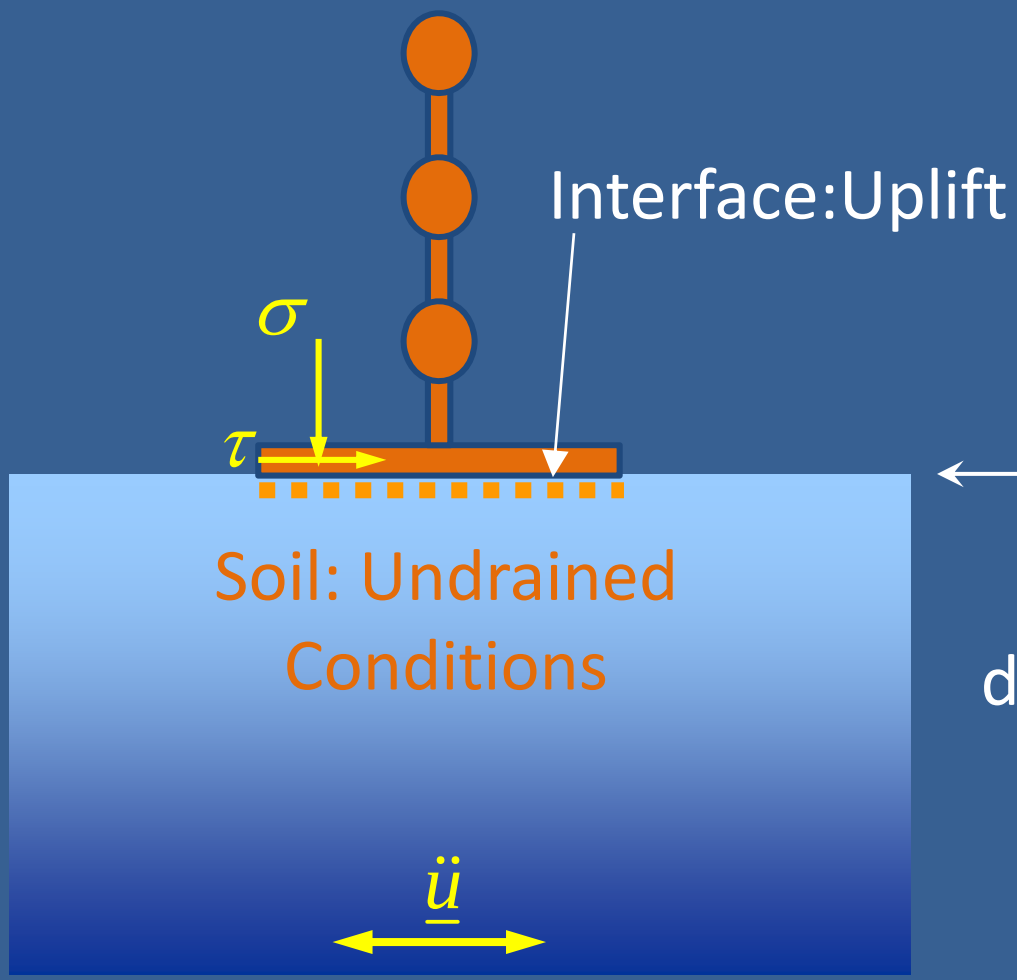


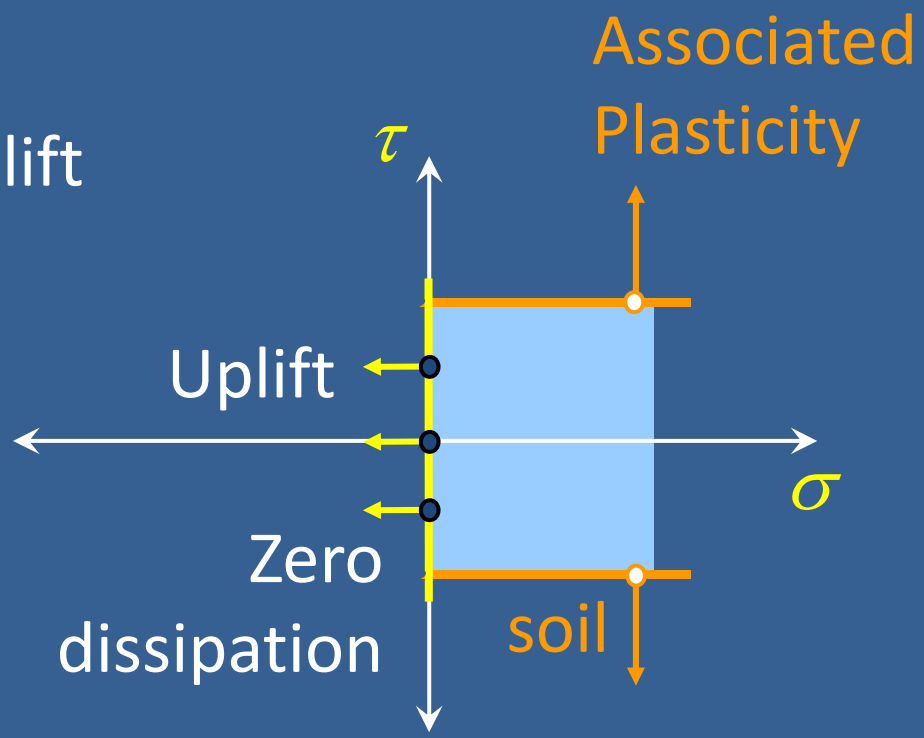
Associative flow rule

Hypoplastic bounding surface plasticity

