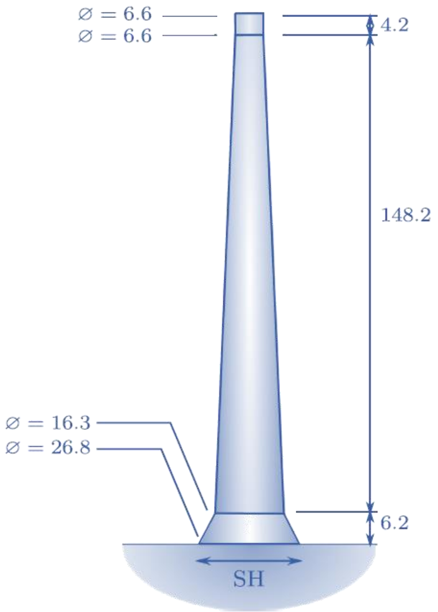
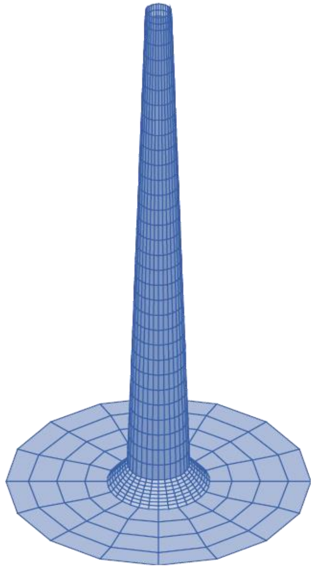
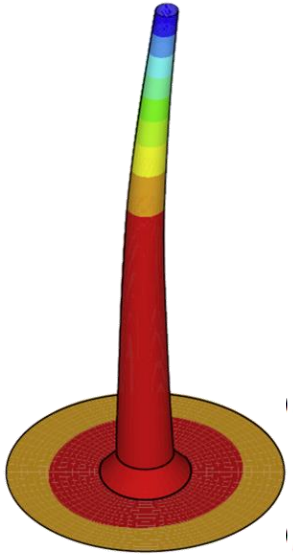
How Wind Turbine Engineers Confront Structural Nonlinearities?







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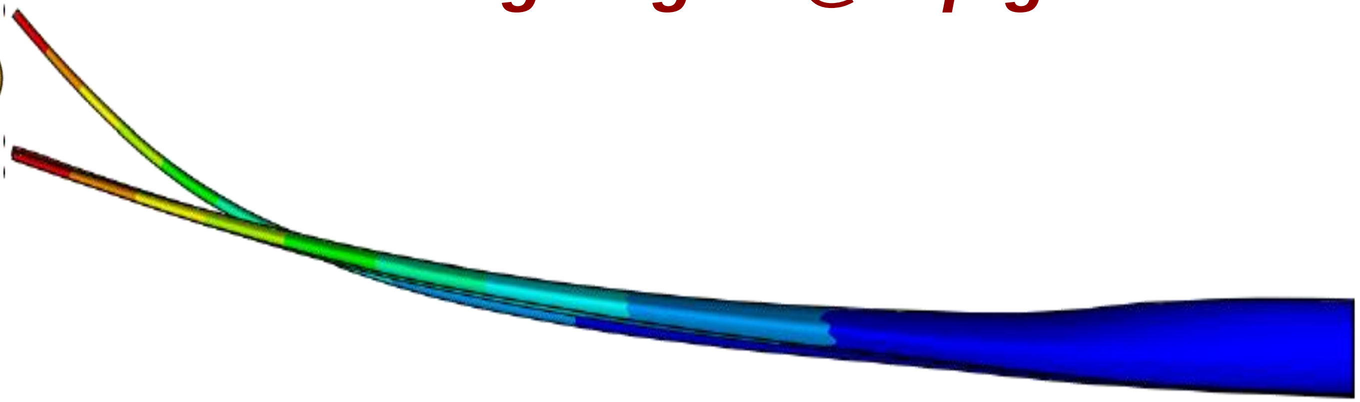

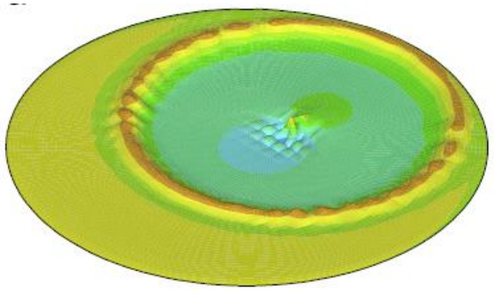

DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

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UNIVERSITY OF PATRAS

Outline

- **Background**
  - **Nonlinear behavior of tower**
  - **Nonlinear behavior of foundation**
  - **Nonlinear behavior of soil**
  - **Nonlinear behavior of flanges**
  - **Nonlinear behavior of blades**

Background

Wind turbines consist of a plethora of sub-components, which can number up to 8,000. Five parts, however, are vital and can behave nonlinearly: soil, foundation, hub, tower and blades. This brief presentation depicts how wind turbine engineers confront these structural nonlinearities.

Brief description of critical parts behave nonlinearly

TOWERS

The tower is constructed to hold the rotor blades off the ground and at an ideal wind speed. Towers are usually between 50-100 m above the surface of the ground or water. Offshore towers are generally fixed to the bottom of the water body, although research is ongoing to develop a tower that floats on the surface.

Brief description of critical parts behave nonlinearly

TOWERS

Taller towers for wind turbines make sense. For instance, an 80-m tower can let 2 to 3-MW wind turbines produce more power, and enough to justify the additional cost of 20-m more, than if installed at 60 m. Taller towers will also let larger turbines enter the market. Taller towers allow putting turbines in less turbulent winds, thereby decreasing wear and fatigue. Haliade-X, the most powerful offshore wind turbine in the world (14 MW capacity) has a 260 m high tower.

Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?

Tubular steel tower | Tubular concrete tower | Lattice tower | Three-legged tower | Guy-wired pole tower

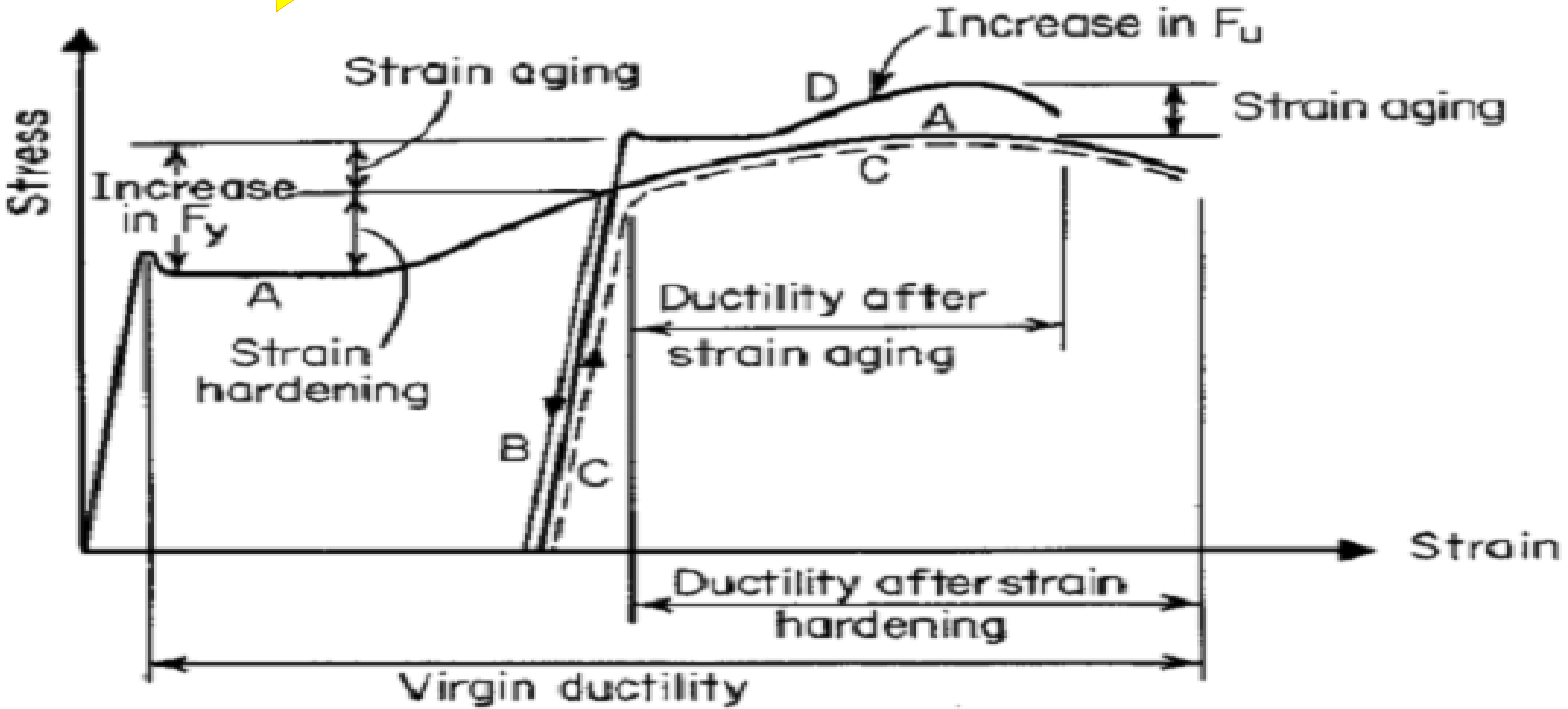
Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?

