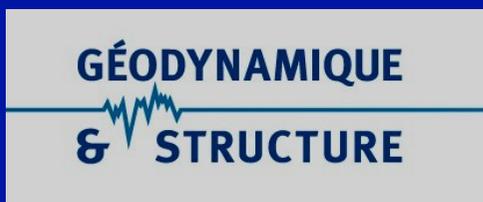


INTERACTION SOL STRUCTURE NON LINEAIRE

Une nécessité pour le dimensionnement des
fondations

Alain PECKER , Charisis CHATZIGOGOS , Jean SALENÇON

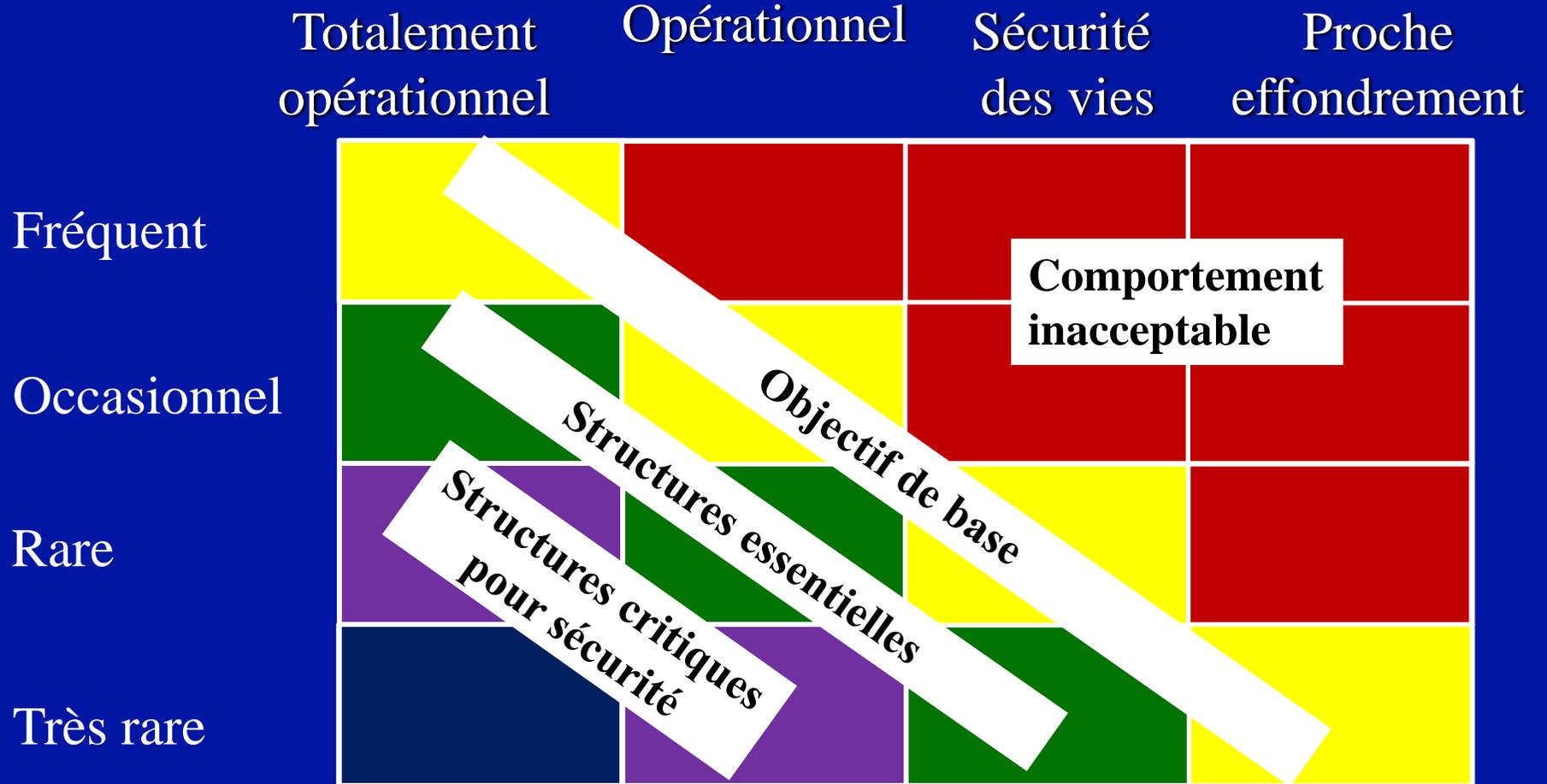


CONCEPTION PARASISMIQUE DES FONDATIONS

- Environnement géologique et géotechnique
-  Objectif de performance de l'ouvrage
- Evaluation de la demande sismique
- Résistance sismique
 - ⇒ Charge, déformation, coefficient de sécurité
- Méthodes de construction & contraintes
- Evaluation des risques potentiels

CRITERE DE PERFORMANCE SISMIQUE

SEISME DE
DIMENSIONNEMENT



APPLICATION EN GEOTECHNIQUE

- Structures sont fondées sur sols
 - ⇒ Matériau fortement non linéaire de résistance limitée
- Interaction sol structure joue un rôle fondamental dans la réponse sismique de la structure
 - ⇒ Déplacements générés au niveau de la fondation
 - “The seismically induced ground deformation [...shall be] compatible with the essential functional requirements of the structure” (Eurocode 8 – Part 5)



MOSS LANDING (Loma Prieta, 1989)



MEXICO
(Michoacan, 1985)



FOTOLINICA
FOTO MEDICA
TRANSPARENCIAS P... FERENCIAS
ARTICULOS FOTOGRAFICOS...
FOTOSTATICOS LE...
...
...

TO REY

MINOLTA XD-5

59

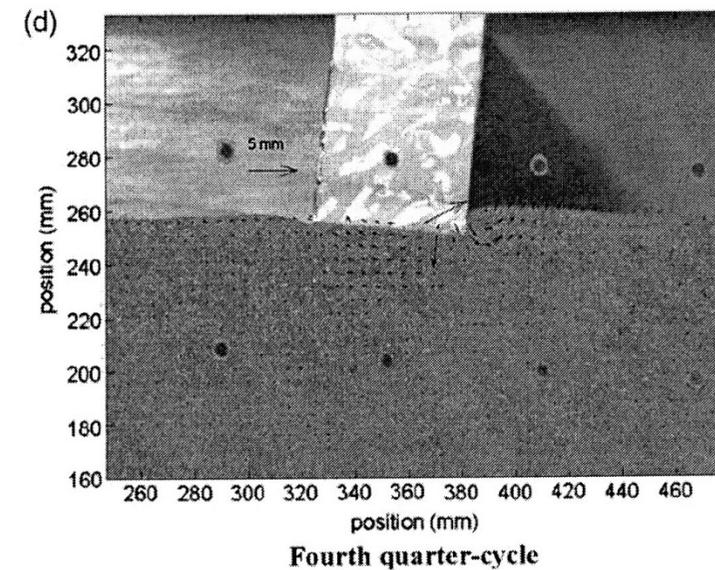
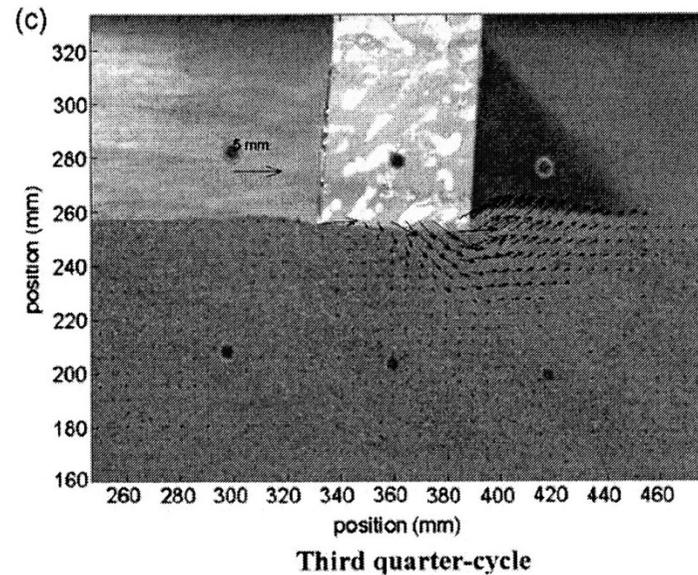
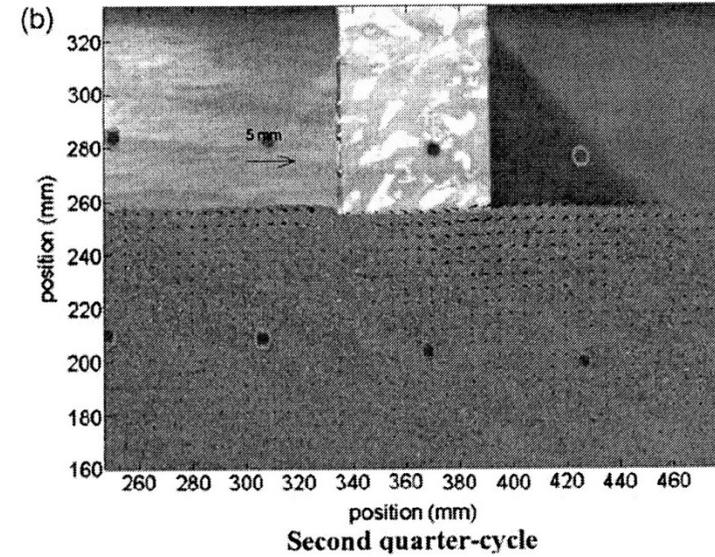
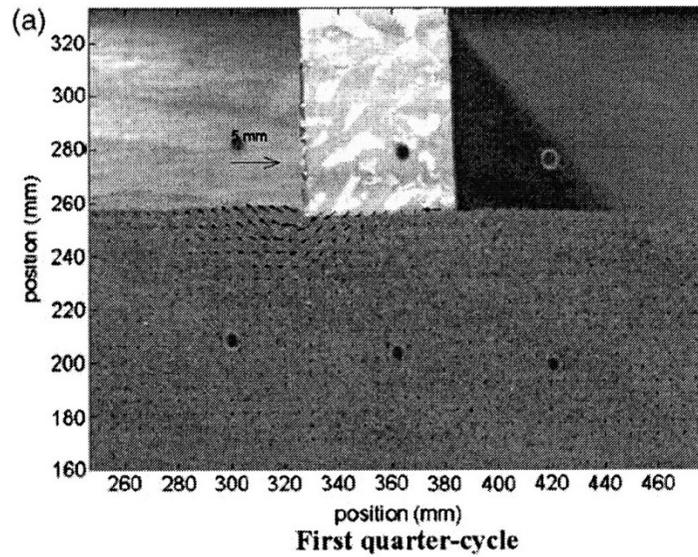
HORARIO
LUNES A VIERNES
1000 A
1800 A

MOTIVATION POUR ANALYSE EN DEPLACEMENT

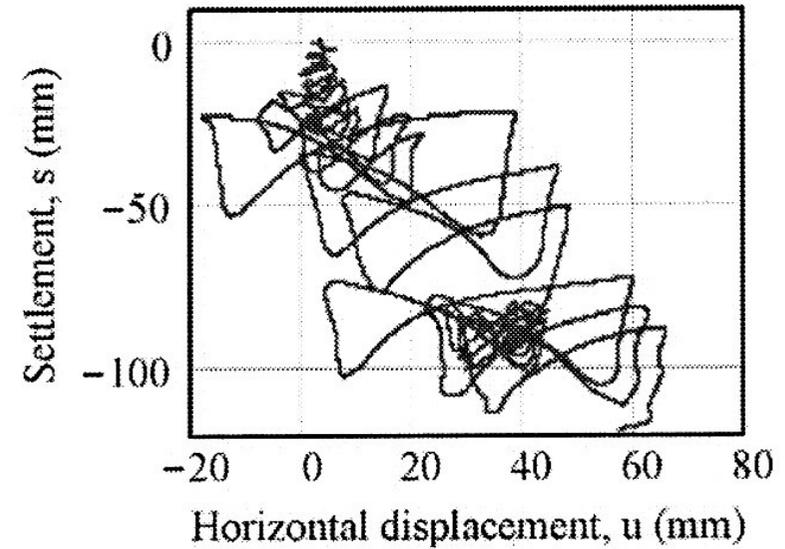
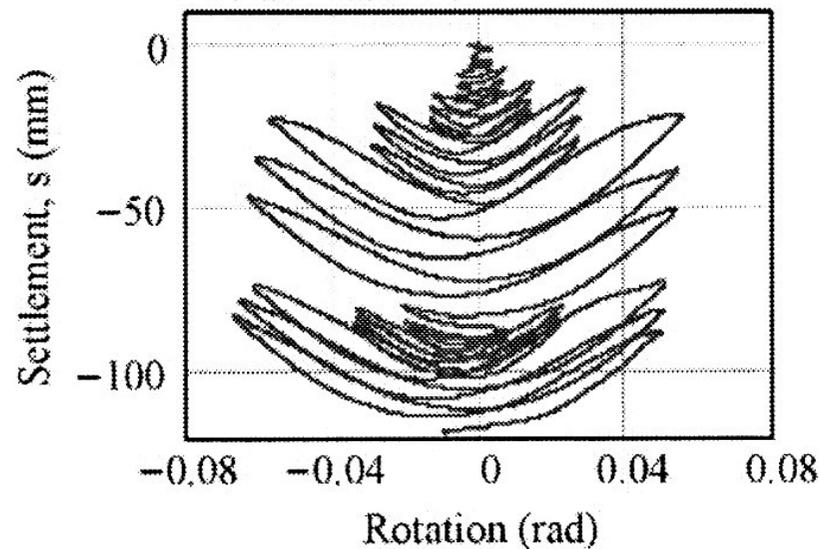
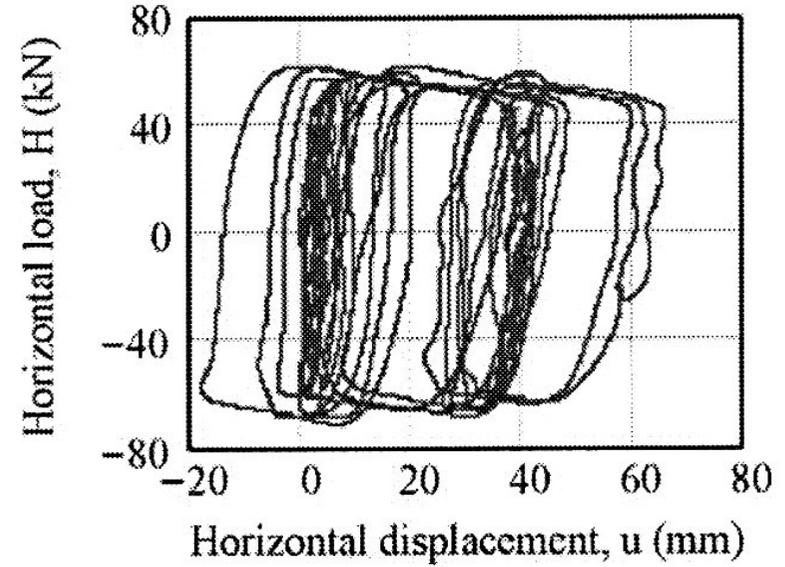
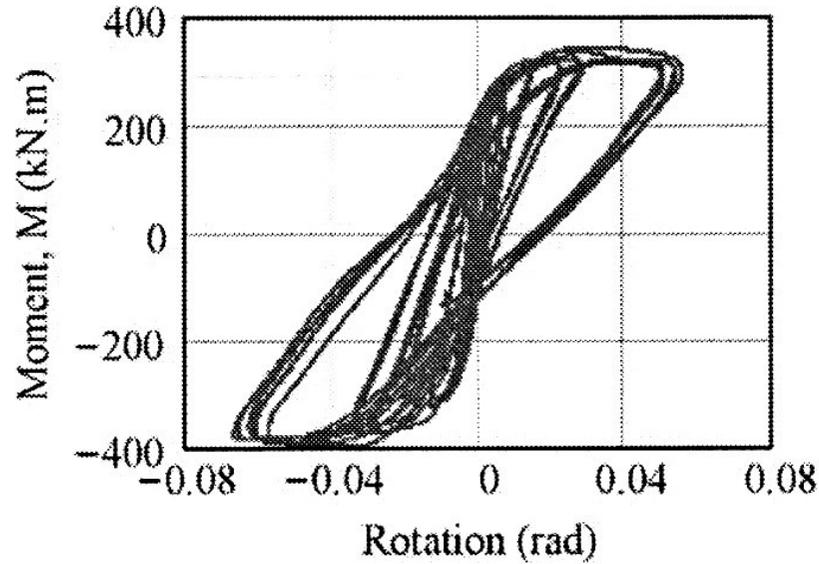
- Déplacements de la fondation affectent le comportement de la structure
- Charges sismiques varient dans le temps et $S_d > R_d$ n'implique pas rupture mais apparition de déplacements permanents (Newmark, 1958)
- Nécessité de mettre en oeuvre ces concepts en ingénierie des fondations
 - “Non linear soil behaviour should be taken into account in determining possible permanent deformations” (Eurocode 8 – Part 5)