1. Cyclic loading
2. Continuous variation of plastic modulus
3. Numerical implementation

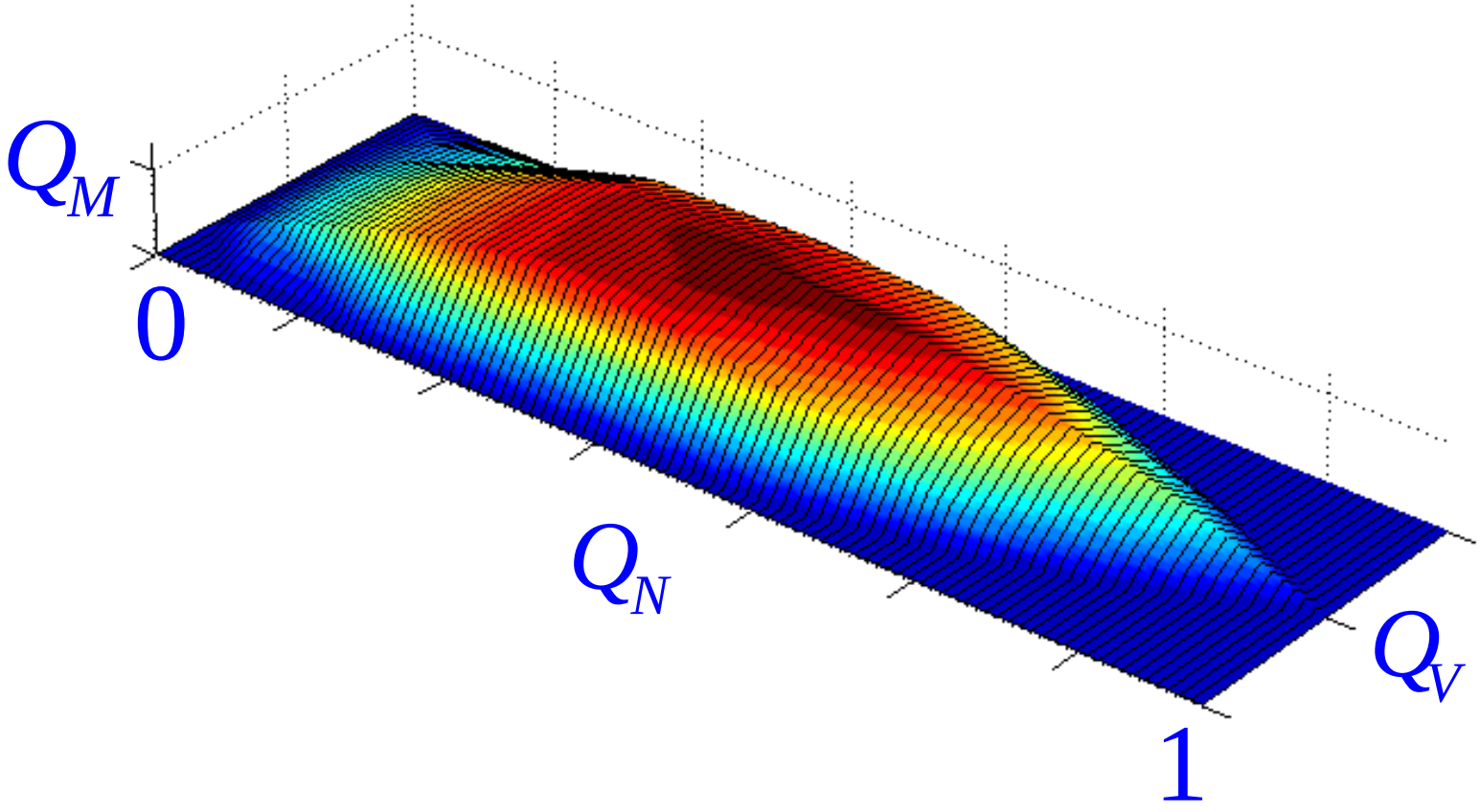