- Wind turbine tower design is a key parameter in contemporary wind generator design in general.
- Tower cost is about 15% of total cost of a wind turbine.
- The prevailing structural configuration of the total installed wind capacity is the **steel tubular tower**, providing the advantage of robust structural design, prefabrication of large wind tower parts, limited on-site labor and easier mounting between parts. Cylindrical shells are traditionally preferred by designers in order to minimize material use in structures, because due to their geometry they are capable of carrying great loads with small shell thicknesses.

Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?



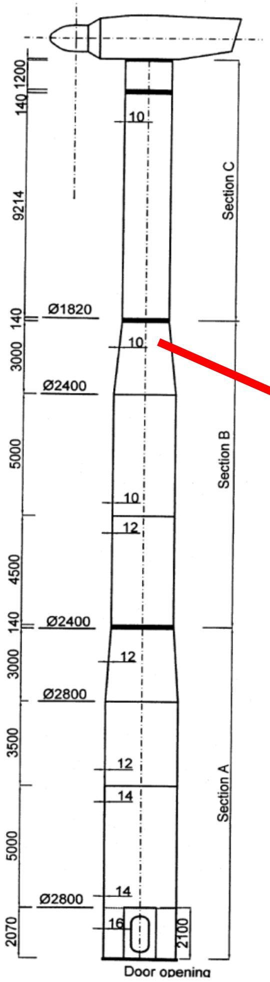
Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?

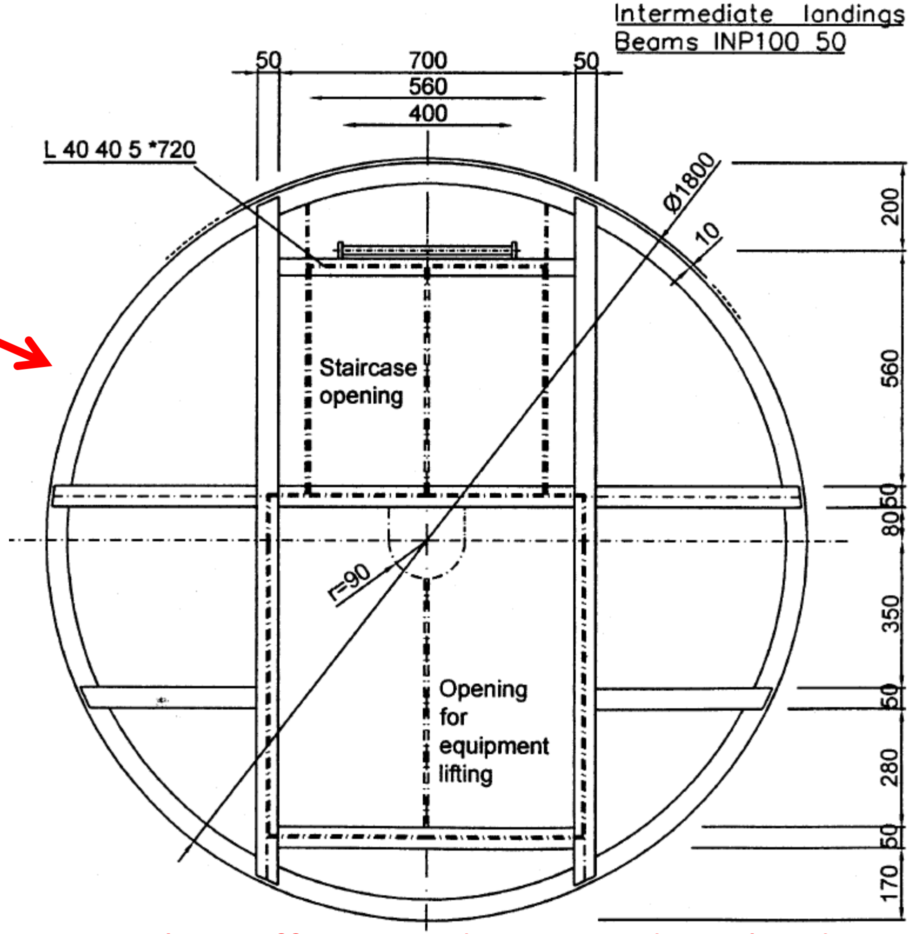
Buckling accident of wind turbine tower due to cyclones

Brief description of critical parts behave nonlinearly

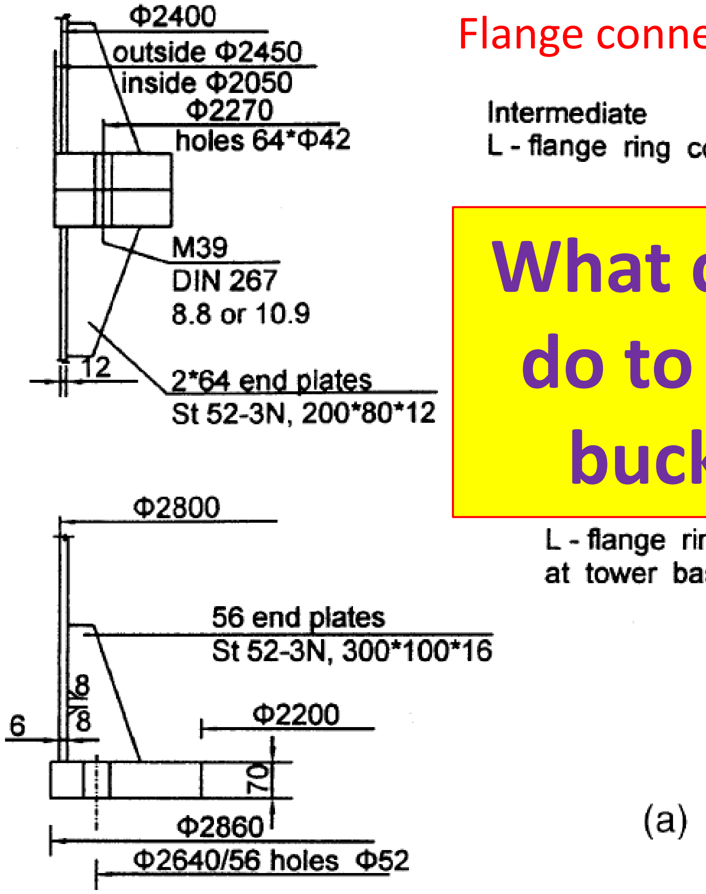
TOWERS: Steel, Concrete or both of them?



Steel tower



Circular stiffener and intermediate landing

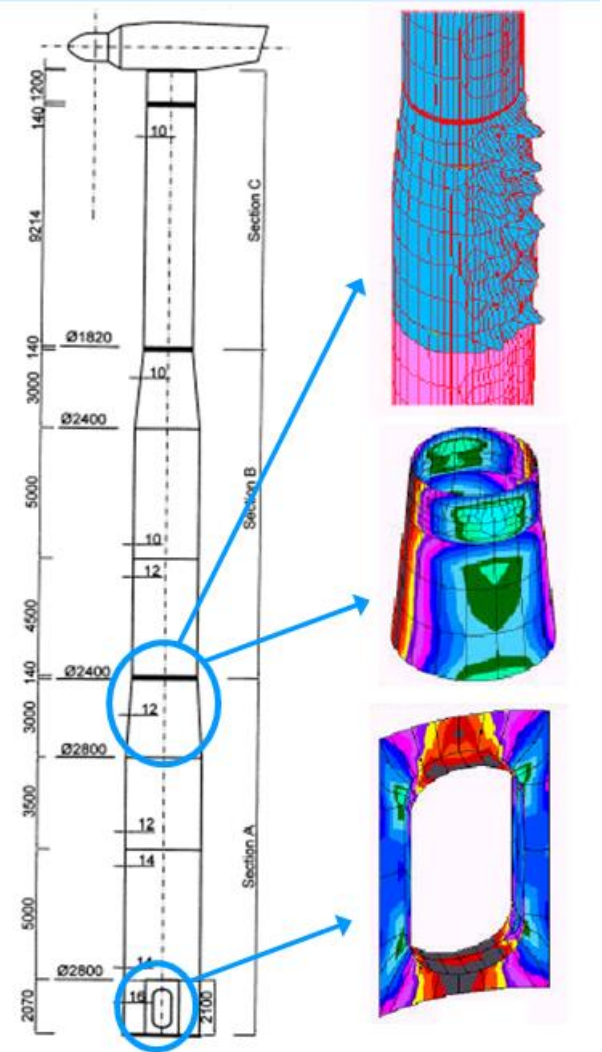


Flange connections

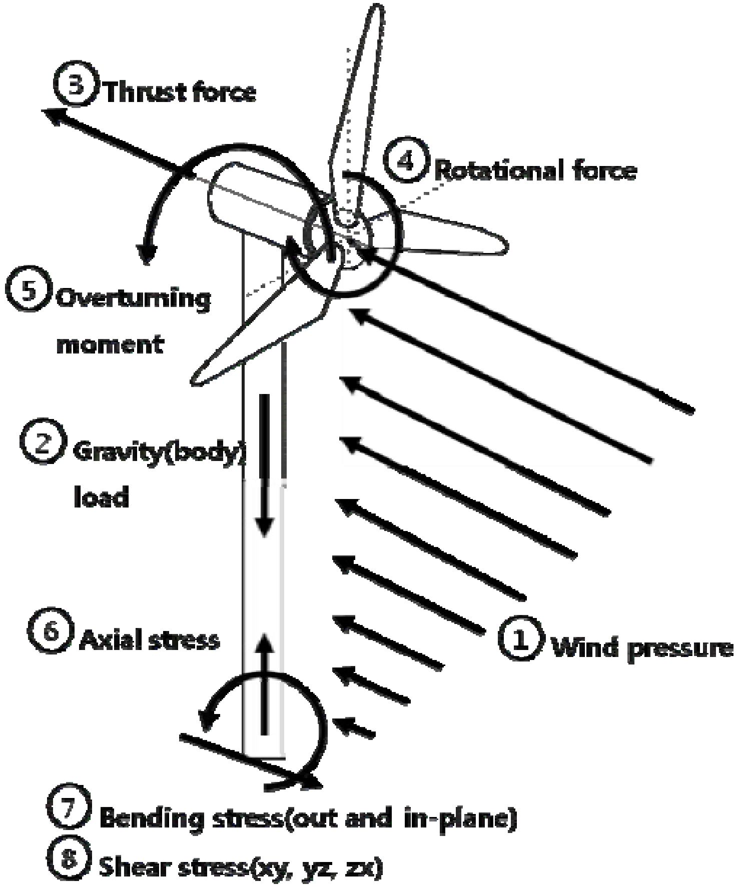
What can we do to avoid buckling

Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?