ESSAIS SUR TABLE VIBRANTE

(Knappett et al., 2006)



Modélisation en centrifugeuse du comportement d'une fondation superficielle [Gajan et al (2005)]

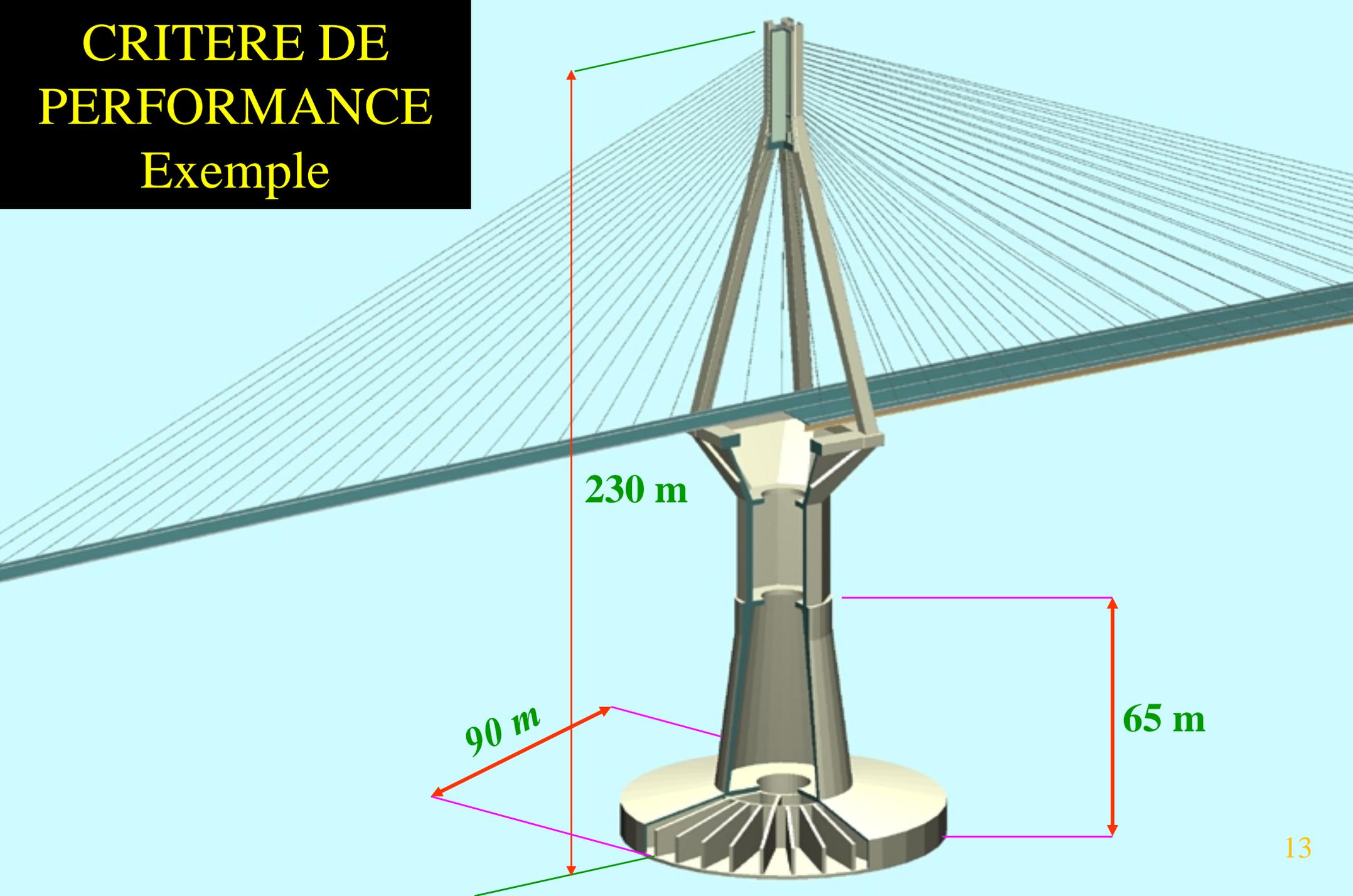


REQUIS FOR PBD

- Nécessité de préciser l'objectif de performance de l'ouvrage
- Développement des outils appropriés
 - ⇒ Analyse de type Newmark : pratique courante
(*analyse découplée*)
 - ⇒ Macro élément dynamique : stade de recherche
(*analyse totalement couplée*)
 - ⇒ Mise en œuvre dans les codes de construction : obligation

CRITERE DE PERFORMANCE

Exemple



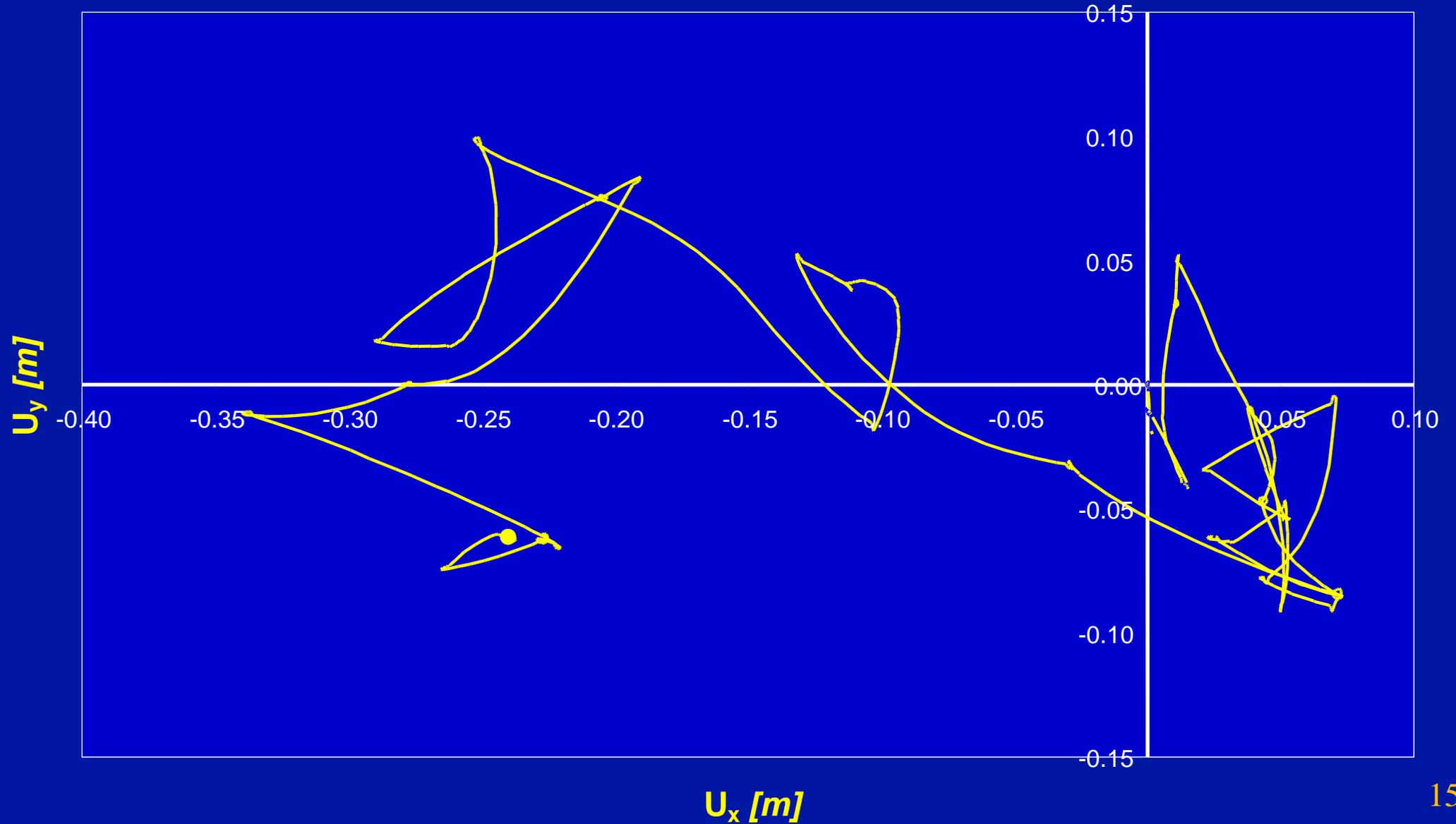
CRITERE DE PERFORMANCE

Critère de performance (période de retour : 2000 ans)

⇒ Dommages sont acceptables mais le pont doit être réparable et réutilisable

- **Déplacement horizontal acceptable**
- **Rotation prohibée (<0.1 %)**

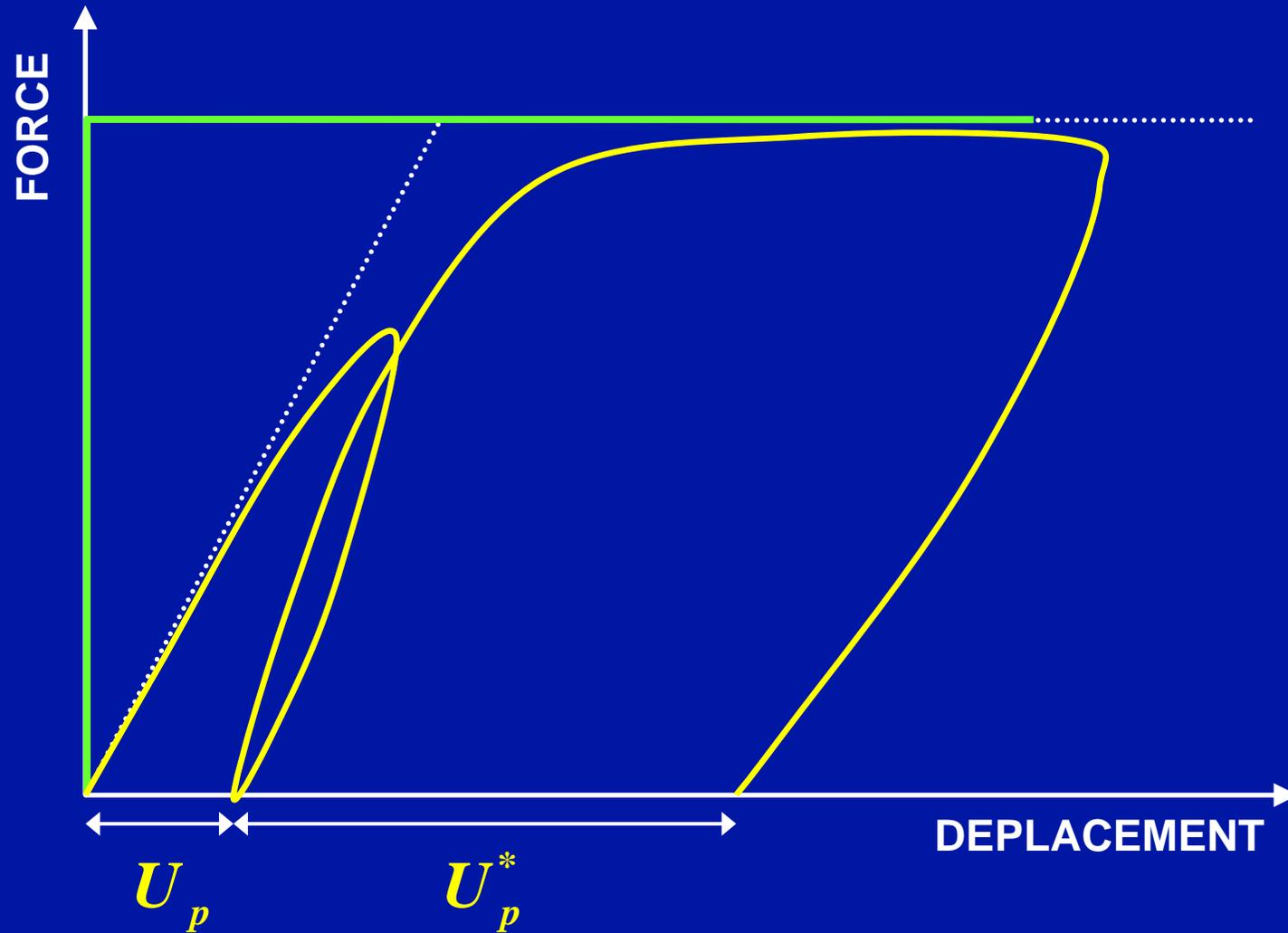
DEPLACEMENT D'UNE FONDATION PENDANT SEISME