DEFINITION OF ULTIMATE LOADS



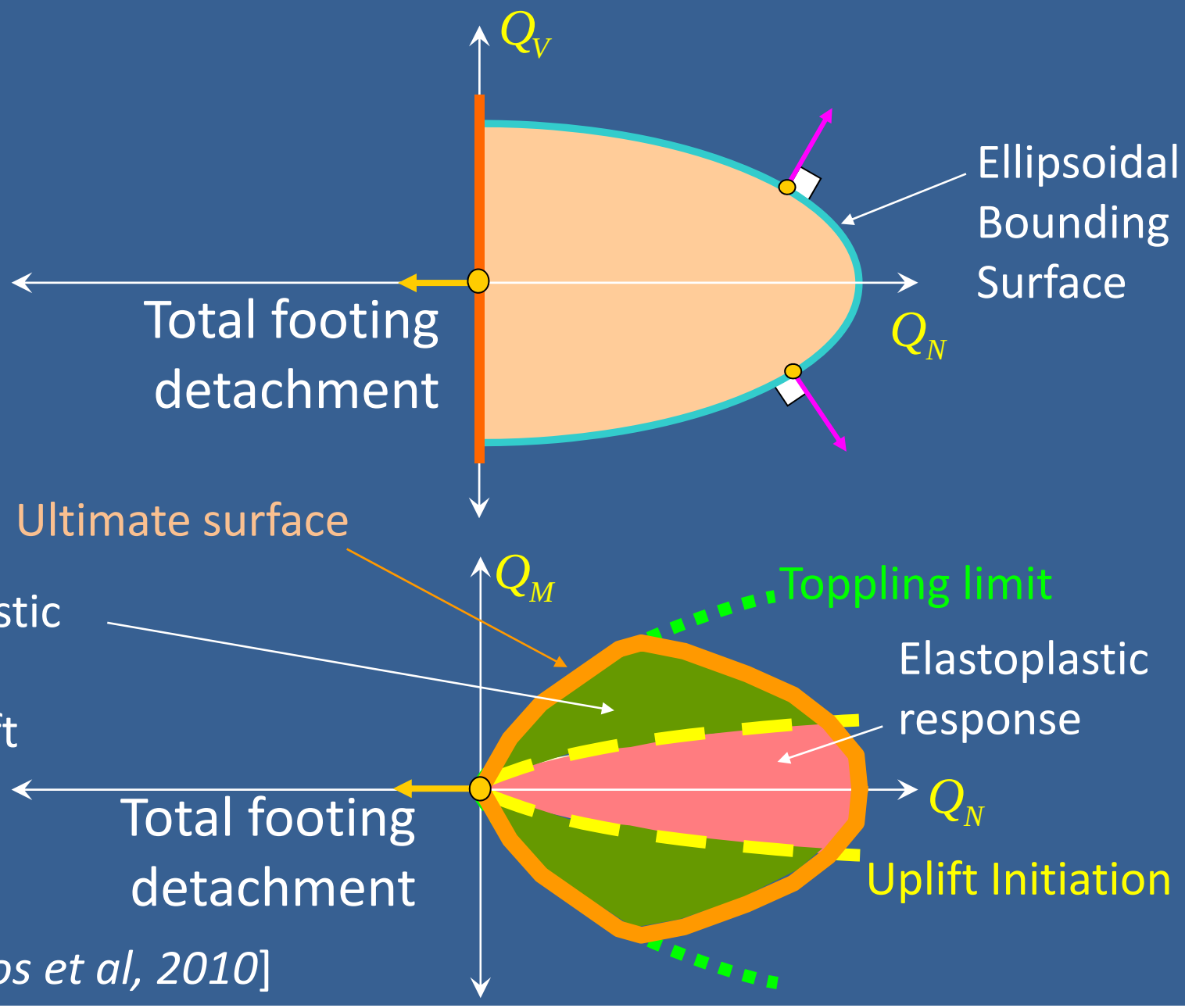


SURFACE OF ULTIMATE LOADS

(Chatzigogos *et al*, 2007)