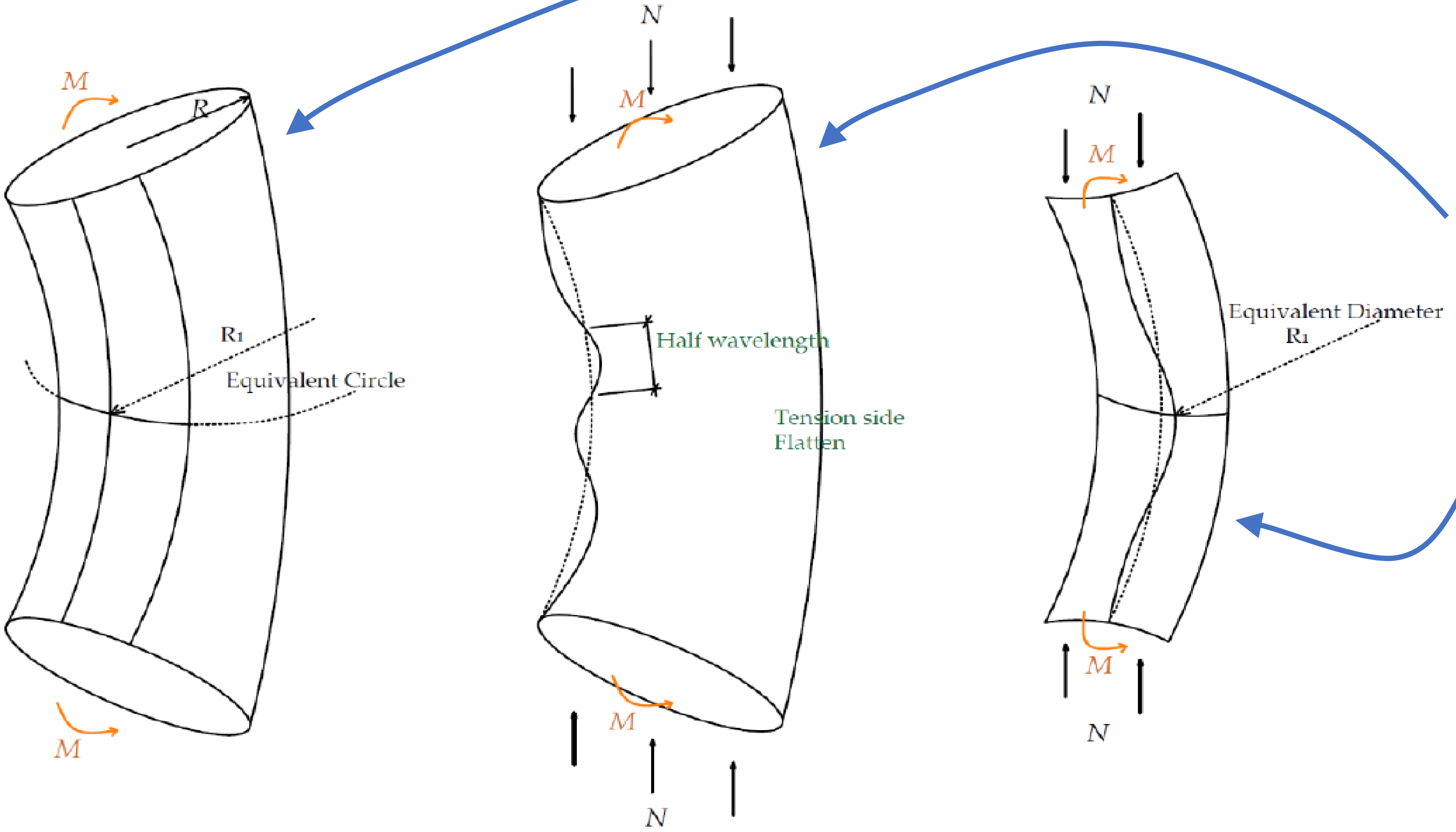


The purpose of nonlinear buckling analysis is to find the load at which the buckling occurs. The buckling wind speed is calculated backwards by matching the sum of the main horizontal forces, i.e. the wind pressure force and rotor thrust, to the buckling limit load.



Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?



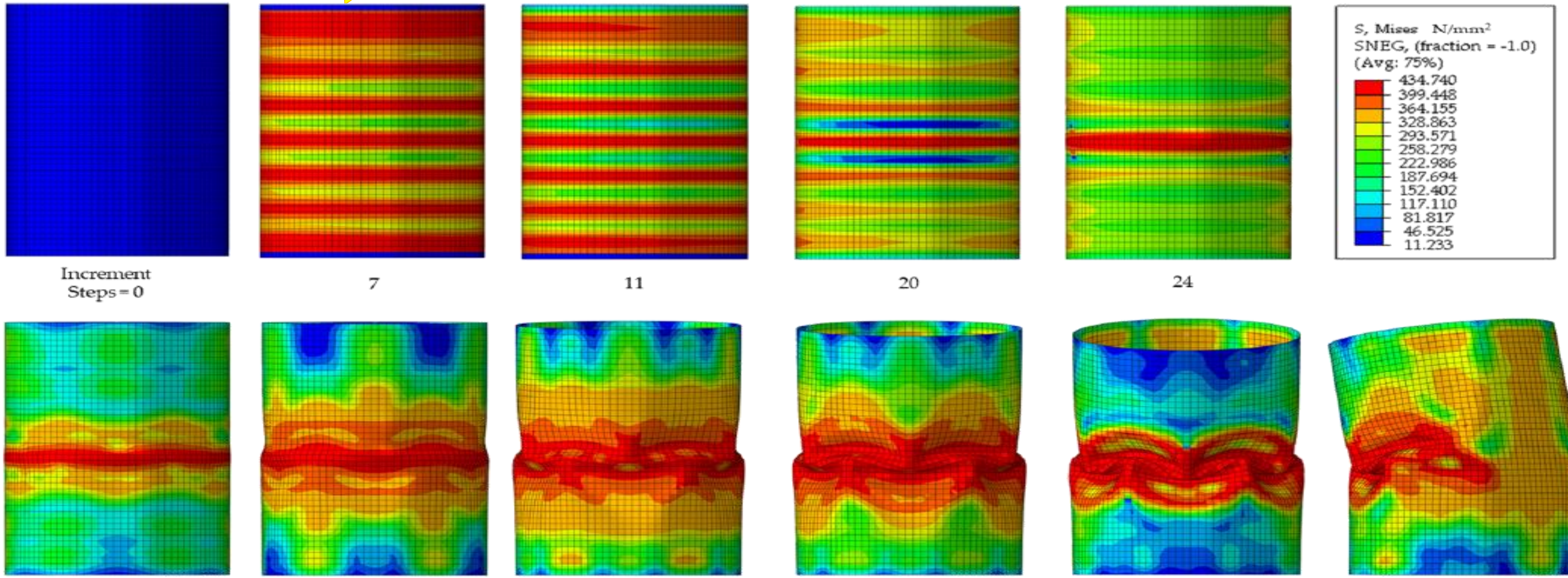
Section ovalisation of a bending cylindrical shell;

The resulted effect of combined loads;

The strip of a highly stressed shell segment.