EVALUATION DES DEPLACEMENTS PERMANENTS

Approche de Newmark
“Sliding block analysis”

DEPLACEMENTS PERMANENTS



EVALUATION DES DEPLACEMENTS

Analyse de Newmark

- Système suit un comportement élastique parfaitement plastique
- La frontière des charges extrêmes \Leftrightarrow apparition des déformations plastiques
- Les mécanismes cinématiques **Virtuels** \Leftrightarrow mécanisme de rupture **réel**
- Comportement plastique satisfait la règle de normalité

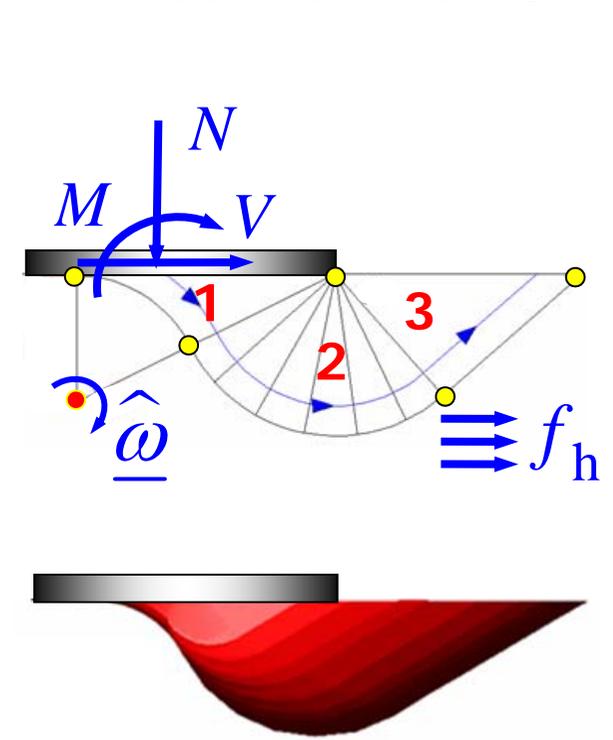
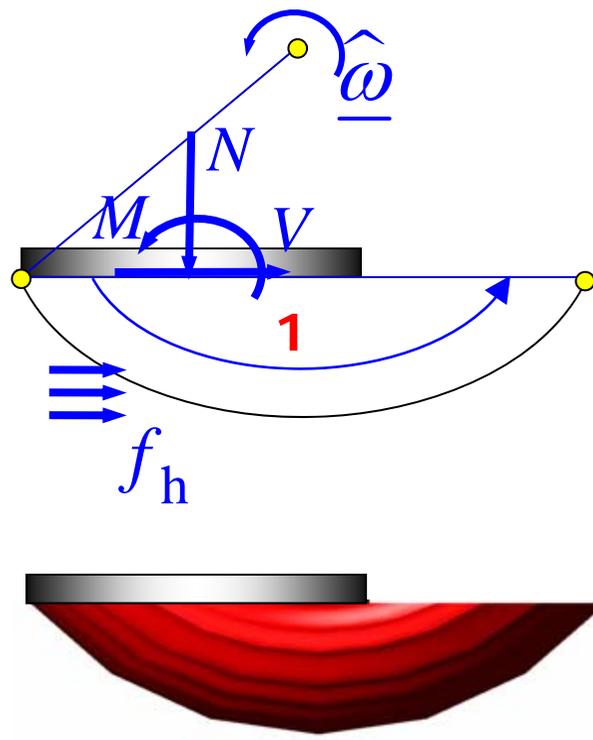
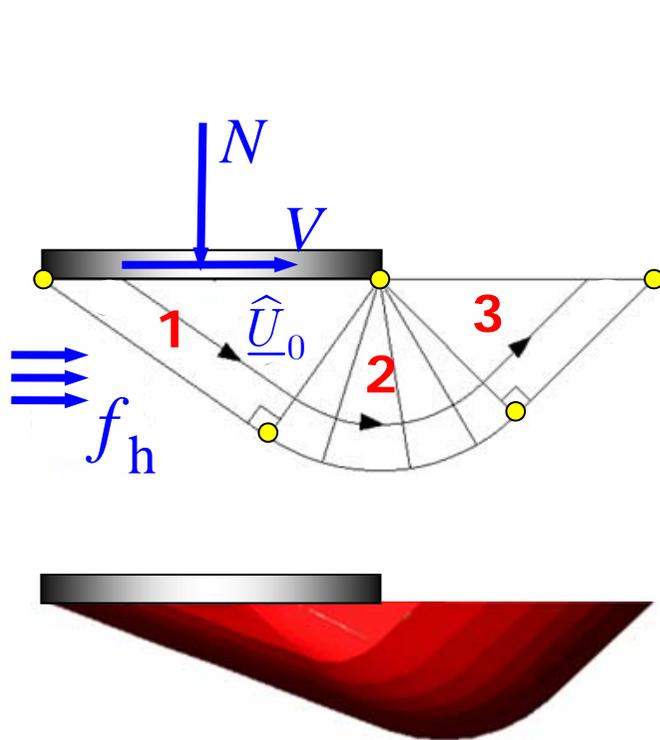
MECANISMES CINEMATIQUE VIRTUELS

Fondation Circulaire (Chatzigogos *et al*, 2007)

Mécanisme translation

Mécanisme rotation

Mécanisme rotation avec cisaillement



2 geometric parameters

2 geometric parameters

3 geometric parameters

THEOREME ENERGIE CINETIQUE

Mécanisme virtuel $\hat{\underline{U}}$ = Mécanisme réel \underline{U}

$$\mathcal{P}_E(\underline{U}) + \mathcal{P}_I(\underline{U}) = \frac{dK(\underline{U})}{dt}$$

$$F(T_0) = \tilde{F} \quad U(T_1) = \mathbf{0}$$

$$D(t) = \int_0^t U(\tau) d\tau$$

ECOLE 159
Mexico (1985)



EXEMPLE : ECOLE 159 (Mexico, 1985)

(Pecker *et al*, 1996)