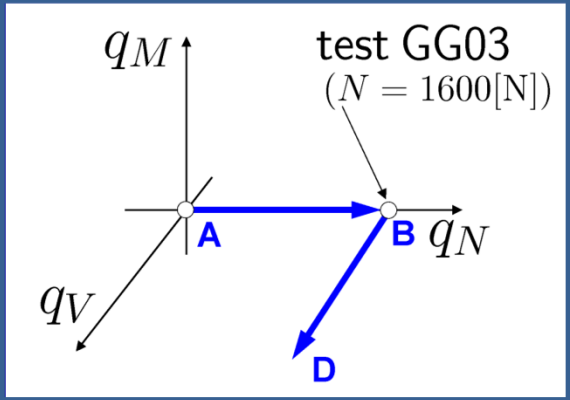
UPLIFT – PLASTICITY COUPLING

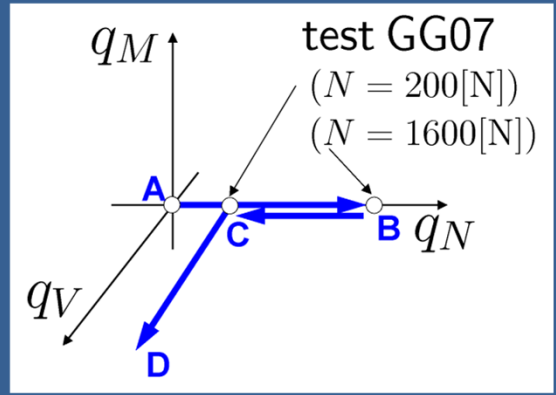


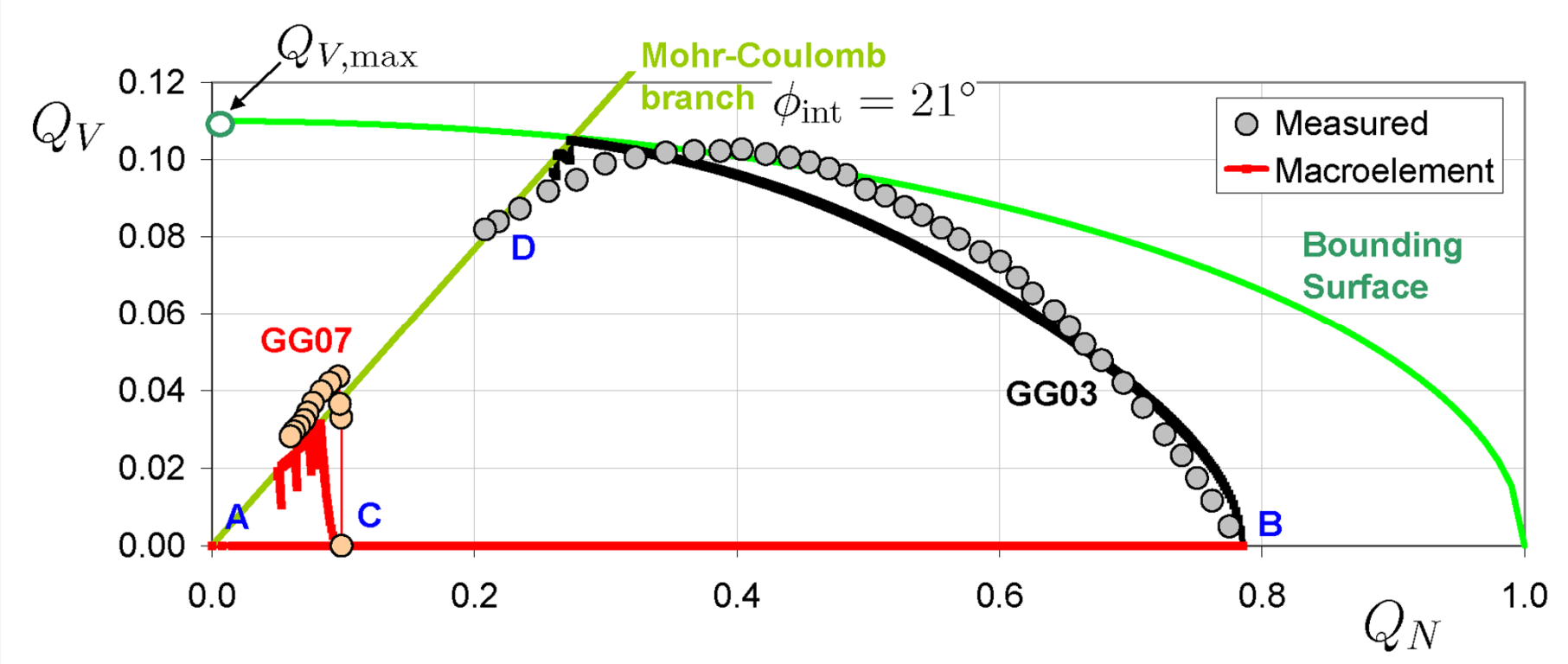
[*Chatzigogos et al, 2010*]

SWIPE TESTS

Imposed Horizontal Displacement







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INCREMENTAL DYNAMIC ANALYSIS
(Cornell, 2002)

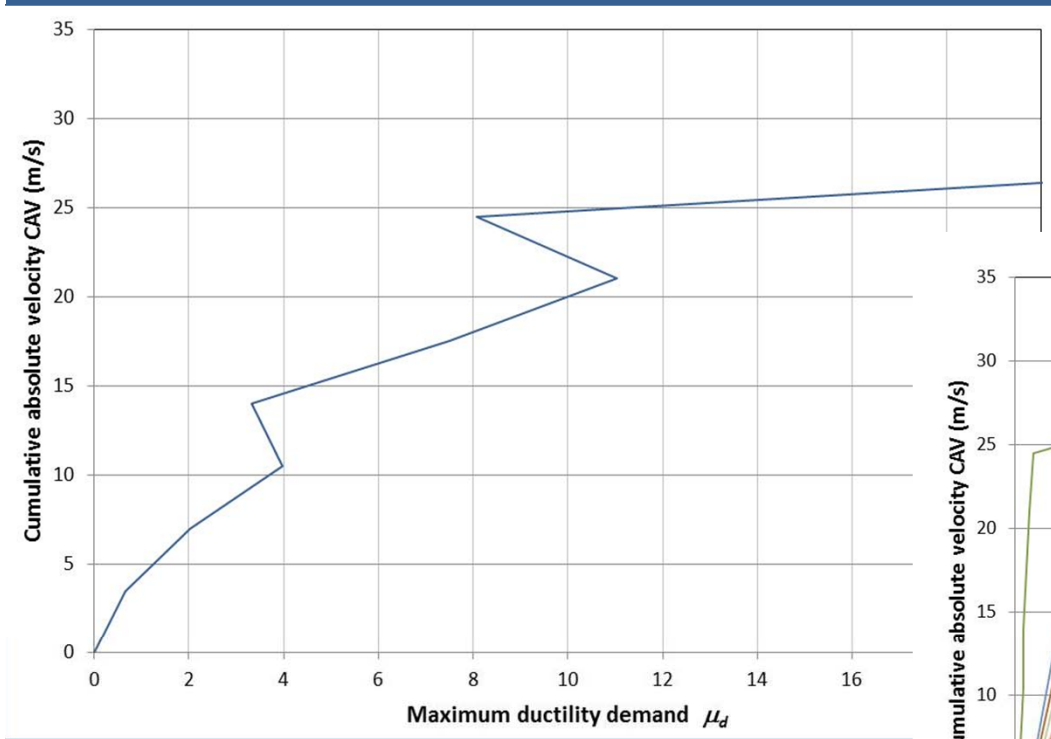
- Series of nonlinear time histories analyses
  - Same time history scaled to increasing amplitudes
  - Track of characteristic quantities of the response