Brief description of critical parts behave nonlinearly

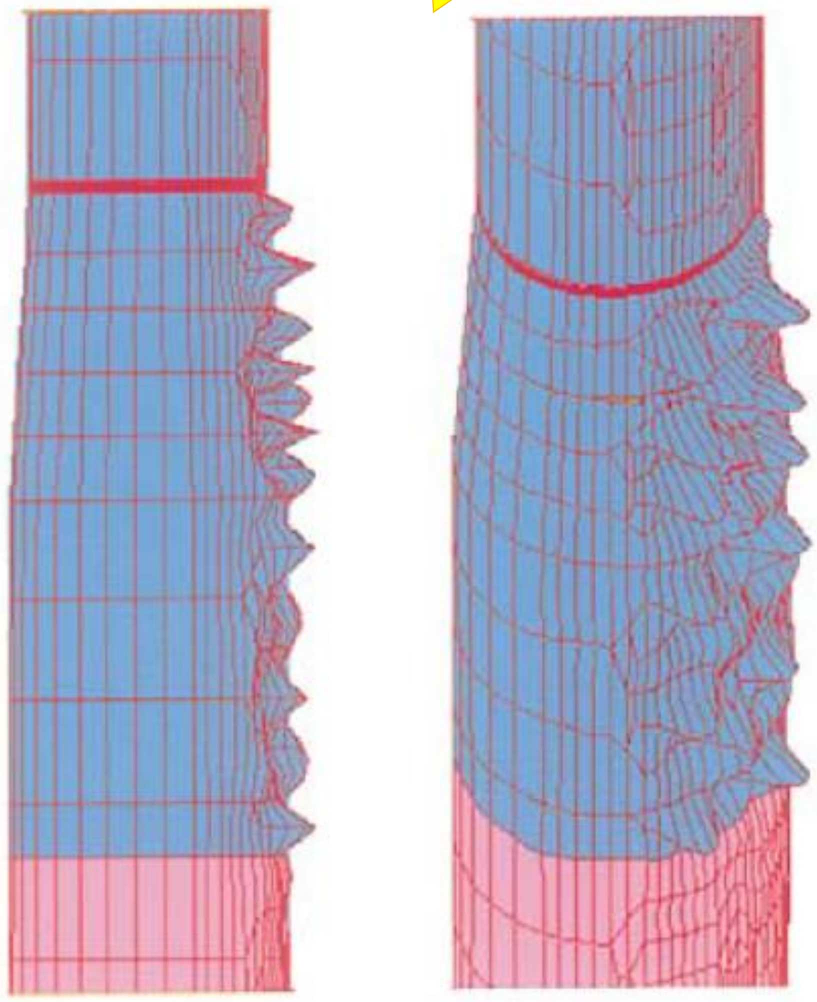
TOWERS: Steel, Concrete or both of them?



Stress distributions and deformations at the compressive side of a cylindrical shell at 10 increment steps.

Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?



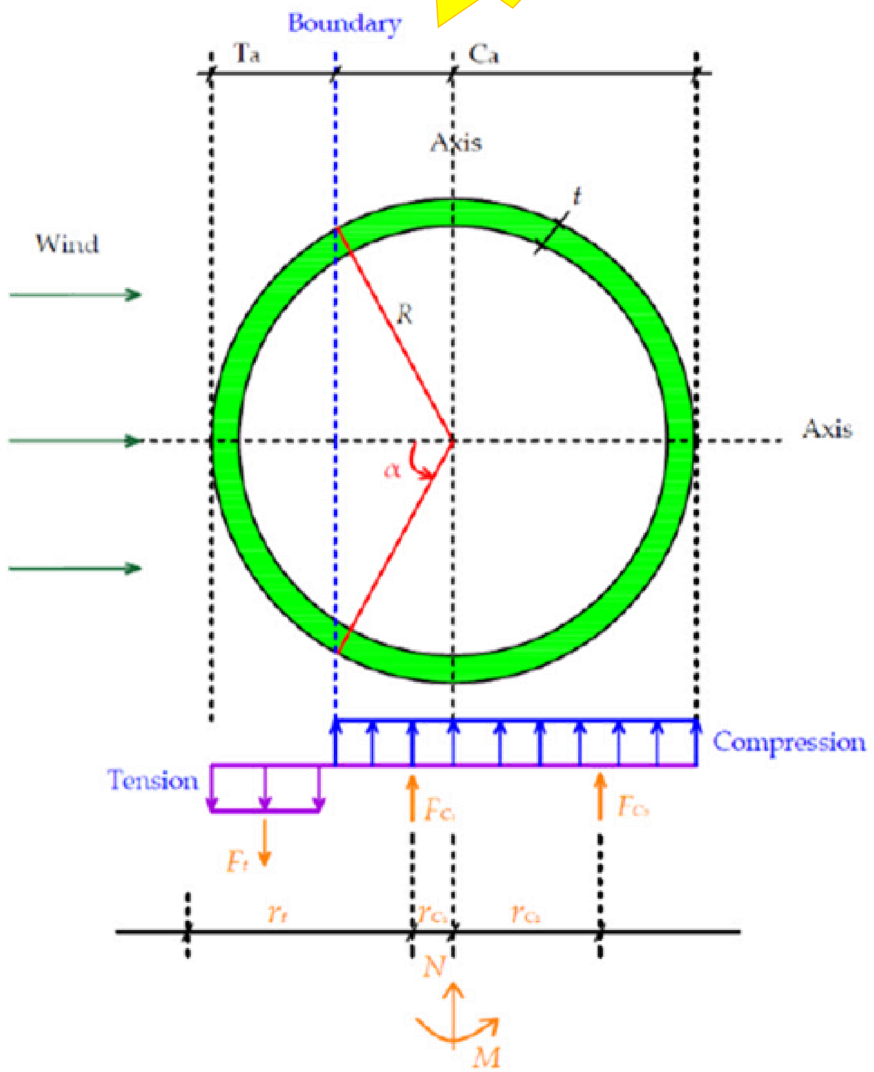
$$[K]\{\phi_i\} = \lambda_i [S]\{\phi_i\}$$

$[K]$ = Structural stiffness matrix
$\{\phi_i\}$ = Eigen vector
λ_i = Eigen value
$\{S\}$ = Stress stiffness matrix

Note: It is well known that it is very difficult or sometimes even impossible to manufacture thin cylindrical shells without imperfections. Hence to obtain accurate result from numerical analysis is necessary to know about the exact shape and size of the imperfections which in turn depends on manufacturing process. As the amplitude of imperfections increases the buckling pressure decreases.

Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?



$$N = F_{C_1} + F_{C_2} - F_t = F_y\left(AreaC_A - AreaT_A\right)$$
$$= F_y\left(2(\pi-\alpha)rt - 2\alpha rt\right)$$
$$= F_y\left[2rt(\pi - 2\alpha)\right]$$

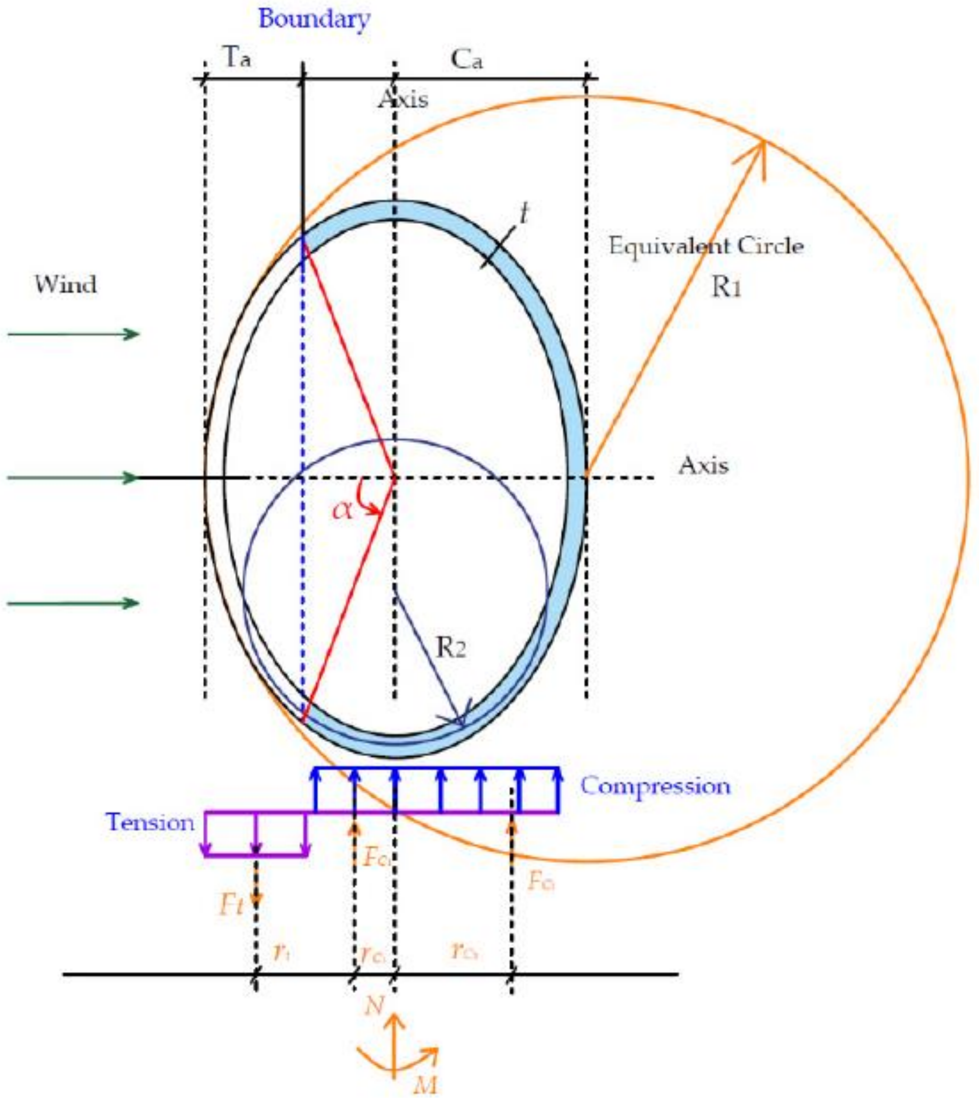
$$M = F_t\left(r_t + r_{C_1}\right) - F_{C_1} r_{C_1} + F_{C_2} r_{C_2}$$
$$= F_y\left\{2\alpha rt\left(r_t + r_{C_1}\right) - \left[2\left(\frac{\pi}{2} - \alpha\right) r_t r_{C_1}\right] + \left(\pi rt \cdot r_{C_2}\right)\right\}$$

Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?

$$N = F_{C_1} + F_{C_2} - F_t = F_y\left(AreaC_A - AreaT_A\right)$$
$$= F_y\left[2\pi R_2(\pi - 2\alpha)t + 2\alpha R_1 t - 2\alpha R_1 t\right]$$
$$= F_y\left[2\pi R_2 t(\pi - 2\alpha)\right]$$

$$M = F_t\left(r_t + r_{C_1}\right) - F_{C_1} r_{C_1} + F_{C_2} r_{C_2}$$
$$= F_y\left\{2\alpha R_1 t\left(r_t + r_{C_1}\right) - \left[R_2(\pi - \alpha)t\left(r_{C_1}\right)\right] + \left(\pi r t \cdot r_{C_2}\right)\right\}$$



Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?