- Cohésion

- ⇒ Statique $C = 20$ kPa

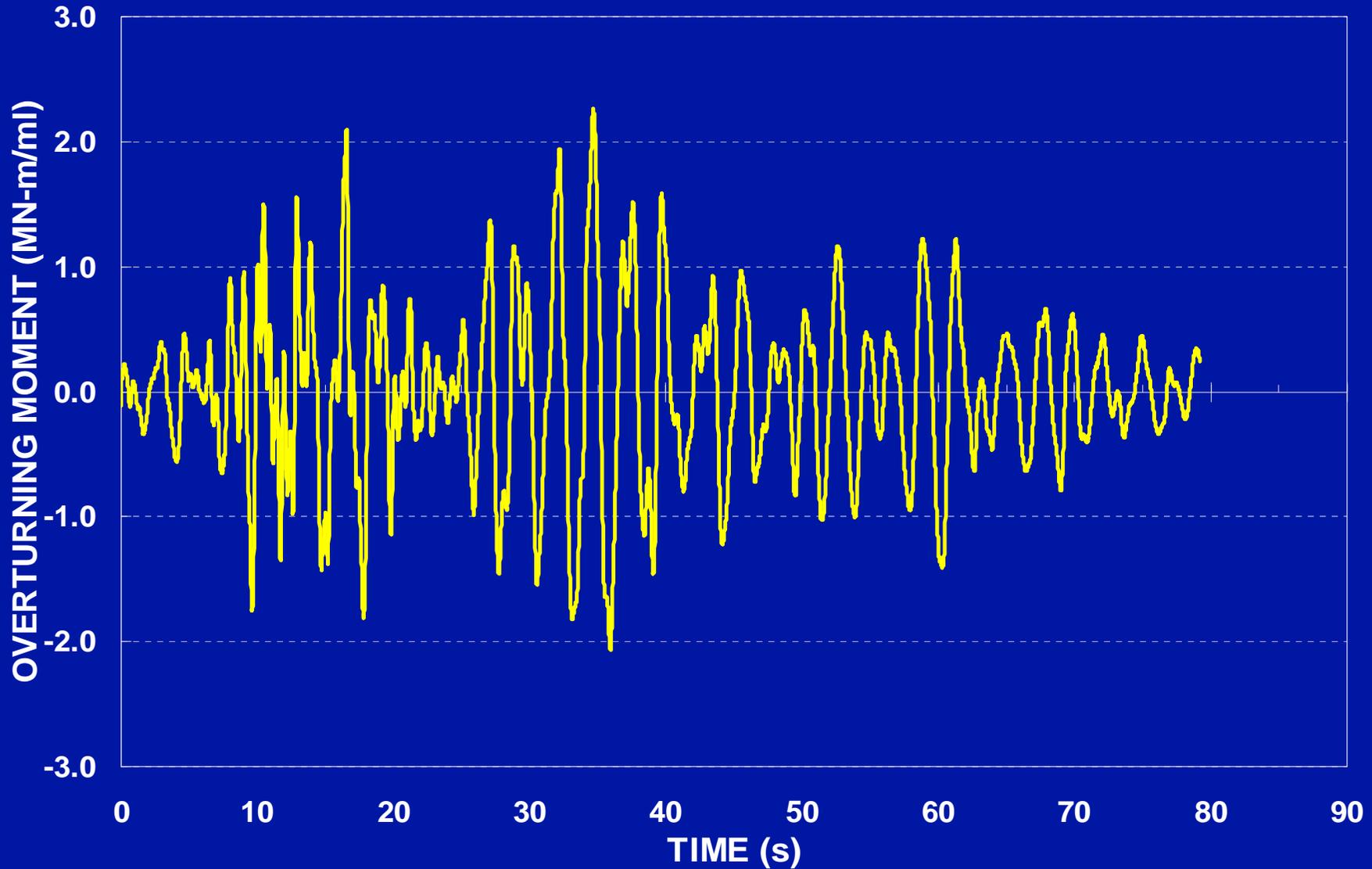
- ⇒ Dynamique $C = 22.5$ to 27.5 kPa

- Déplacements observés

- ⇒ Tassement $W = 0.35$ to 0.50 m

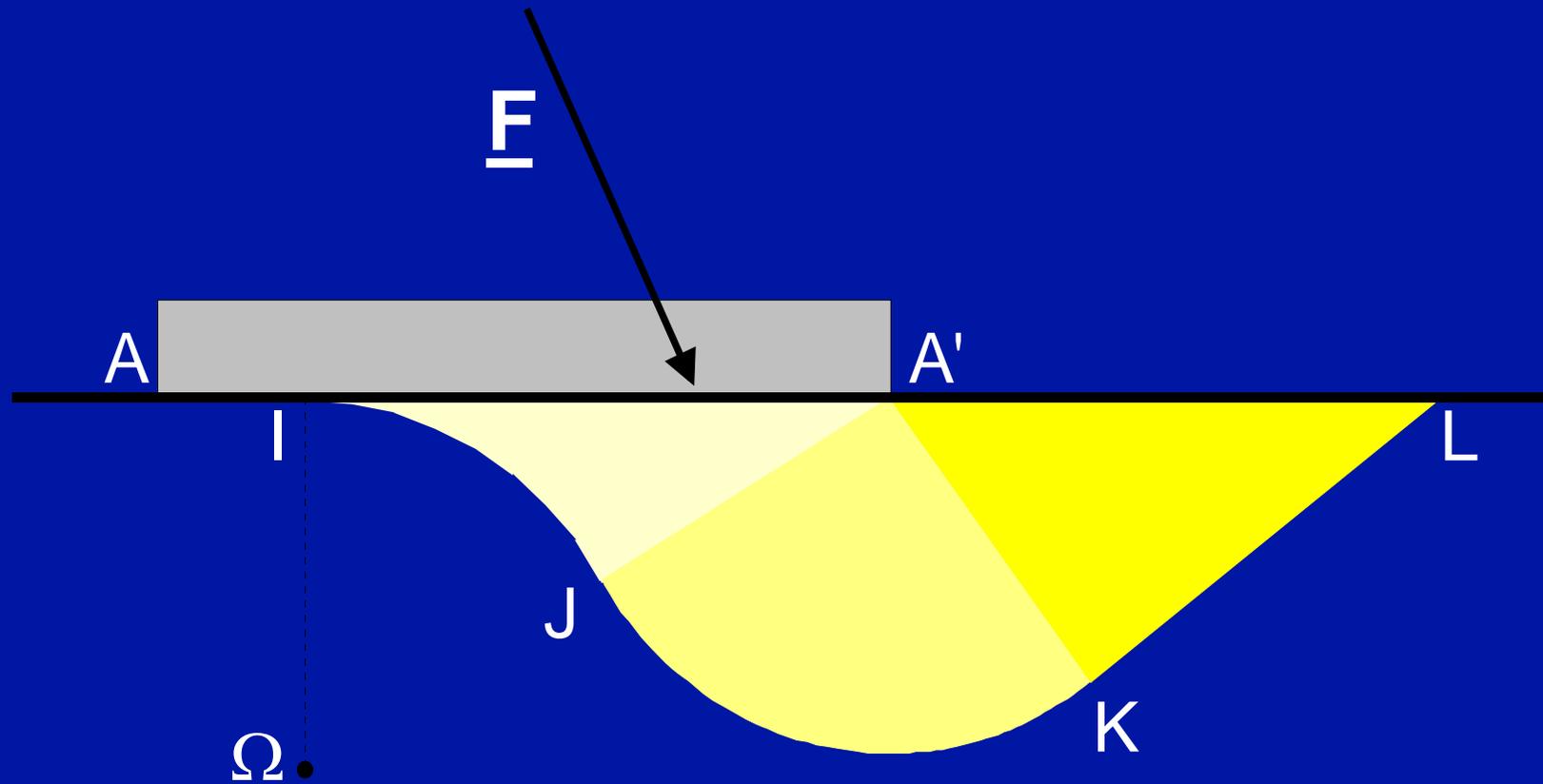
- ⇒ Rotation $R = 3.5$ to 4.5 %

MOMENT SUR FONDATION

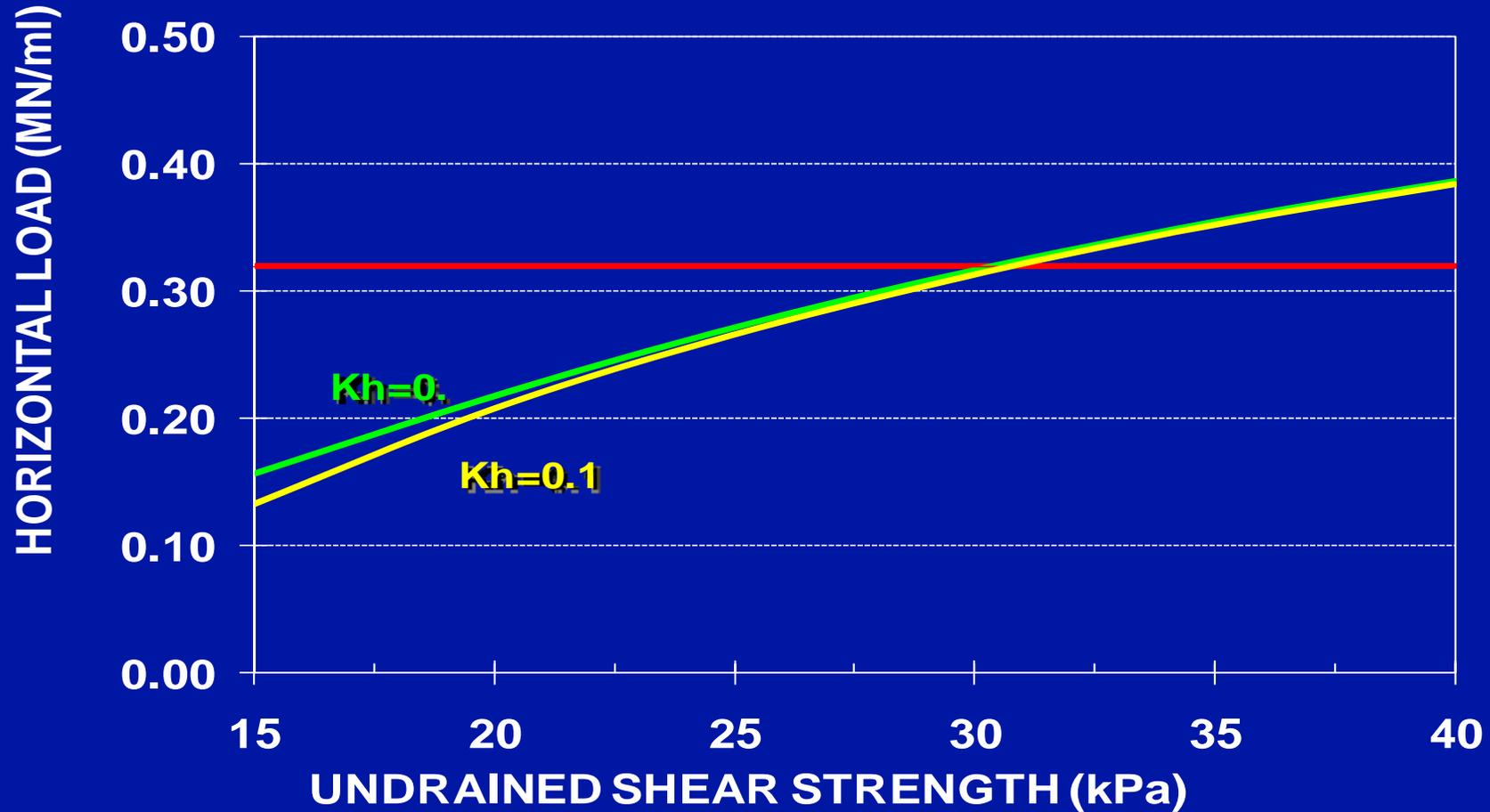


MECANISME CINEMATIQUE VIRTUEL

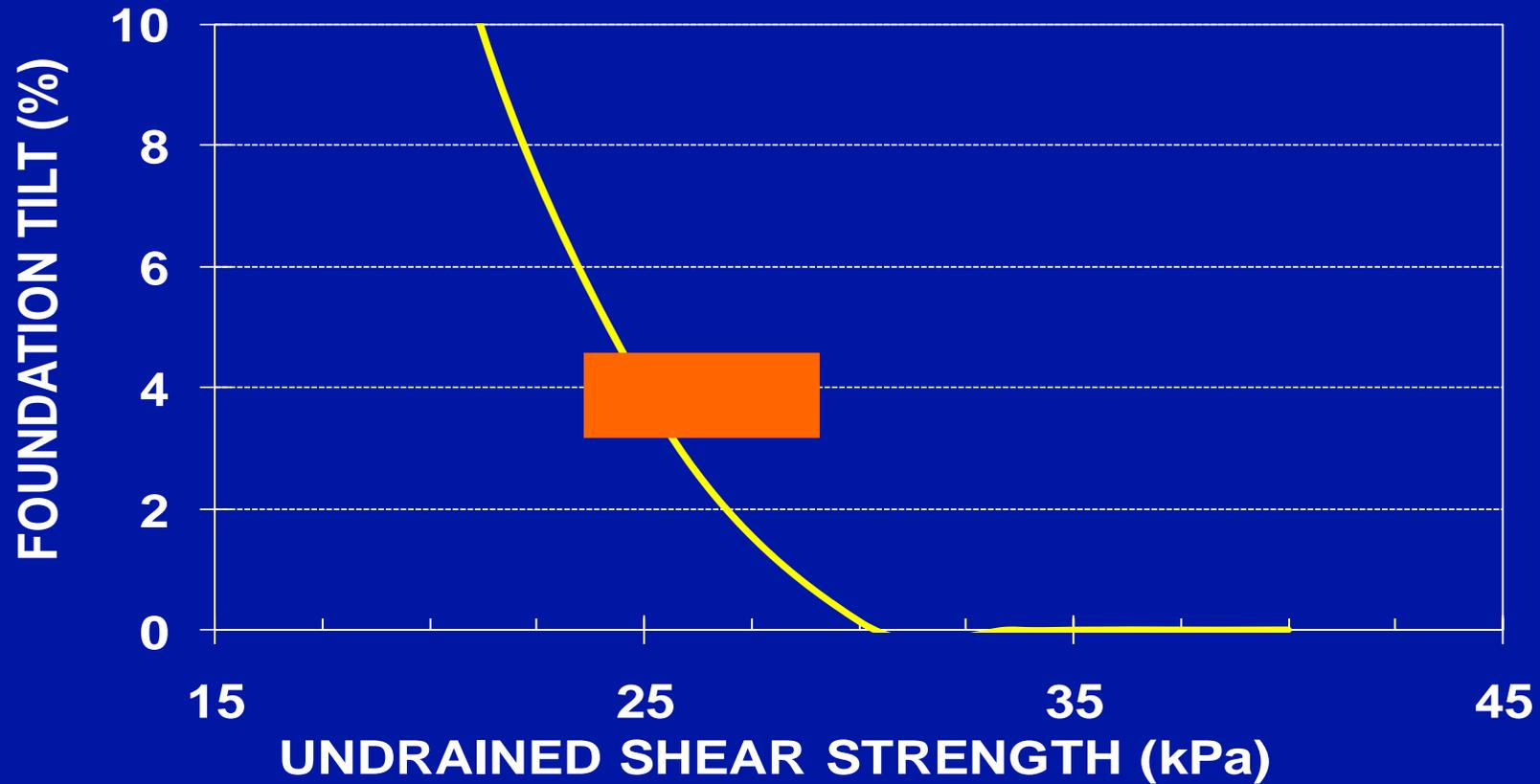
Fondation filante



CAPACITE PORTANTE



ROTATION DE LA FONDATION



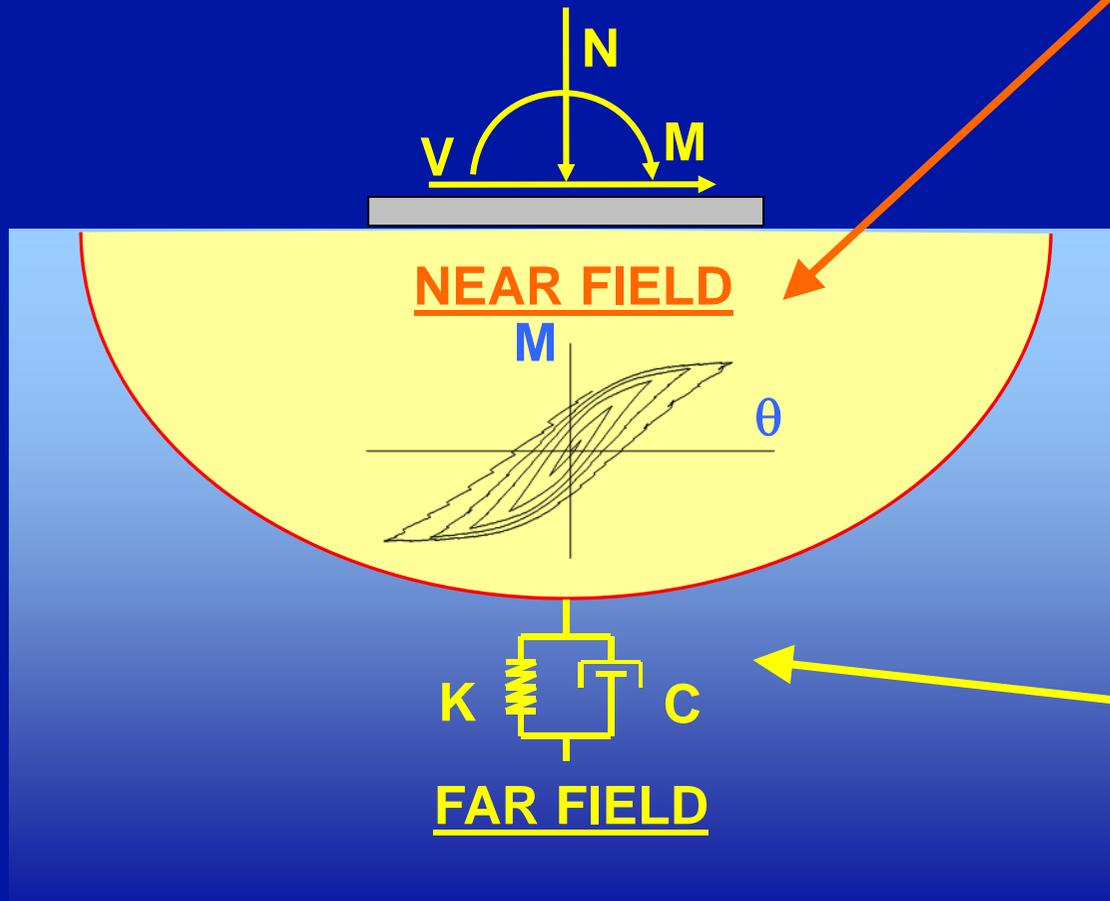
LIMITATIONS

- Seuls déplacements “postrupture” sont estimés
 - ⇒ Déplacements permanents avant rupture peuvent être significatifs pour des séismes fréquents (plus faibles)
- Forces ne sont pas affectées par la rupture
- Le mécanisme de rupture demeure inchangé pendant le séisme



Nécessité d’une approche plus rigoureuse

MACRO ELEMENT DYNAMIQUE



Nonlinearités :

- Géométriques (interface)
→ modèle de décollement
- Matériau (élasto-plastique)
→ modèle de plasticité

Propagation ondes:

- Dissipation par radiation énergie

Impédances dynamiques
élastiques

MACRO ELEMENT DYNAMIQUE

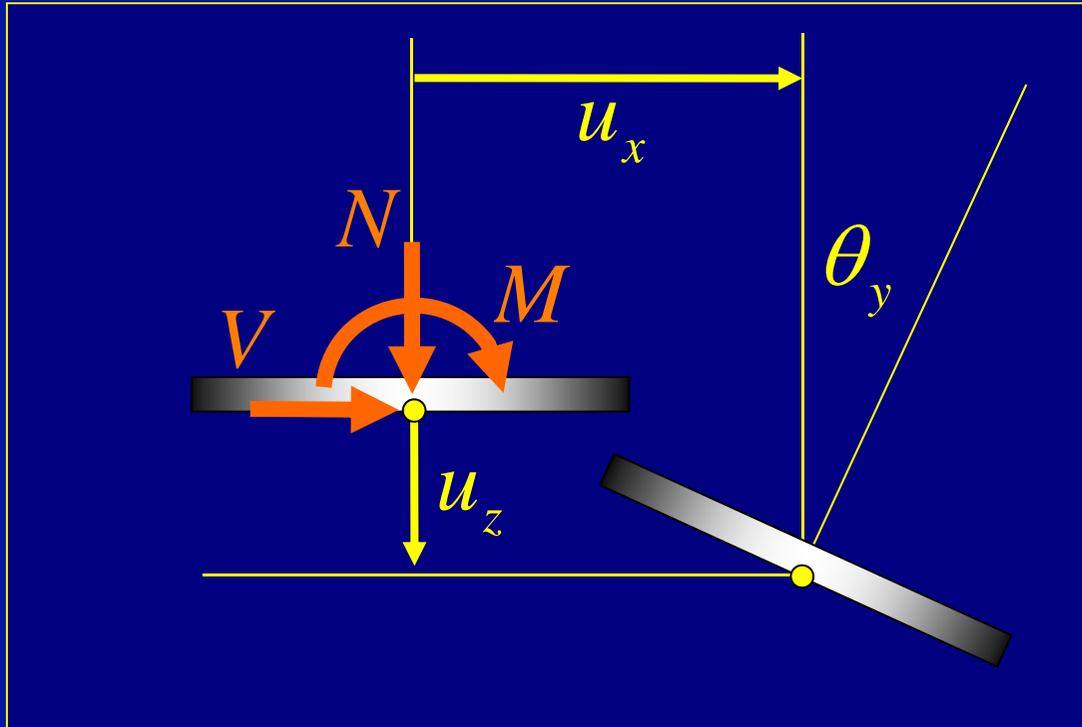


Outil pour Analyse Non Linéaire d'Interaction Sol Structure

Reference	Year	Configuration	Description
 Nova & Montrasio	1991	Strip footing resting on a purely frictional soil	Isotropic hardening plasticity model and non-associated flow rule. Application in the case of quasistatic monotonic loading.
 Paolucci	1997	Strip footing resting on a purely frictional soil	Perfect plasticity model with non-associated flow rule. Application to simple structures subject to seismic loading. Parametric studies.
 Pedretti	1998	Strip footing resting on a purely frictional soil	Hypoplastic model for the description of the system response under cyclic loading. Consideration of uplift by reduction of the elastic stiffness. Applications to structures subject to quasistatic cyclic loading.
 Gottardi <i>et al.</i>	1999	Strip footing resting on a purely frictional soil	Isotropic hardening plasticity model. Detailed description of the system ultimate surface (identified as the yield surface of the plasticity model) via “swipe tests”. Application in the case of quasistatic monotonic loading.
 Le Pape <i>et al.</i> Le Pape & Sieffert	1999 2001	Strip footing resting on a purely frictional soil	Elastoplastic model derived from thermodynamical principles. Rugby ball shaped yield surface and ellipsoidal plastic potential. Application to seismic loading.
 Crémer <i>et al.</i>	2001, 2002	Strip footing resting on a purely cohesive soil without resistance to tension	Non-associated plasticity model with isotropic and kinematic hardening coupled with a model for uplift. Application to seismic loading.
 Martin & Houlsby	2001	Circular footing resting on a purely cohesive soil	Non-associated plasticity model with isotropic hardening. Detailed description of the yield surface via “swipe tests”. Application to quasistatic monotonic loading.
 Houlsby & Calssidy	2002	Circular footing resting on a purely frictional soil	Non-associated plasticity model with isotropic hardening. Detailed description of the yield surface via “swipe tests”. Application to quasistatic monotonic loading.
 Di Prisco <i>et al.</i>	2003	Strip footing resting on a purely frictional soil	Hypoplastic model for the description of the behavior under cyclic loading. Application to quasistatic cyclic loading.
 Cassidy <i>et al.</i>	2004	Circular footing resting on a frictional or cohesive soil	Fully three-dimensional formulation. Application to the off-shore industry. Quasistatic monotonic loading.
 Houlsby <i>et al.</i>	2005	Strip or circular footing resting on cohesive soil. Frictional soil-footing interface	Decoupled Winkler springs with elastic perfectly plastic contact-breaking law derived from thermodynamical principles. Application to quasistatic cyclic loading.
 Einav & Cassidy	2005	Strip footing resting on cohesive soil. Frictional soil-footing interface	Decoupled Winkler springs with elastoplastic contact-breaking law with hardening derived from thermodynamical principles. Application to quasistatic cyclic loading.
 Grange <i>et al.</i>	2006	Circular footing on cohesive soil	Extension of the plasticity model of Crémer to purely three-dimensional setting. No separate uplift model included.

FORCES & DEPLACEMENTS GENERALISES

Fondation circulaire rigide sous chargement plan

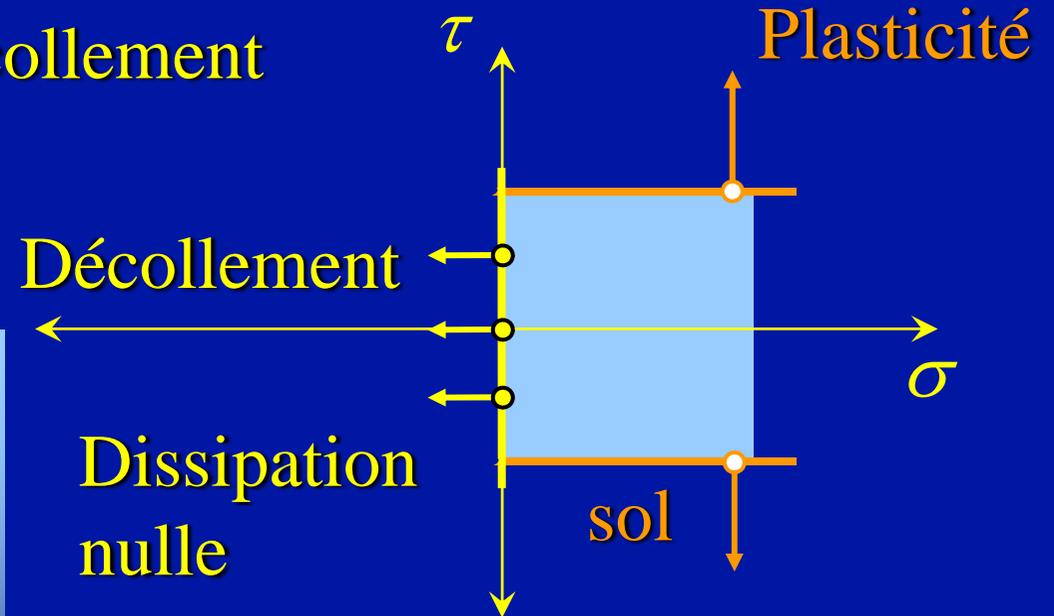
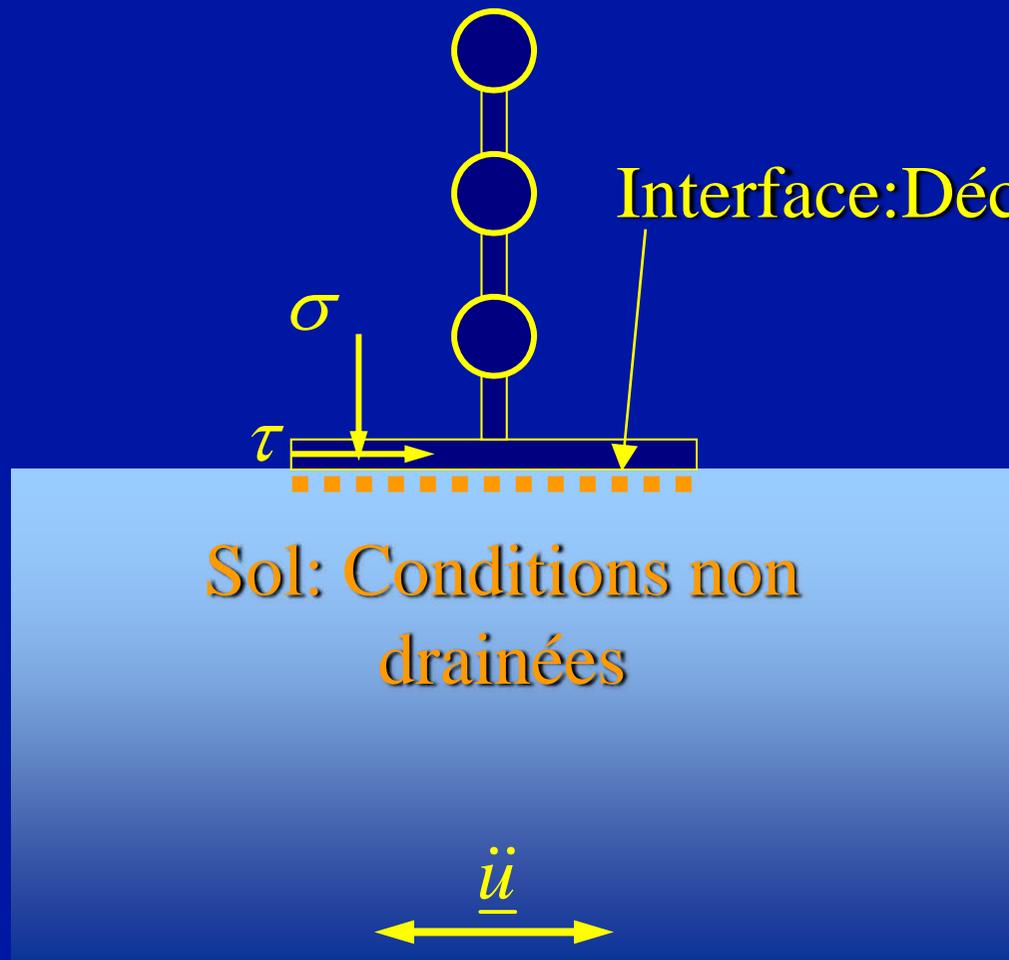


$$\underline{Q} = \begin{bmatrix} Q_N \\ Q_V \\ Q_M \end{bmatrix} = \frac{1}{DN_{\max}} \begin{bmatrix} DN \\ DV \\ M \end{bmatrix}$$

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

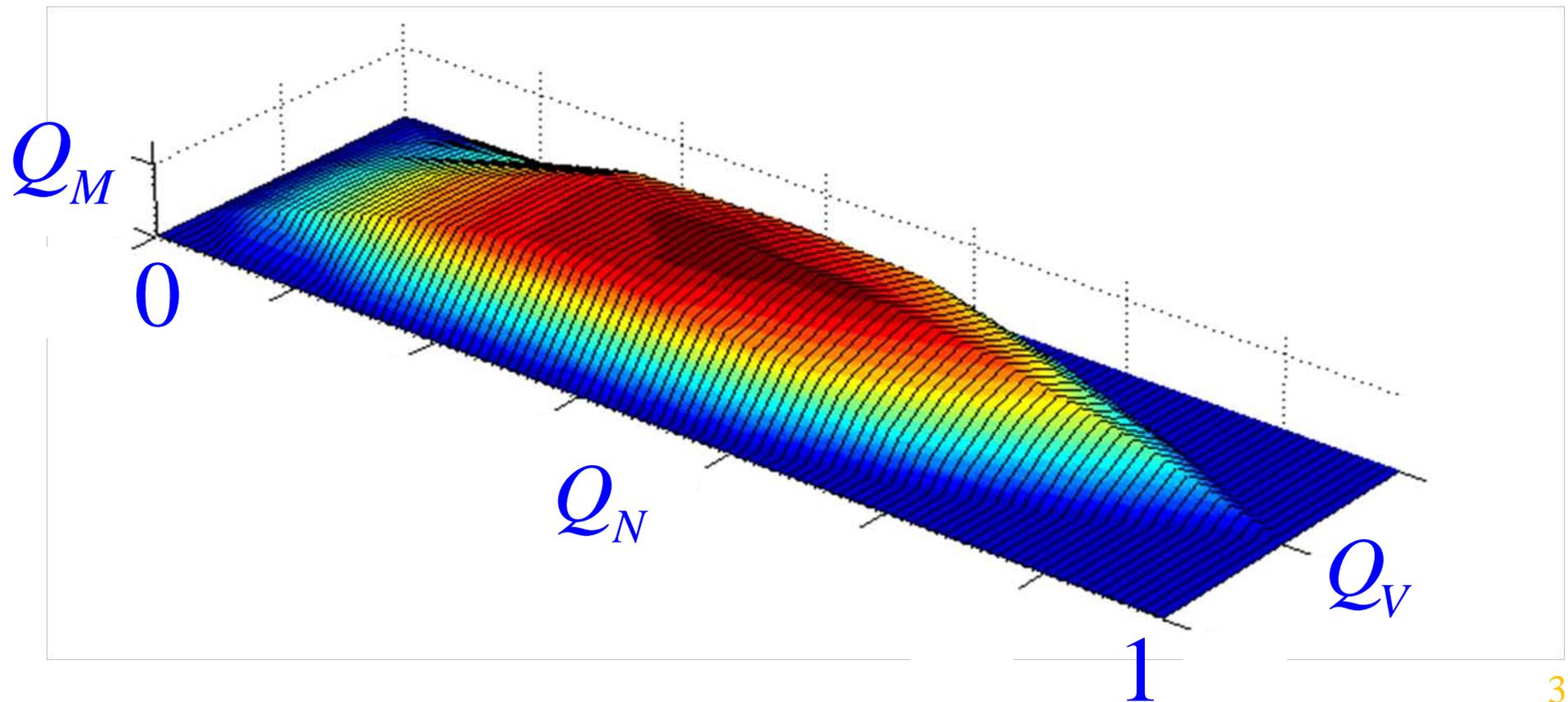
$$\underline{\dot{Q}} \longleftrightarrow ? \longleftrightarrow \underline{\dot{q}}$$

FORMULATION DU MACROELEMENT



SURFACE des CHARGES EXTREMES

(Chatzigogos *et al*, 2007)

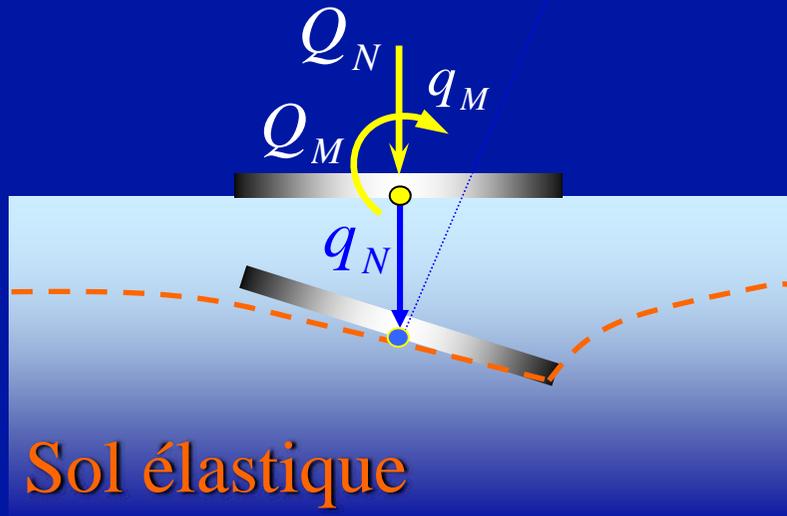


PRINCIPES DU MODELE

MECANISME	DISSIPATION	REVERSIBILITE	NON-LINEARITE	MACROELEMENT
Plasticité	Dissipatif	Irréversible	Matériau	Modèle de Plasticité associée
Décollement	Non – dissipatif	Réversible	Géométrique	Modèle élastique non linéaire

1. Chaque mécanisme modélisé indépendamment
2. Surface des charges extrêmes → obtenue par le couplage des deux mécanismes
3. Surface de charge \neq Surface des charges extrêmes