- IDA curve is a plot of selected IM vs selected DM

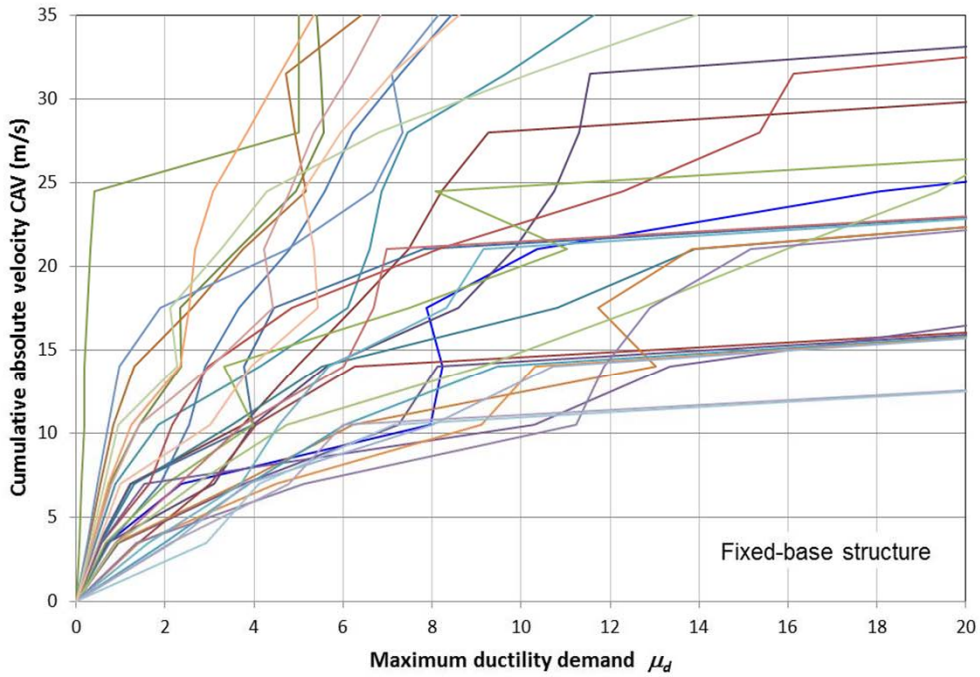
- IDA curve set : collection of IDA curves
  - Several time histories representing one EQ scenario for one selected IM and DM