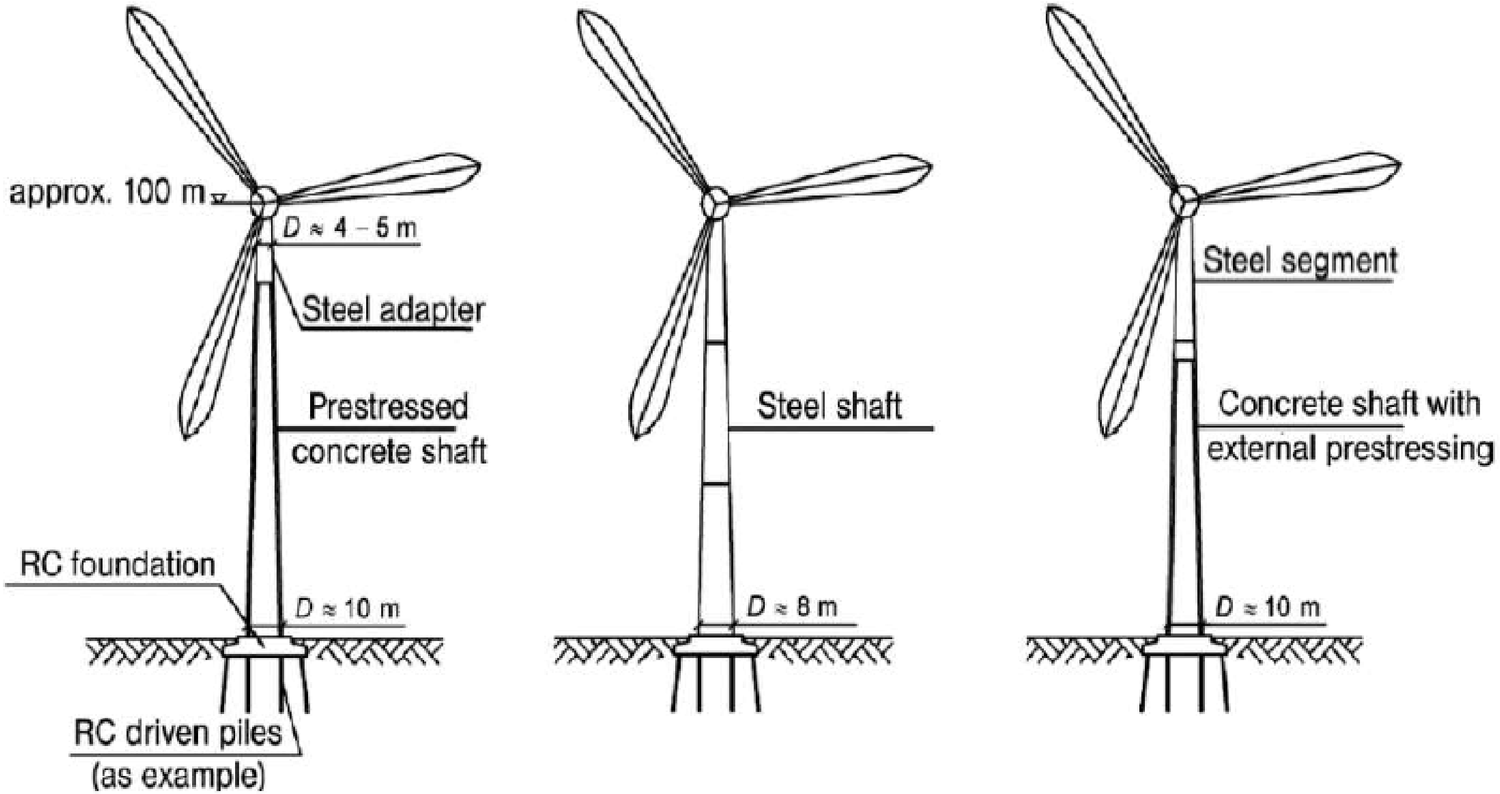
The consequence of taller wind towers is the need to increase the structural strength and stiffness required to carry both increased turbine weight and bending forces under wind action on the rotors and the tower, and to avoid damaging resonance from excitation by forcing frequencies associated with the rotor and blades passing the tower. In turn this will require larger cross sectional diameters, which may introduce significant transportation problems, bearing in mind that **4.5m is the practical limit for the diameter of complete ring sections** that can be transported along the public highway.

Concrete towers can accommodate these requirements and also offer a range of associated benefits.

Brief description of critical parts behave nonlinearly

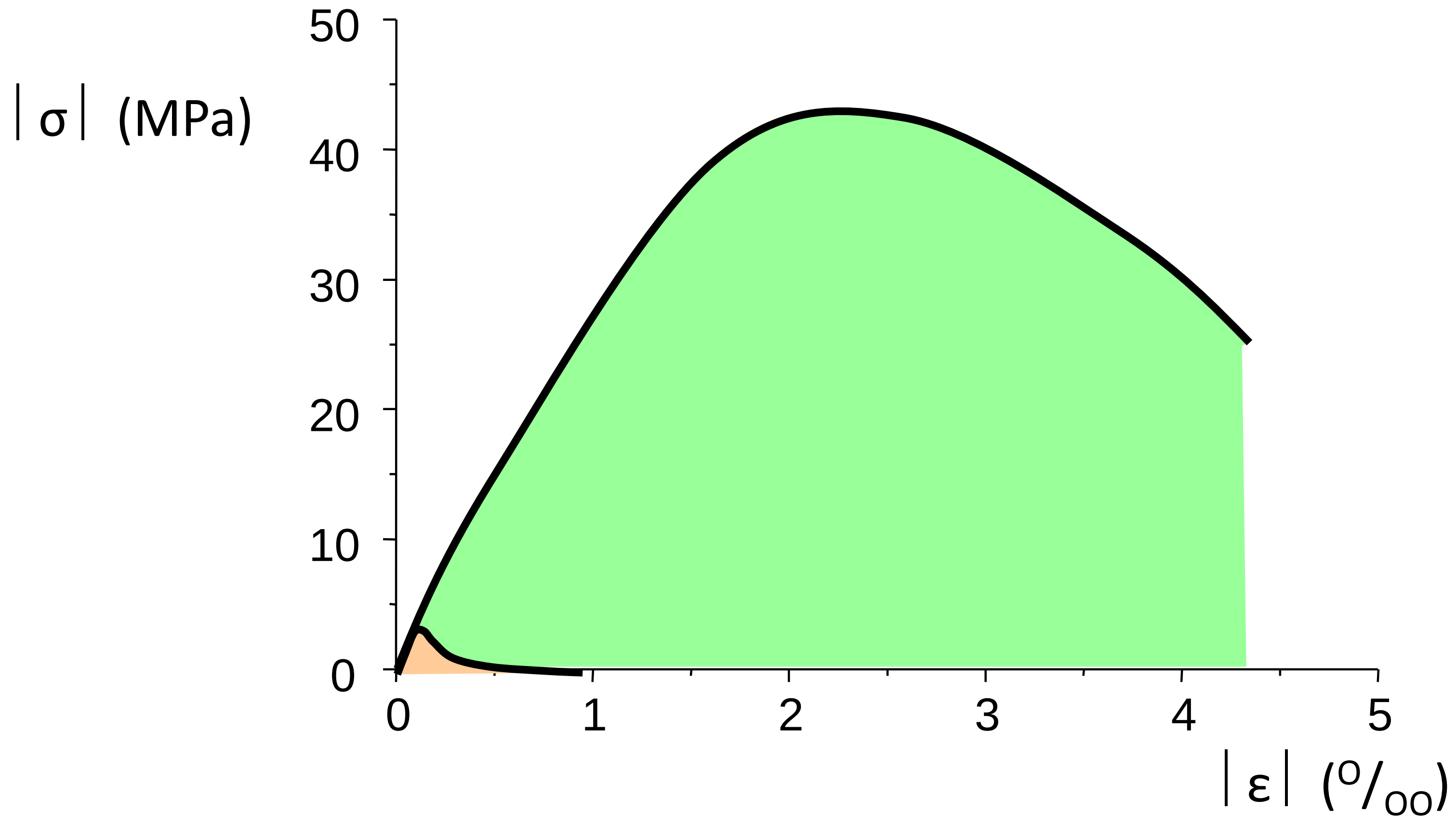
TOWERS: Steel, Concrete or both of them?

Transportation of wind turbine tower’s segments



Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?