DECOLLEMENT SUR SOL ELASTIQUE



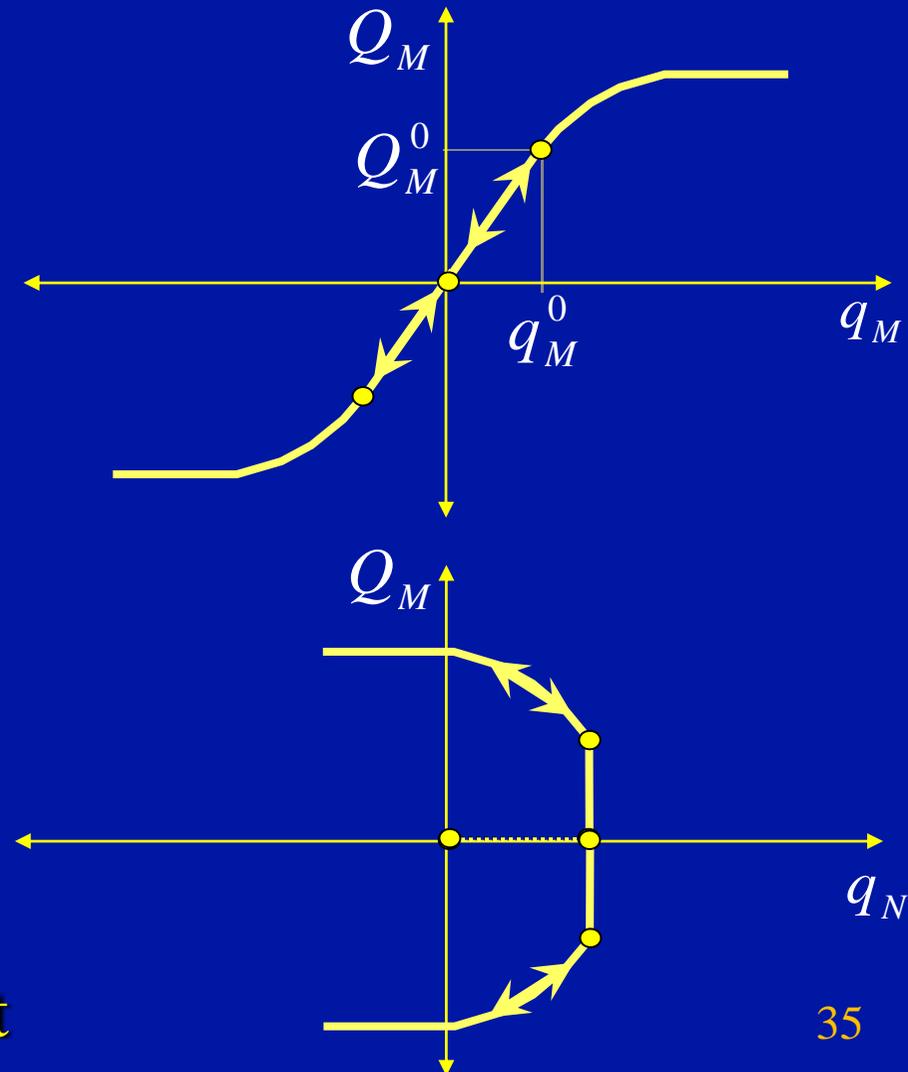
Modèle phénoménologique
non-linéaire élastique

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

1. Matrice $\underline{\underline{K}}$ dépend explicitement \underline{q}
2. Pas influence de Q_V sur décollement

[Crémer et al (2001)]

[Wolf (1985)]

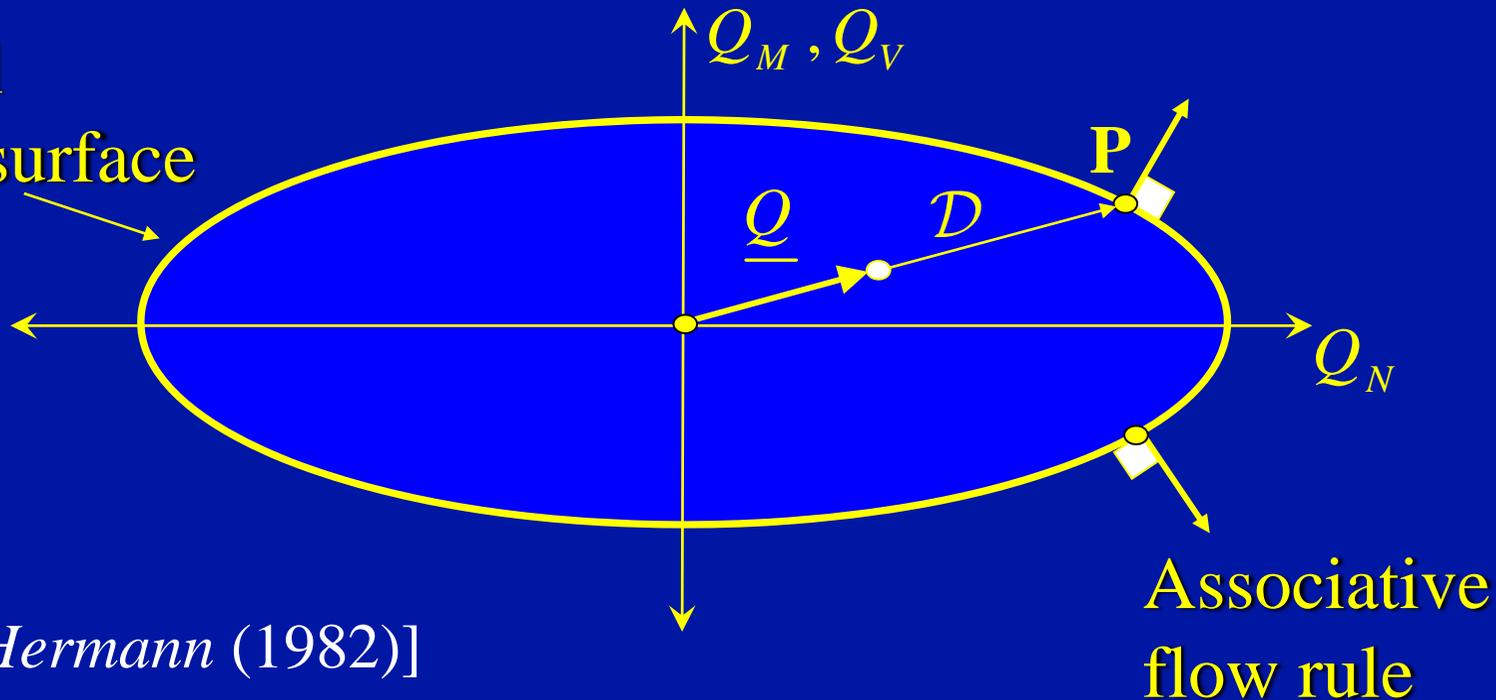


FONDATION "COLLEE" SUR SOL COHERENT

Aucun décollement

[*Randolph & Puzrin (2004)*]

Ellipsoidal
bounding surface

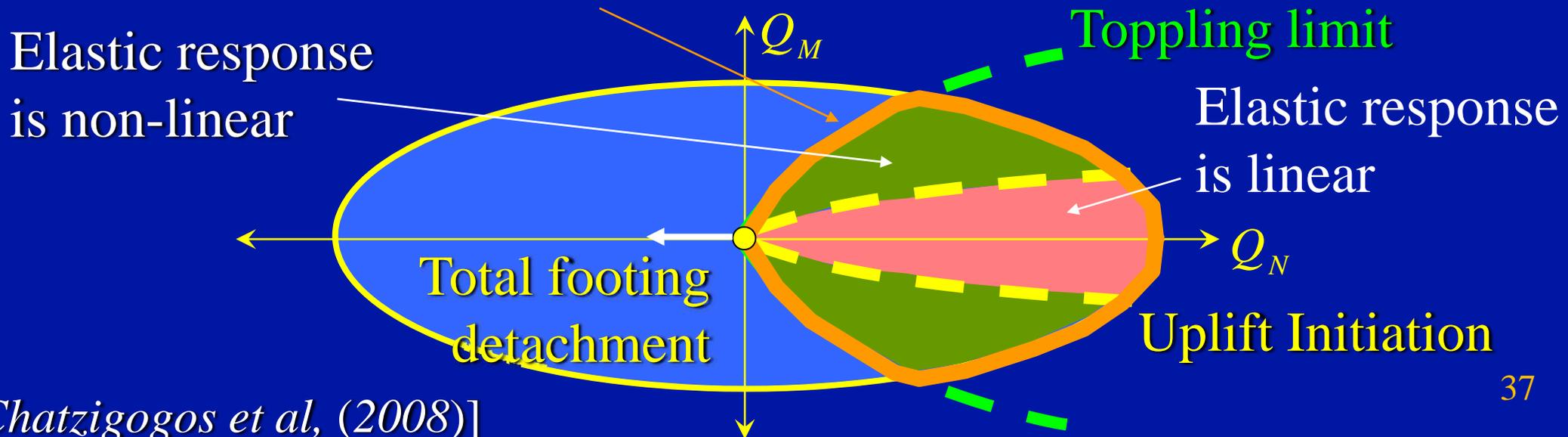
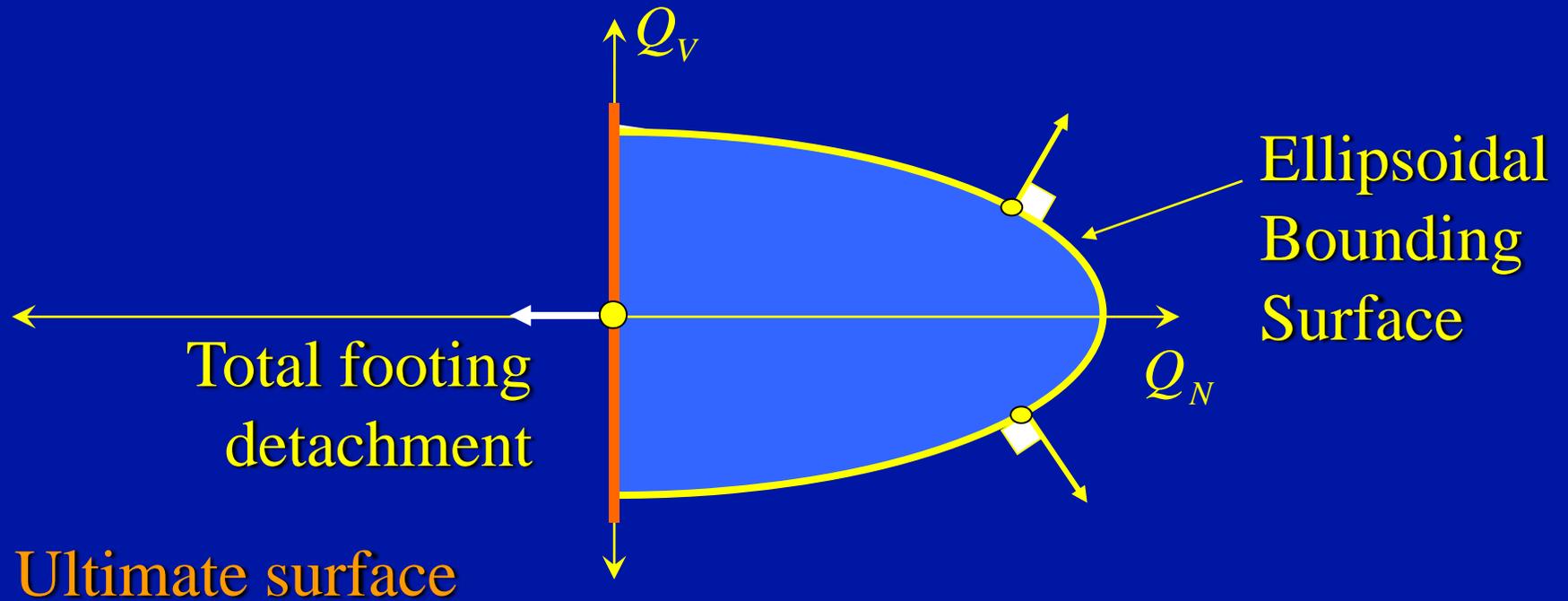


[*Dafalias & Hermann (1982)*]

Hypoplastic bounding surface plasticity

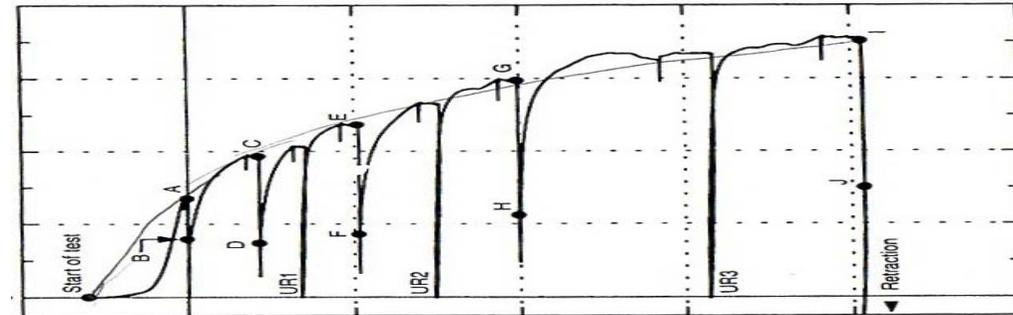
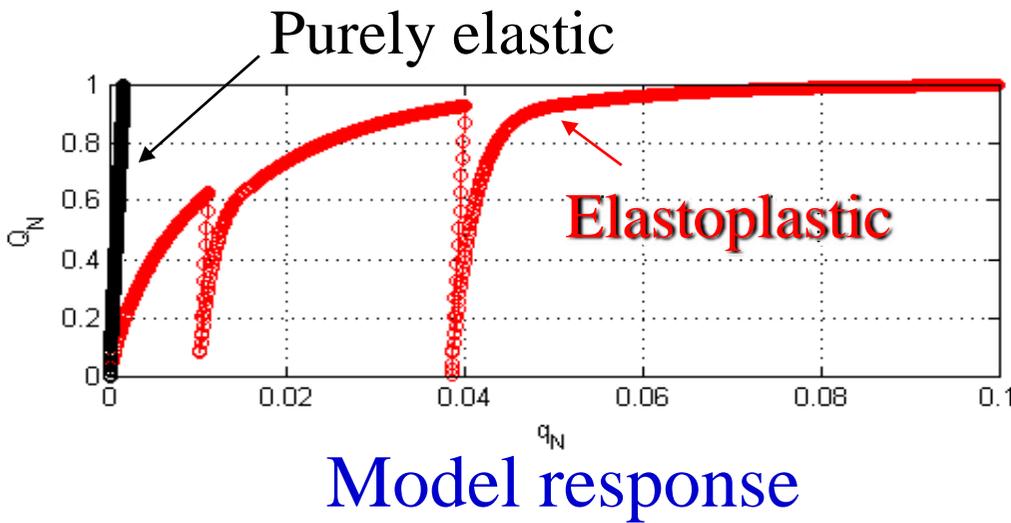
1. Cyclic loading
2. Continuous variation of plastic modulus
3. Numerical implementation