EXAMPLES OF IDA CURVES

IDA curve



IDA curves set

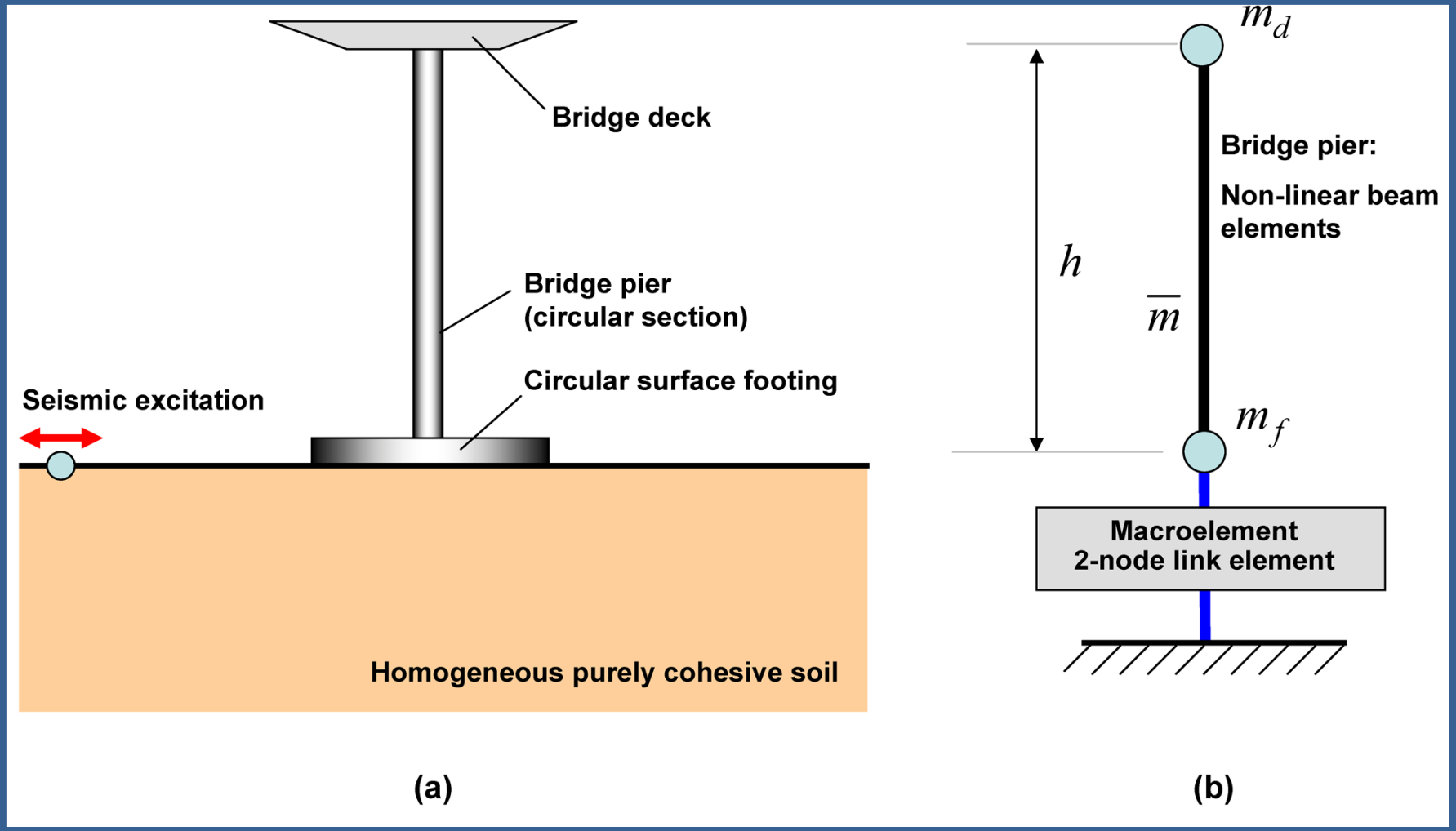


INCREMENTAL DYNAMIC ANALYSES

- Series of non linear time history analyses
  - 30 records representing an earthquake scenario M=6.5-6.9 d=20-30km
  - Time histories scaled up according to Intensity Measures (IM)
    - pga , $SA(T_S)$, $SA(T_{SSI})$, CAV

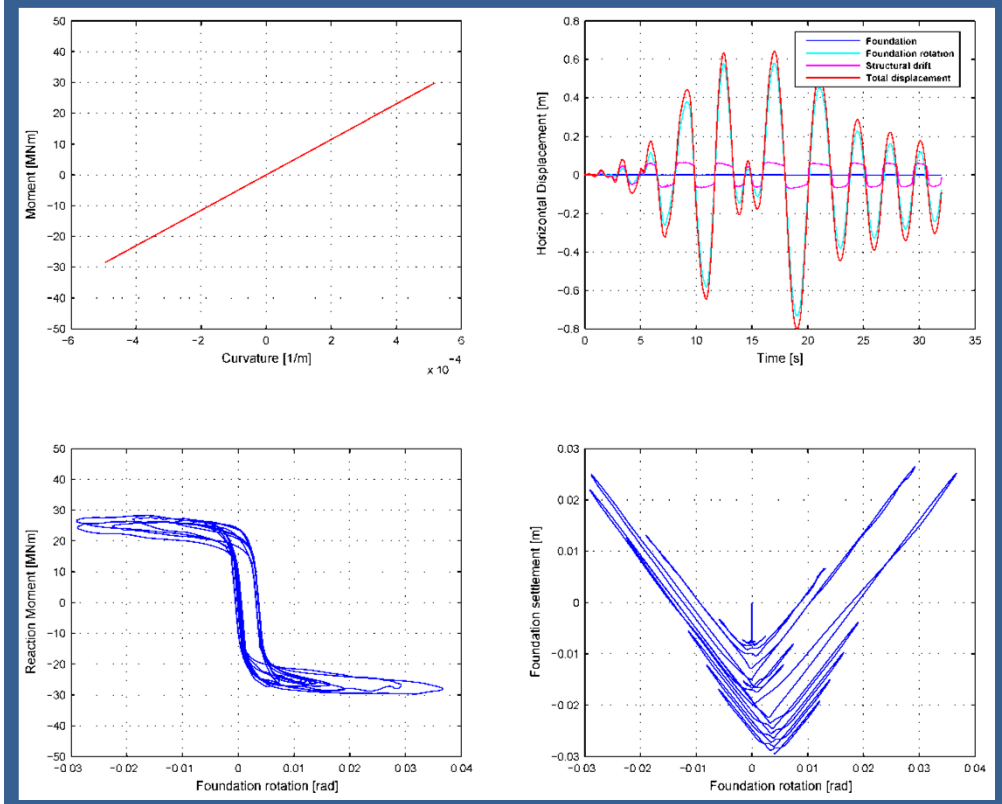
- Damage measures (DM) calculated
  - Foundation settlements (residual or maximum)
  - Foundation rotations (residual or maximum)
  - Deck drift (residual or maximum)
  - Structural ductility demand ……