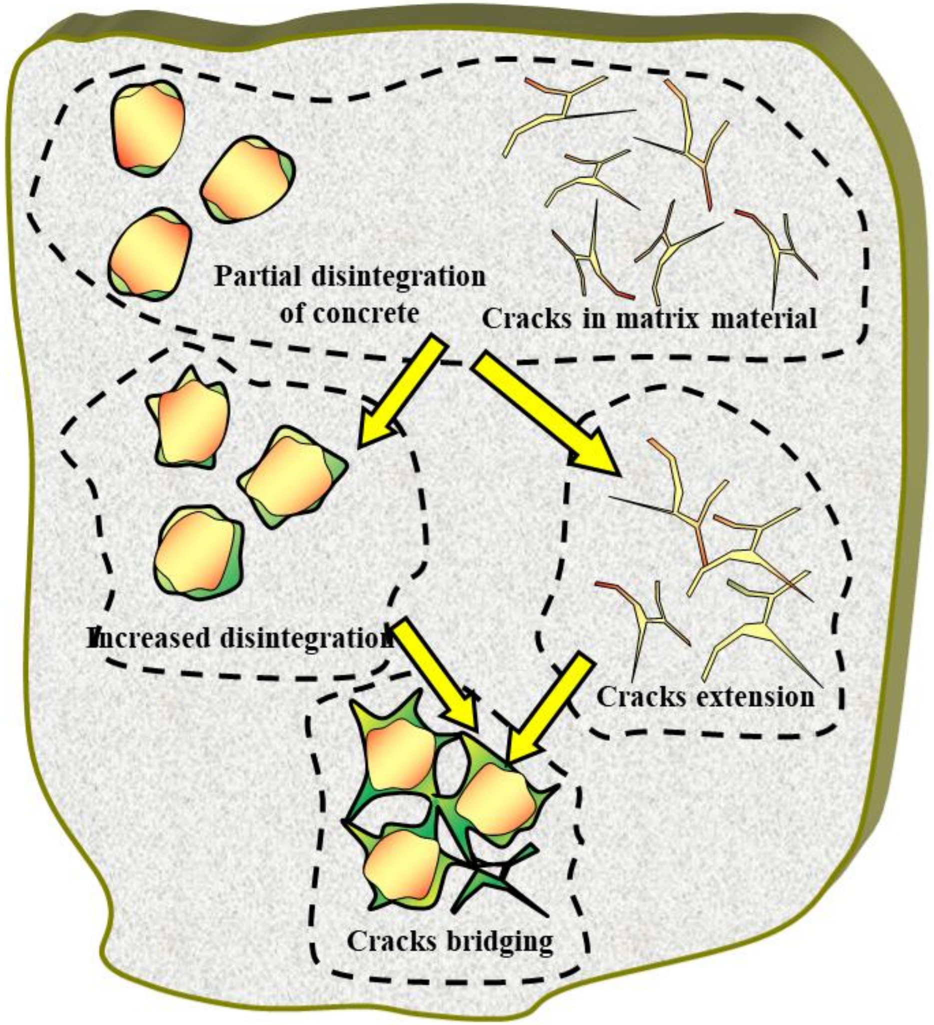


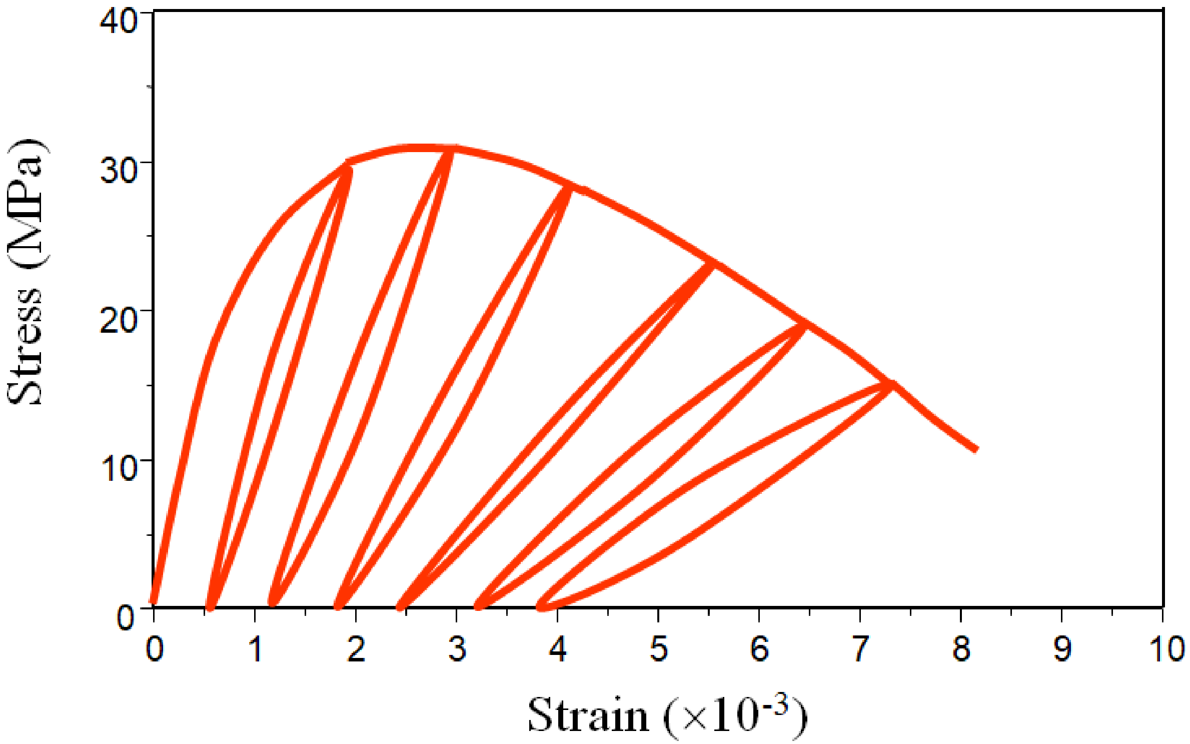
- **Tension and compression – Different behavior**
- **Softening**

Nonlinear behavior of concrete

Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?

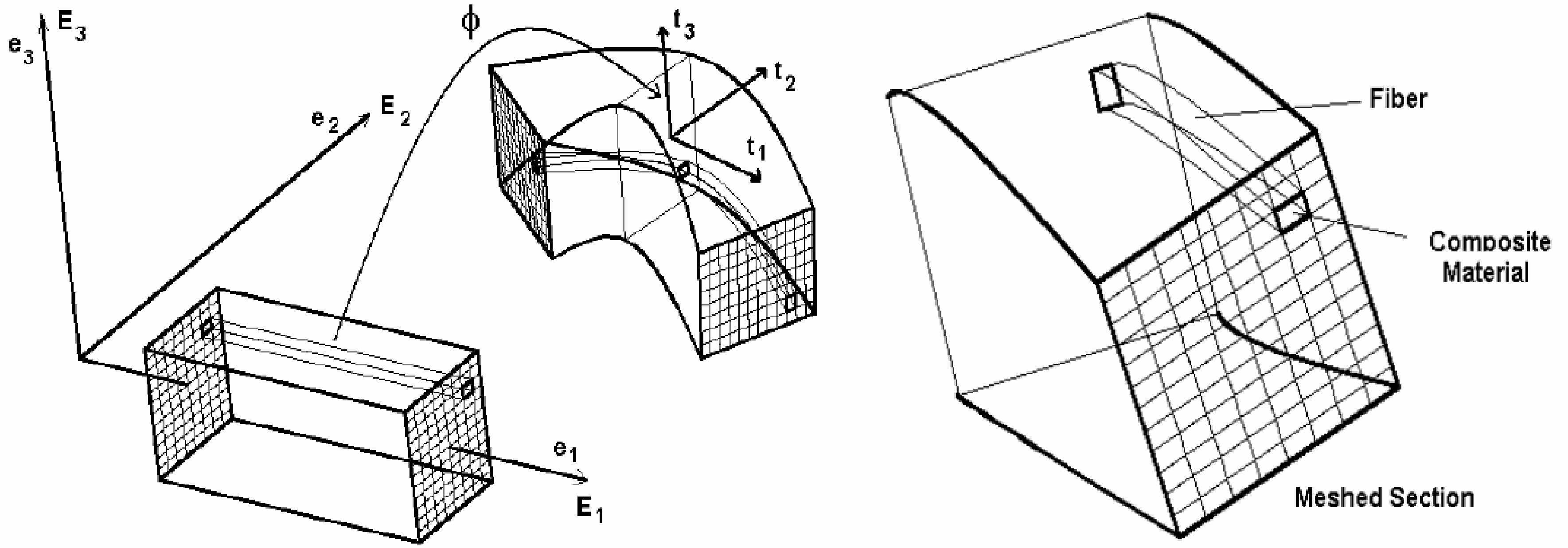




Nonlinear behavior of concrete

Brief description of critical parts behave nonlinearly

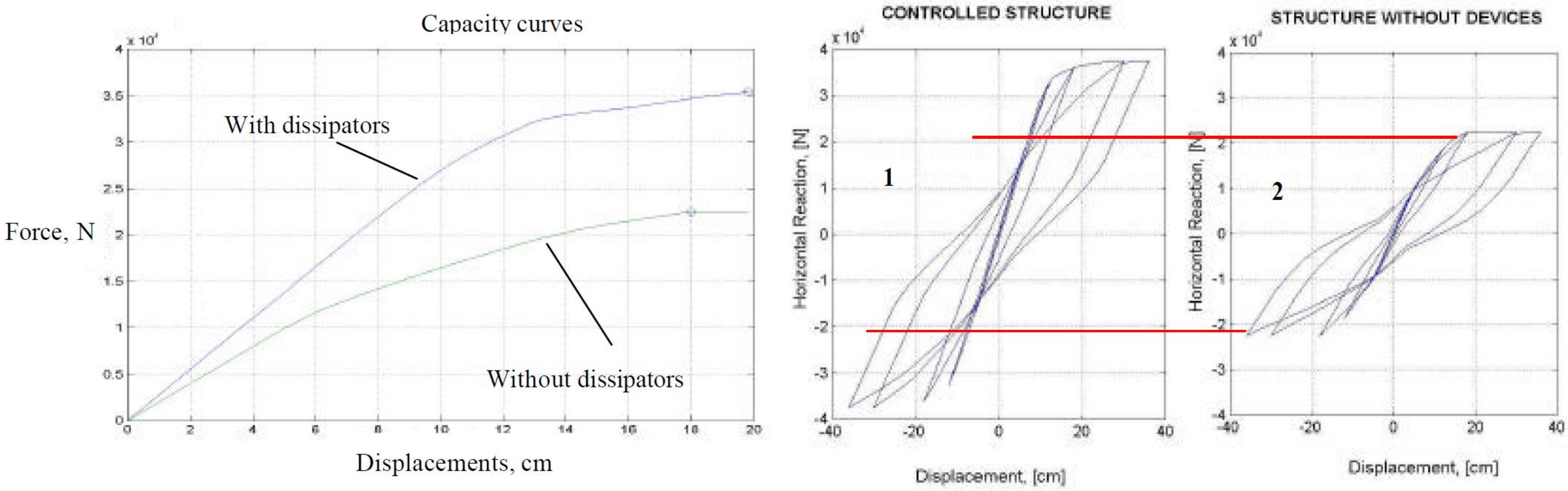
TOWERS: Steel, Concrete or both of them?