UPLIFT – PLASTICITY COUPLING



BEHAVIOR UNDER QUASI-STATIC LOADING

Vertical swipe tests



Experimental results
[Martin & Houlsby (2000)]

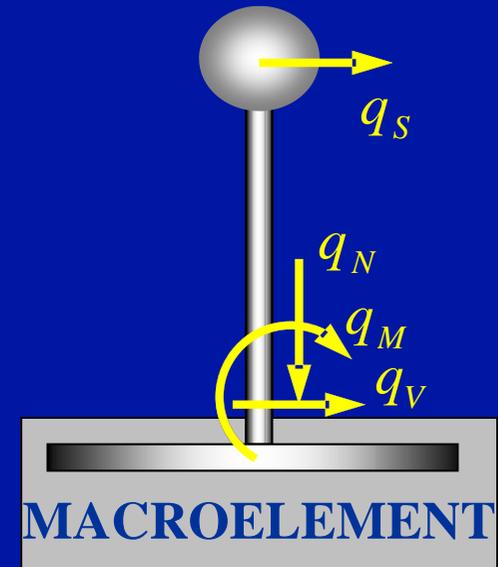
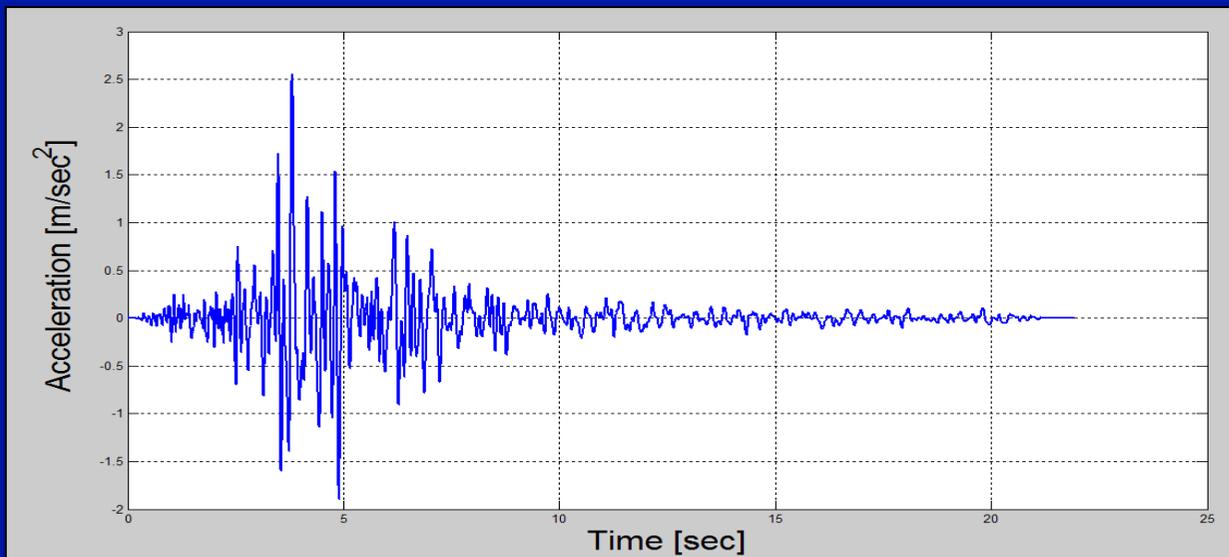
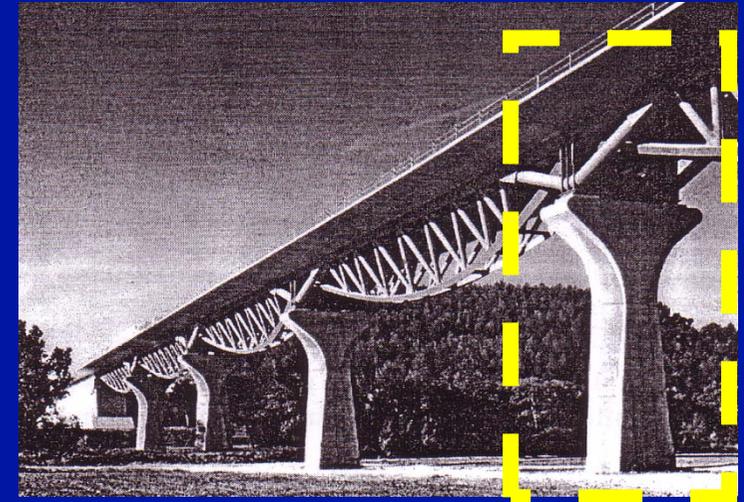
Smooth transition between the phases of reloading – pure loading³⁸



APPLICATION STRUCTURE REELLE

Pylone du Viaduc de l'Arc

La structure soumise à accélérogramme enregistré pendant le séisme du Frioul (Italie, 1976)

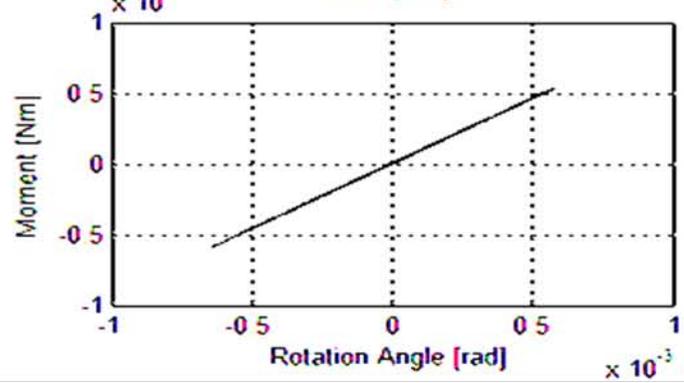
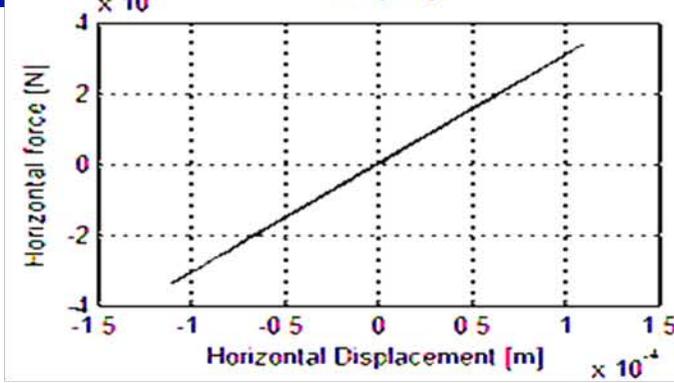
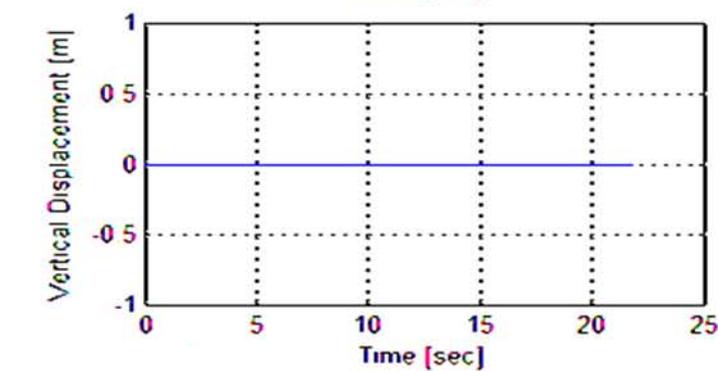
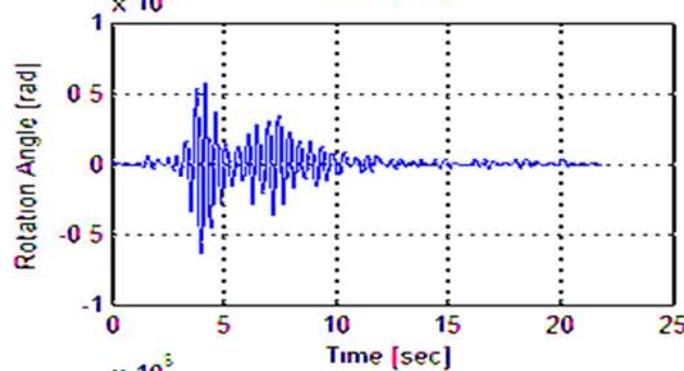
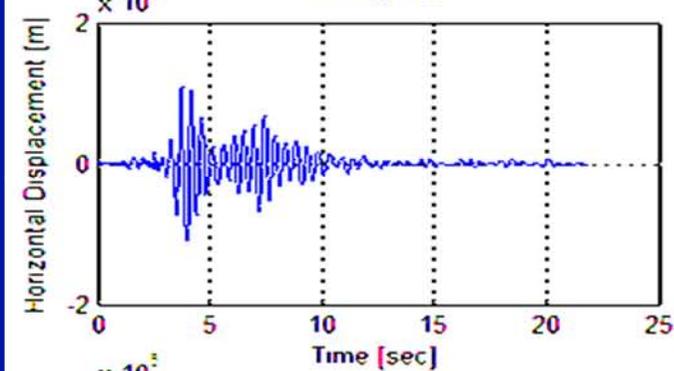
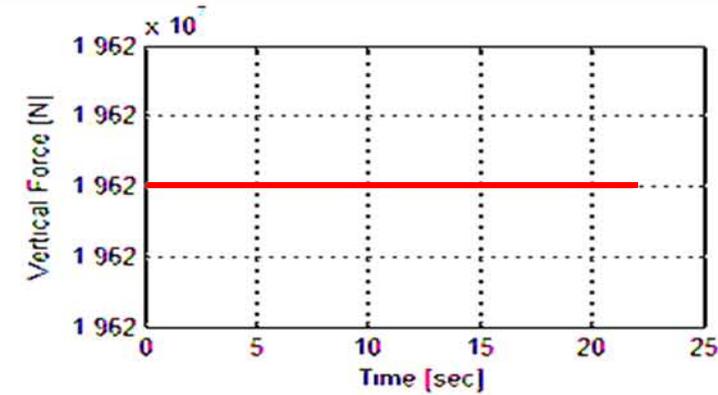
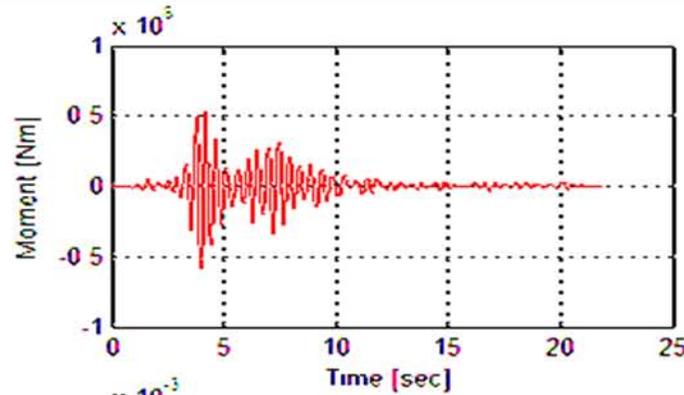
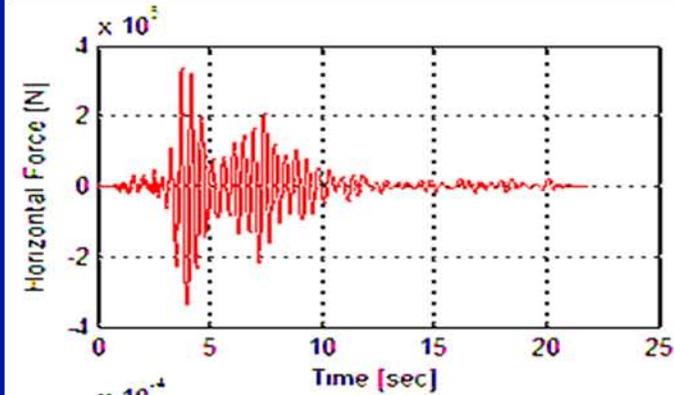


REPONSE LINEAIRE ELASTIQUE

Horizontal Force

Moment

Vertical Force

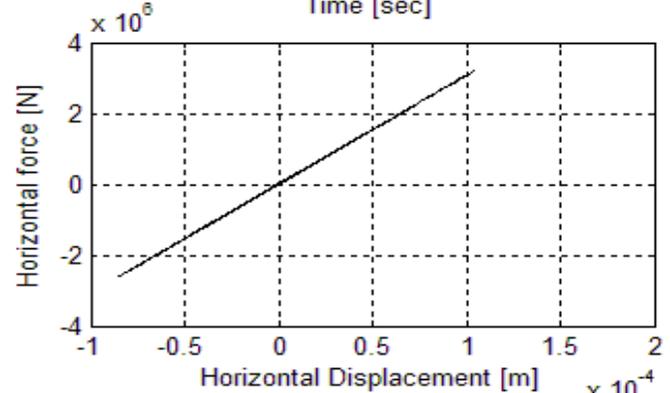
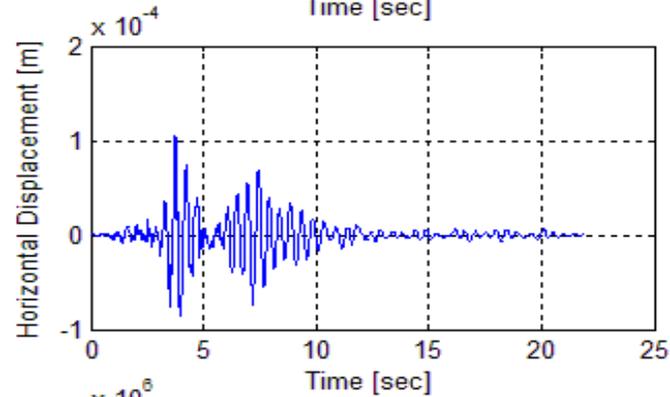
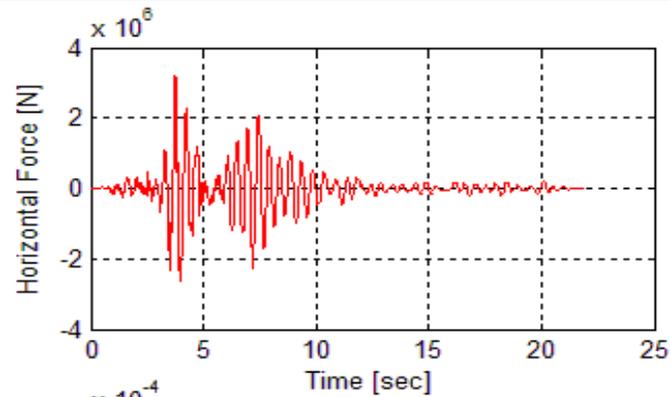