EXAMPLE : BRIDGE PIER

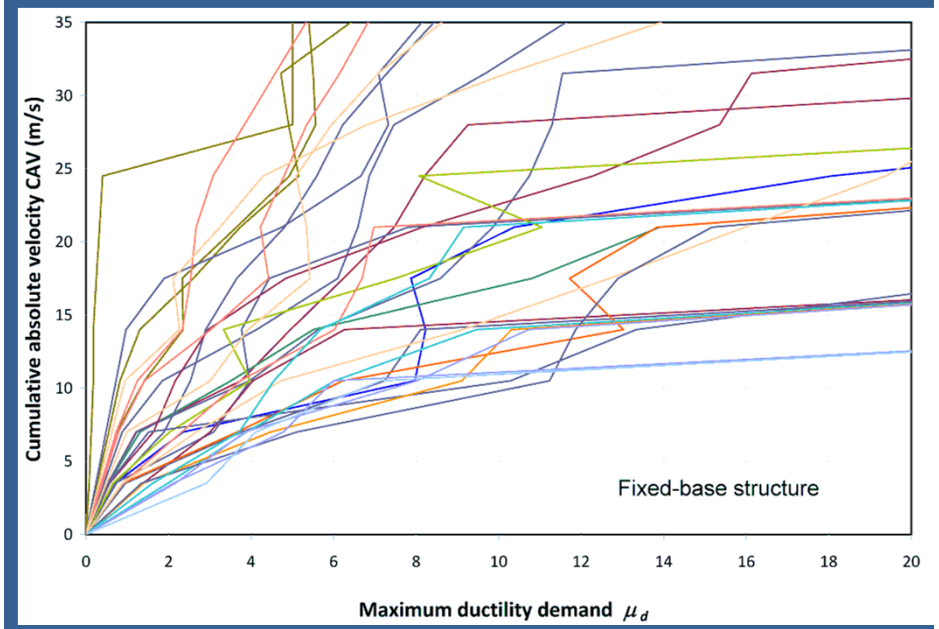


EXAMPLE OF SYSTEM RESPONSE

Single analysis

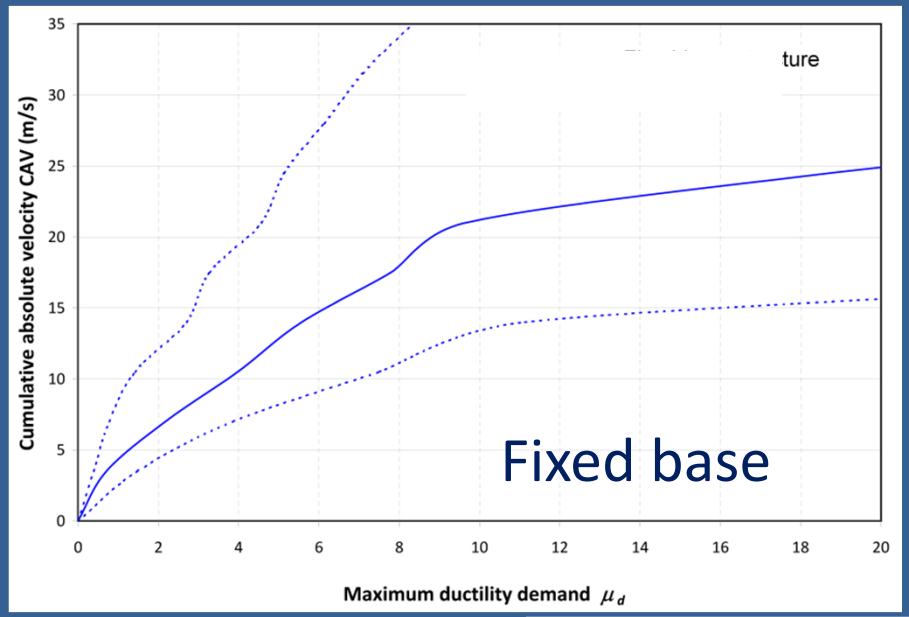


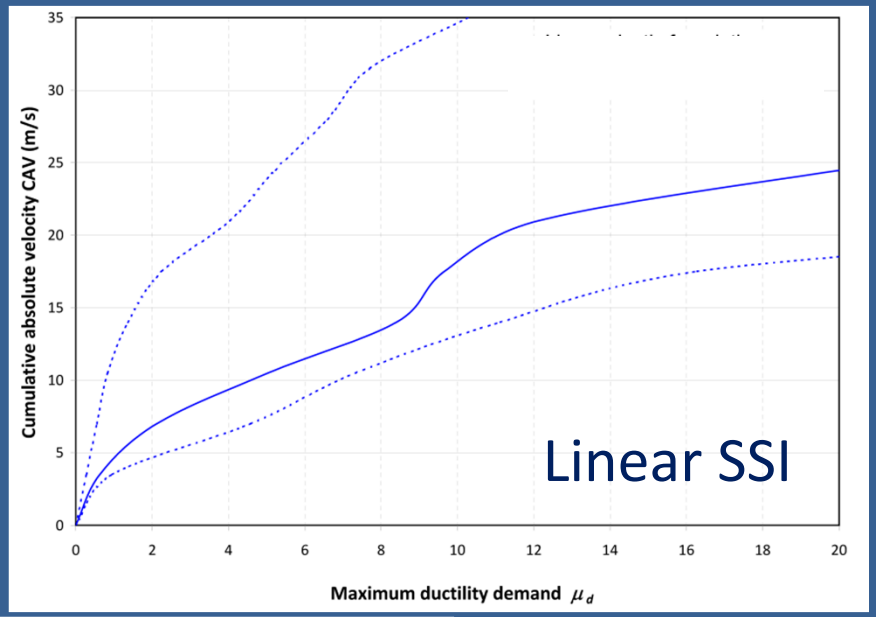
IDA curves μ = f(CAV)



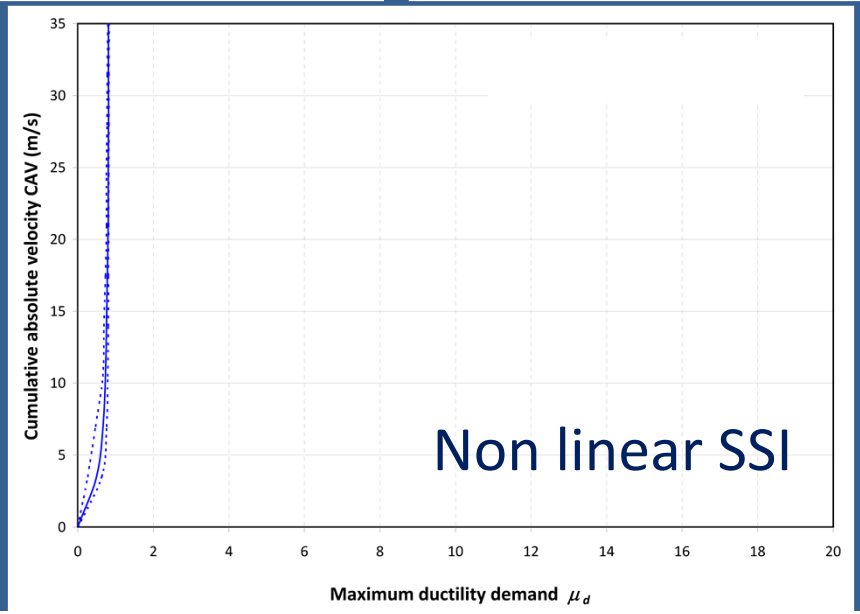
STRUCTURAL DUCTILITY DEMAND $\mu = f(CAV)$