Nonlinear behavior of concrete: fiber modeling

Brief description of critical parts behave nonlinearly

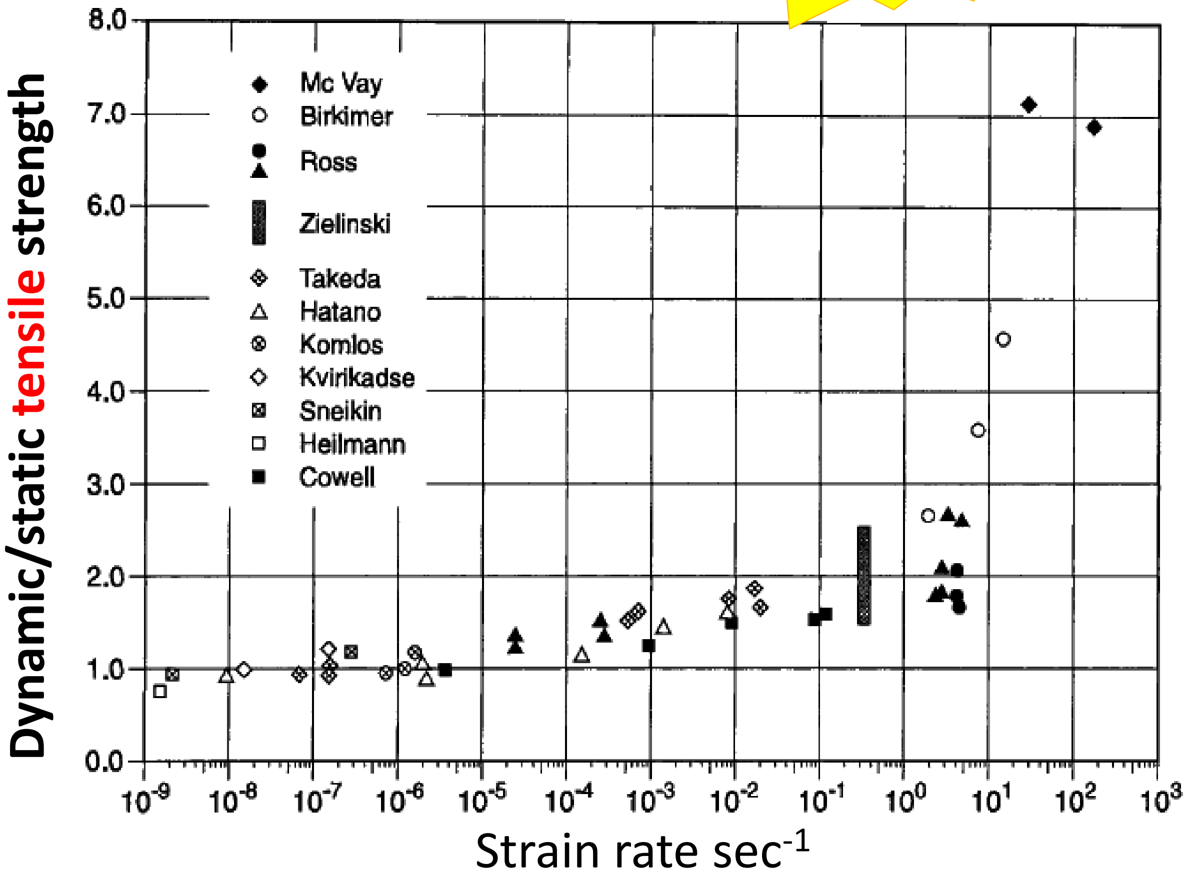
TOWERS: Steel, Concrete or both of them?

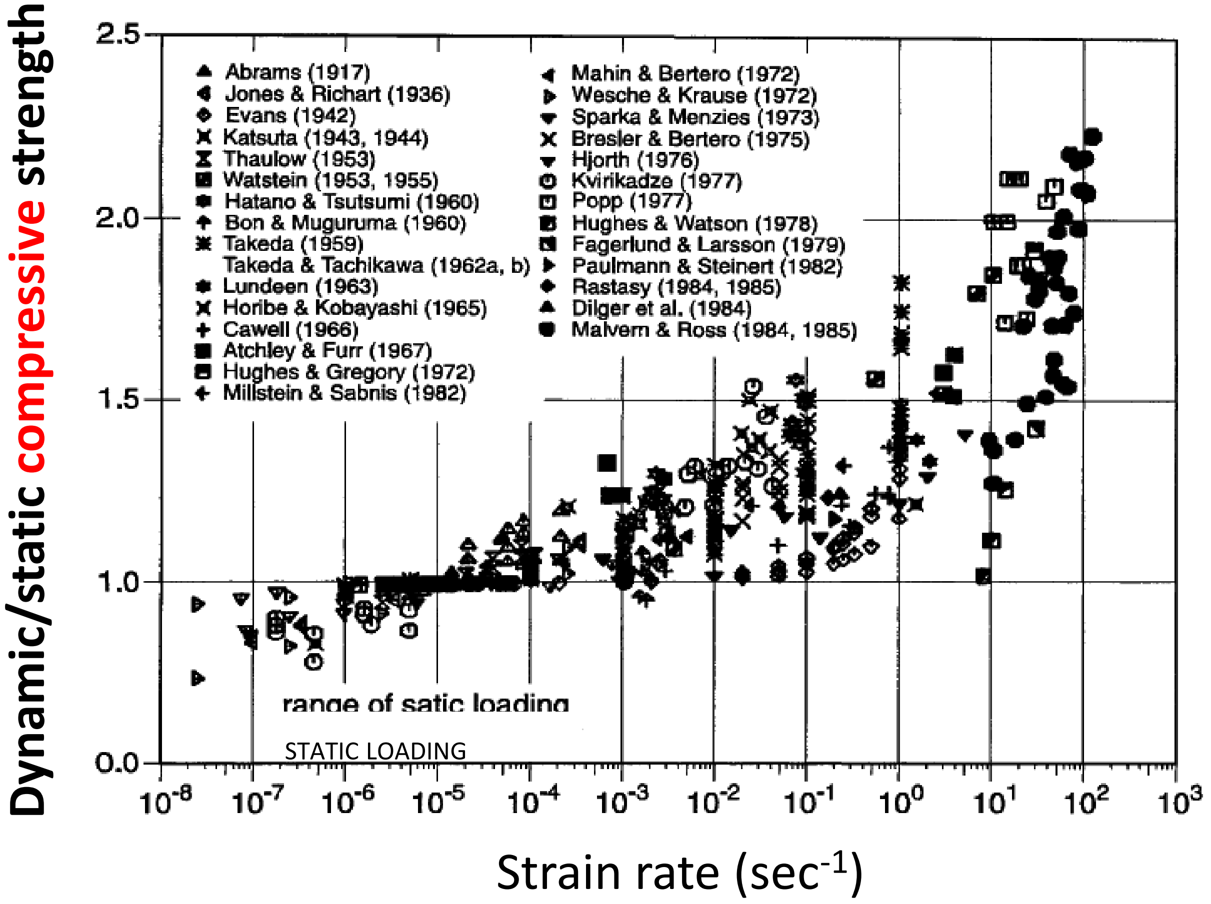


Concrete towers under monotonic and cyclic loading

Brief description of critical parts behave nonlinearly

TOWERS: Steel, Concrete or both of them?





Strain rate effects

Brief description of critical parts behave nonlinearly

TOWERS: static loads (self-weight, wind loads, e.t.c.)

Two sets of static loads can be considered:

(a) The pseudostatic aerodynamic loads under survival and operational conditions. The concentrated aerodynamic loads at the elevation of the power transmission axis, are due to the wind resistance and/or operation of the runner. In addition, aerodynamic loads distributed along the body of the tower itself should be computed and be accounted for in the analysis under survival conditions. Aerodynamic loads under survival, shut down, conditions have a recurrence period of 50 years.

(b) The second set of static loads due to gravity, consists of a concentrated load at the top of the tower representing the weight of the nacelle, runner, generator, gear box, etc. the tower itself distributed along its height (78,500 N/m^3 , specific weight of steel, or, 25,000 N/m^3 , specific weight of concrete).