$$M_{\max} = 50 \text{ [MNm]}$$

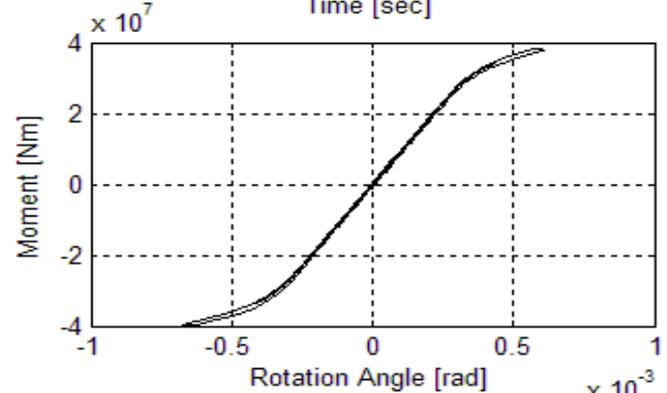
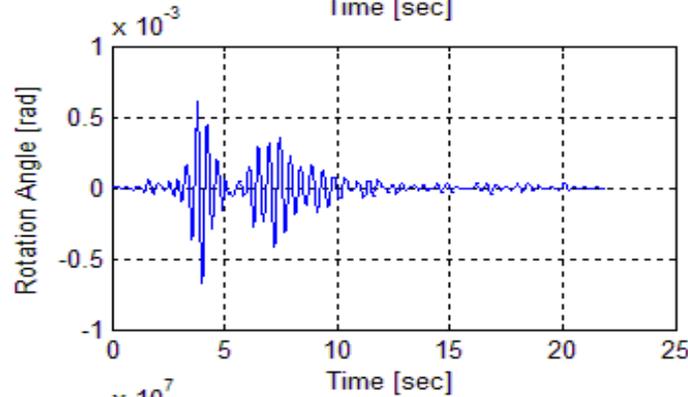
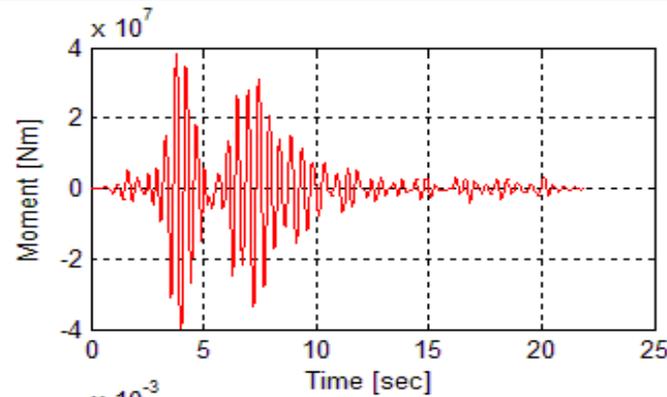
$$V_{\max} = 3.2 \text{ [MN]}$$

REPOSNE ELASTIQUE AVEC DECOLLEMENT

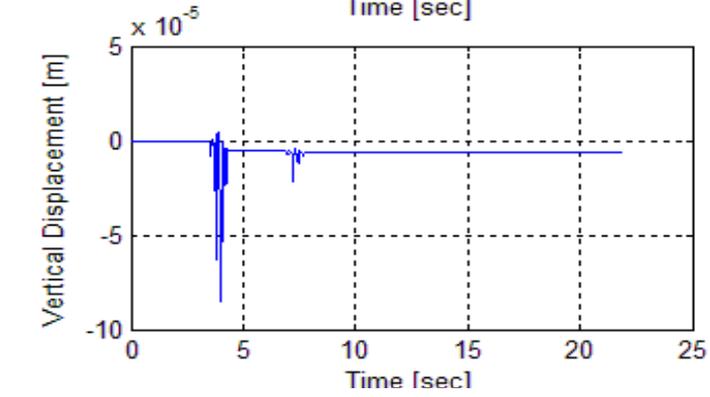
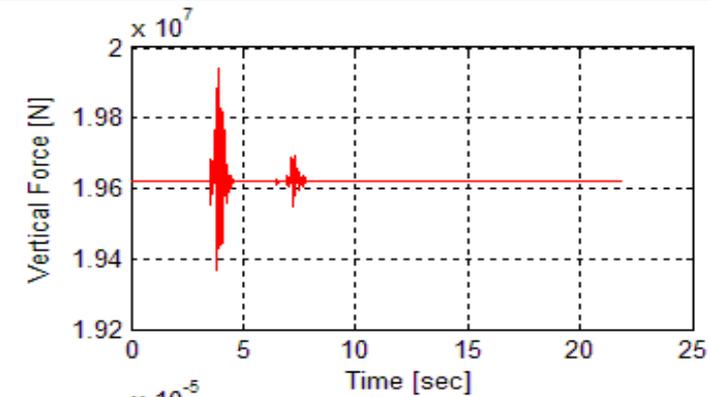
Horizontal Force



Moment



Vertical Force

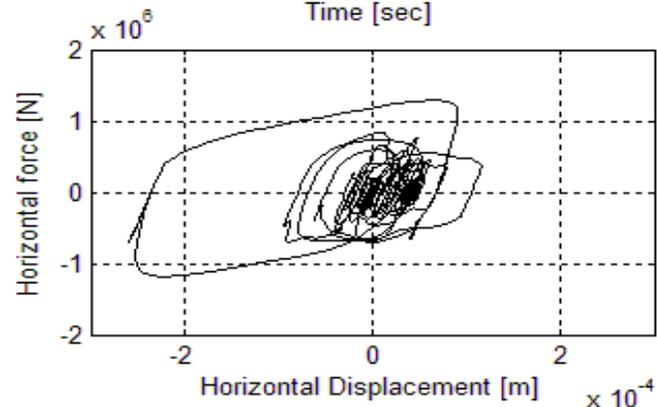
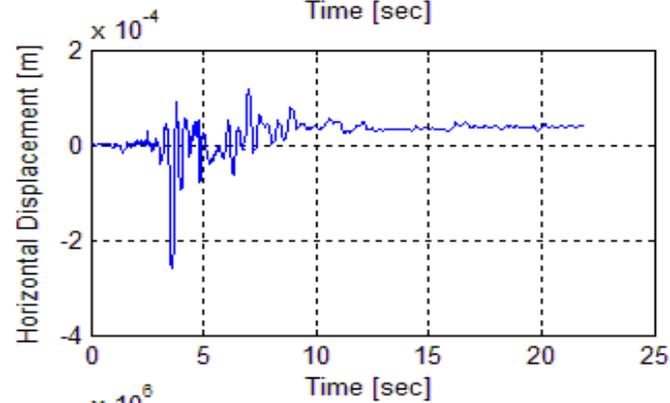
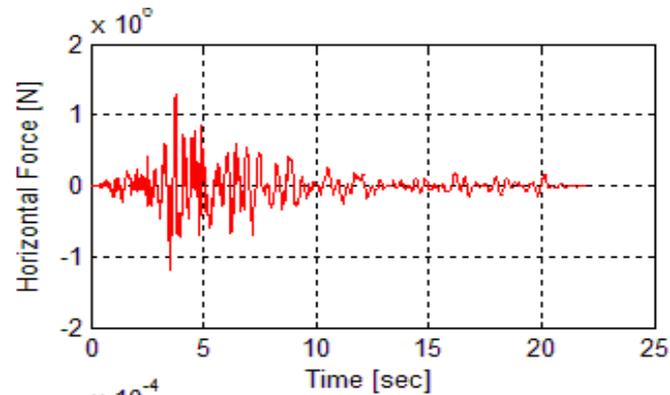


$$M_{\max} = 40 \text{ [MNm]}$$

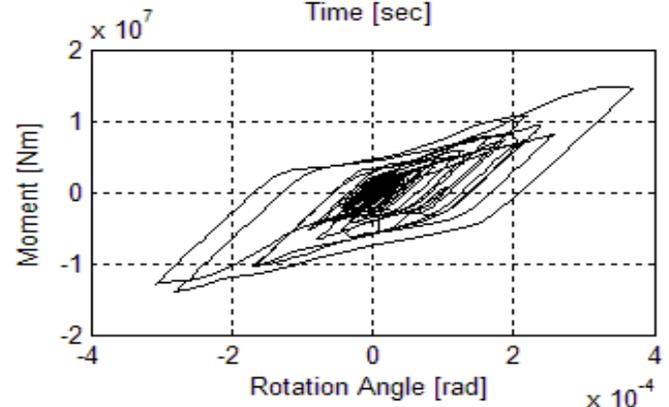
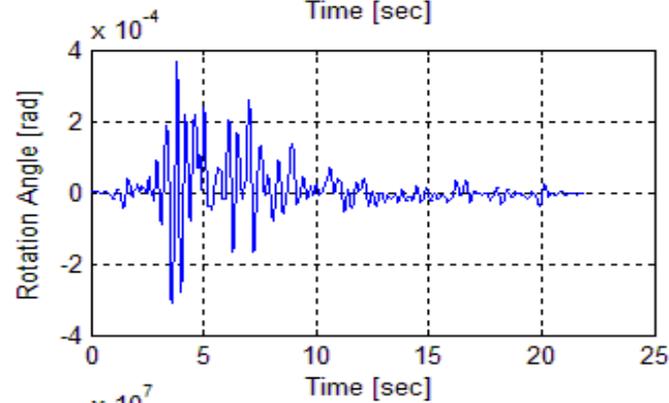
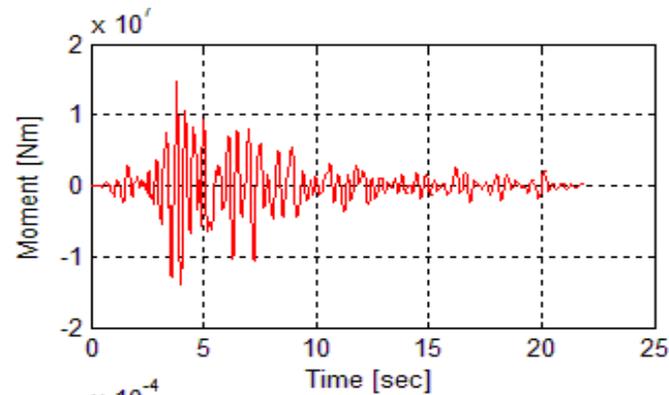
$$V_{\max} = 3.2 \text{ [MN]}$$

REPONSE ELASTOPLASTIQUE AVEC DECOLLEMENT

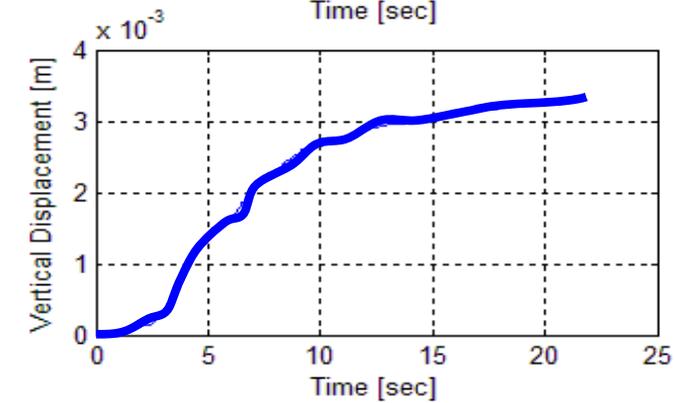
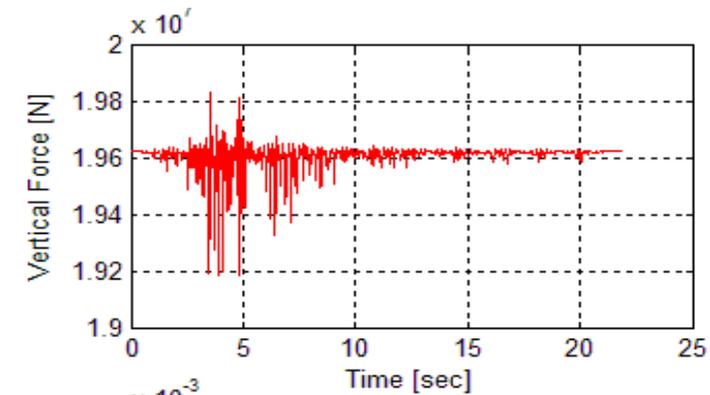
Horizontal Force



Moment



Vertical Force



$$M_{\max} = 15 \text{ [MNm]}$$

$$V_{\max} = 1.3 \text{ [MN]}$$

CONCLUSIONS ON MACROELEMENT

1. Modèle Macroélément avec non linéarités **matérielle** (plasticité) et **géométrique** (décollement).
2. **Charges extrêmes** obtenues par couplage des deux mécanismes.
3. Permet **analyses non-linéaires ISS** numériquement efficaces.
4. Grande **flexibilité** : modifier, ajouter ou désactiver les différents mécanismes.
5. Extension possible à des configurations totalement 3D.

MISE EN ŒUVRE PRATIQUE DE DBA

CODE DE CONSTRUCTION PARASISMIQUE

Exigences du code

$$S_d \leq R_d$$

$$S_d (\gamma_F \cdot \text{actions}) \leq \frac{1}{\gamma_{Rd}} R_d \left(\frac{\text{paramètres de résistance}}{\gamma_m}, \text{géométrie} \right)$$

γ_{Rd} : Coefficient de modèle

COEFFICIENT DE MODELE γ_{Rd}

- Reflète incertitudes du modèle utilisé pour évaluer la résistance R
 - $\Rightarrow \gamma_{Rd} > 1.0$ pour des charges invariables
- Pour des charges variables il est admissible que $S_d > R_d$ si déplacements permanents sont acceptables
 - $\Rightarrow S_d = \lambda R_d$ avec $\lambda > 1.0$

$$S_d = \frac{1}{\gamma_{Rd}} R_d \quad \left. \vphantom{S_d} \right\} \Leftrightarrow \gamma_{Rd} < 1.0$$

VALEURS PROVISOIRES EC8

Capacité portante des fondations

Medium to dense sand	Loose dry sand	Loose saturated sand	Non sensitive clay	Sensitive clay
1.0	1.15	1.50	1.0	1.15

CONCLUSIONS

- ISS non linéaire essentielle pour analyses basées sur critère de performance
- Modèles simplifiés, préservant les aspects fondamentaux, deviennent disponibles
- Calibration et validation des modèles encore nécessaire
- Mise en oeuvre de DBA dans les codes de construction est possible dans le format actuel

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