CAV

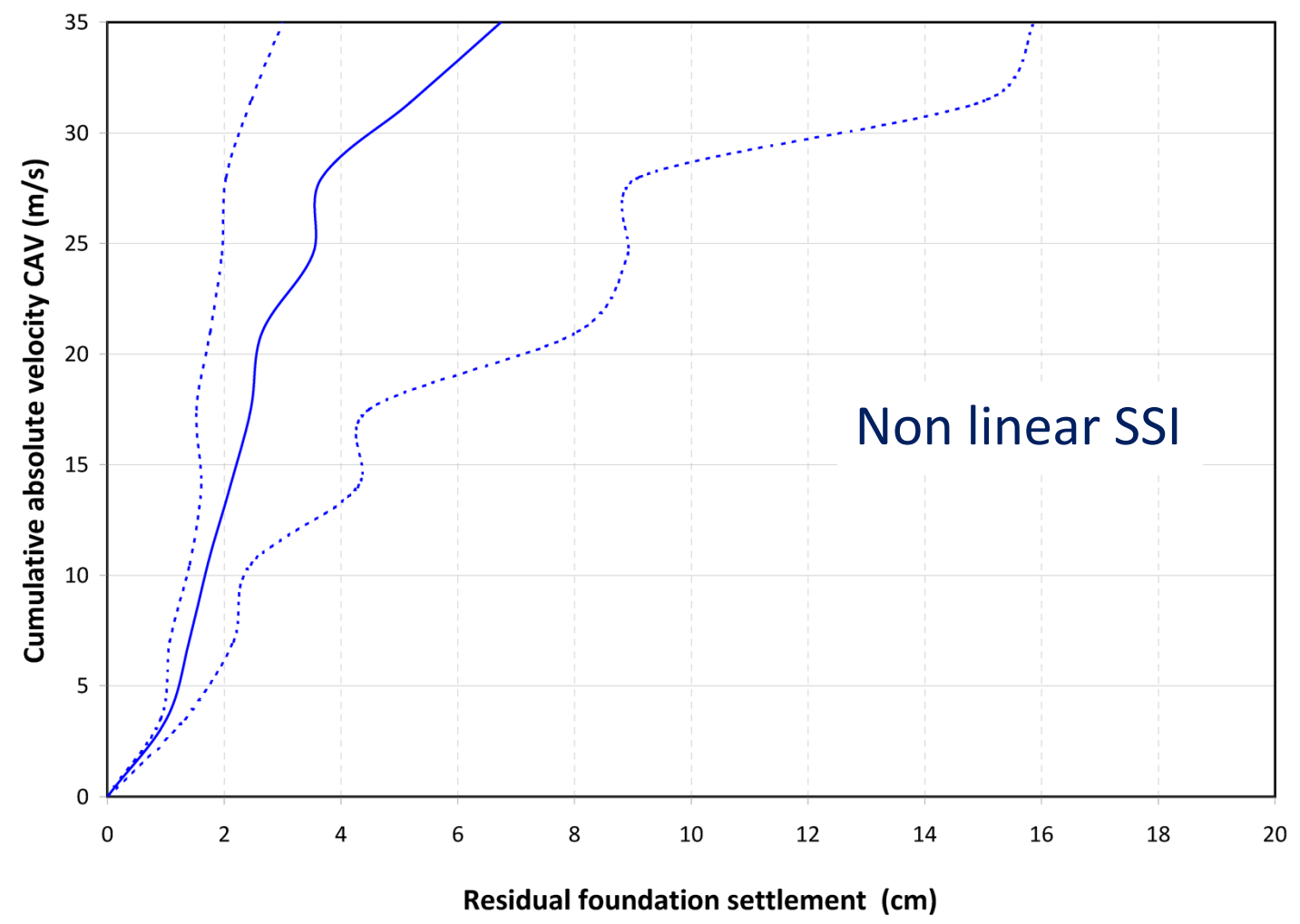




μ



FOUNDATION SETTLEMENTS



Price to pay for change in ductility demand

No sign of distress even for increasing motion

RESULTS OF NUMERICAL ANALYSES

- Consideration of non linear soil structure interaction beneficial
  - drastically reduces the ductility demand in the structure
- Counterbalanced by
  - larger displacements and rotations at the foundation
    - ✓ May become unacceptable
- Variability in the response becomes large as more demand is placed on the foundation

REMAINING ISSUES

- Increased variability
  - ➢ care must be exercised before accepting to transfer the ductility demand from the structure to the foundation
  - ➢ thorough investigation of the variability of the response
- Requires careful definition of acceptable criteria for the foundation performance
- IDA may represent a convenient tool for analysis

CONCLUSION

- It is time to move from the concept of
  - ➢ ductility demand restricted to the superstructure
  - ➢ elastic behavior of foundations

- To
  - ➢ controlled share of ductility demand between the superstructure and the foundation