The safety factors for the static loads are specified as [1]:

Favorable gravity loads: 1.00

Unfavorable gravity loads: 1.35

Aerodynamic loads: 1.50

Brief description of critical parts behave nonlinearly

TOWERS: seismic loads

EUROPÄISCHE NORM

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Supersedes ENV 1998-3:1996

English version

Eurocode 8: Design of structures for earthquake resistance - Part 6: Towers, masts and chimneys

Eurocode 8: Calcul des structures pour leur résistance aux séismes - Partie 6 : Tours, mâts et cheminées

Eurocode 8: Auslegung von Bauwerken gegen Erdbeben - Teil 6: Türme, Maste und Schornsteine

Brief description of critical parts behave nonlinearly

TOWERS: seismic loads

The seismic loads are in accordance with the specifications of a Seismic Code where the design seismic motion has a 10% likelihood of being exceeded during a period of 50 years. For the case of EC8, the corresponding elastic design spectrum of horiz. acceleration $S_d(T)$ is defined as:

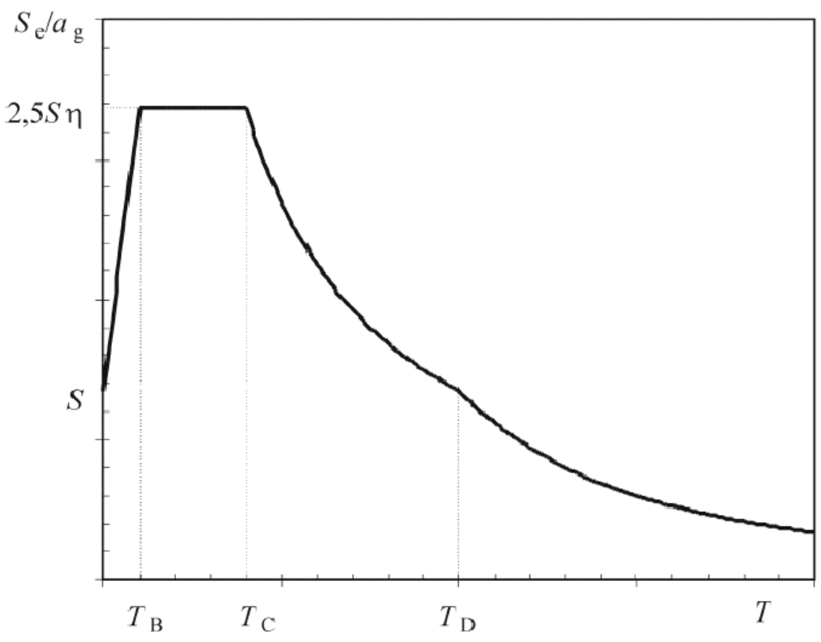
$$0 \le T \le T_B : S_d(T) = a_g \cdot S \cdot \left[\frac{2}{3} + \frac{T}{T_B} \cdot \left(\frac{2,5}{q} - \frac{2}{3} \right) \right]$$

$$T_B \le T \le T_C : S_d(T) = a_g \cdot S \cdot \frac{2,5}{q}$$

$$T_C \le T \le T_D : S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2,5}{q} \cdot \left[\frac{T_C}{T} \right] \\ \ge \beta \cdot a_g \end{cases}$$

$$T_D \le T : S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2,5}{q} \cdot \left[\frac{T_C T_D}{T^2} \right] \\ \ge \beta \cdot a_g \end{cases}$$

$S_d(T)$	design spectrum
T	vibration period of a linear SDOF system
a_g	design ground acceleration on type A ground ($a_g = \gamma_I \cdot a_{gR}$)
T_B, T_C	limits of the constant spectral acceleration branch
T_D	value defining the beginning of the constant displacement response range of the spectrum
S	soil factor
q	behaviour factor
η	damping correction factor with reference value η = 1 for 5% viscous damping
β	lower bound factor for the horizontal design spectrum. Recommended value: β=0,2



The EC8 response spectrum

Brief description of critical parts behave nonlinearly

TOWERS: seismic loads

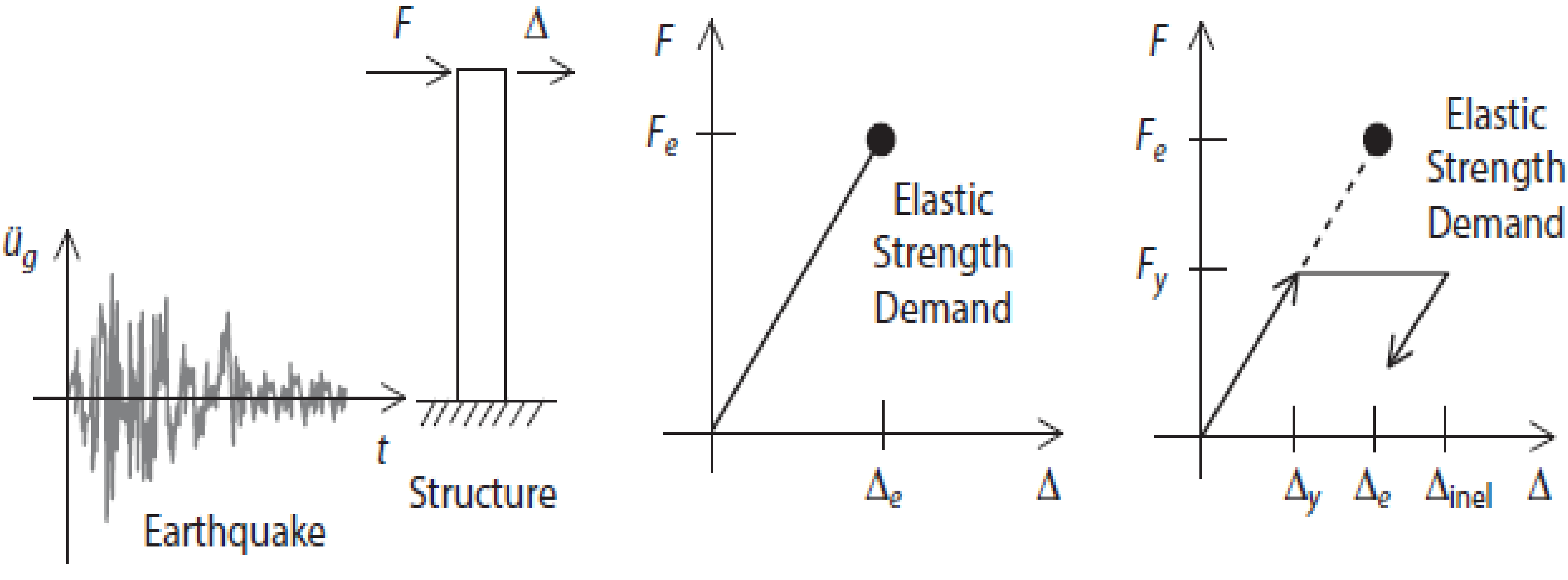
Table 4.1 Importance classes for towers, masts and chimneys

Importance class	
I	Tower, mast or chimney of minor importance for public safety
II	Tower, mast or chimney not belonging in classes I, III or IV
III	Tower, mast or chimney whose collapse may affect surrounding buildings or areas likely to be crowded with people.
IV	Towers, masts or chimneys whose integrity is of vital importance to maintain operational civil protection services (water supply systems, an electrical power plants, telecommunications, hospitals).

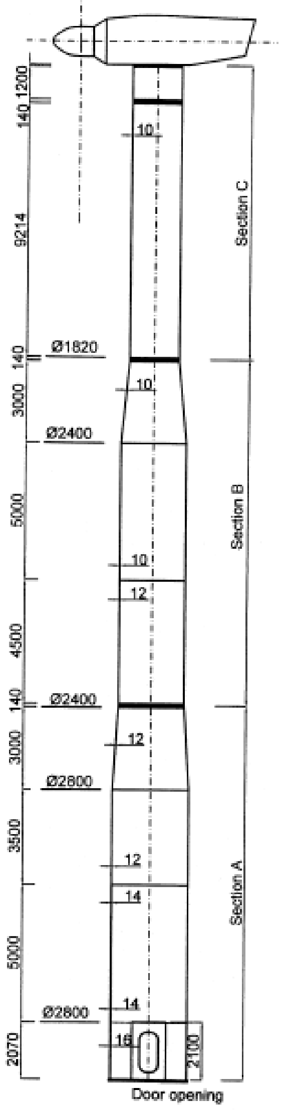
Importance factor γ_{IV}=1.40 (i.e. seismic forces are 40% than that of 'regular' structures.

Brief description of critical parts behave nonlinearly

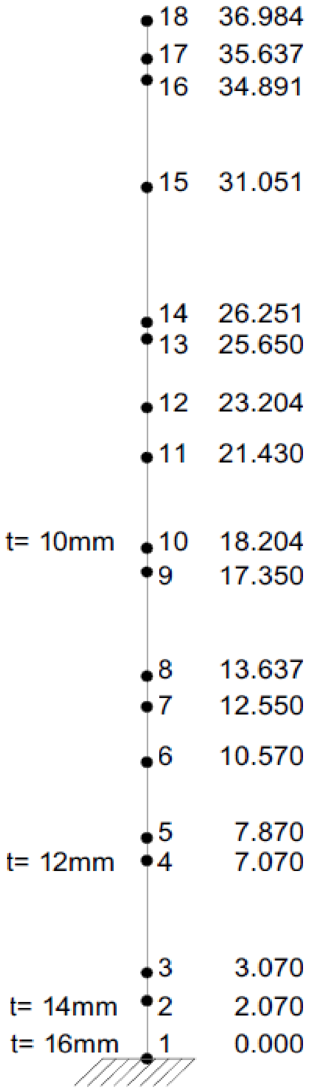
TOWERS



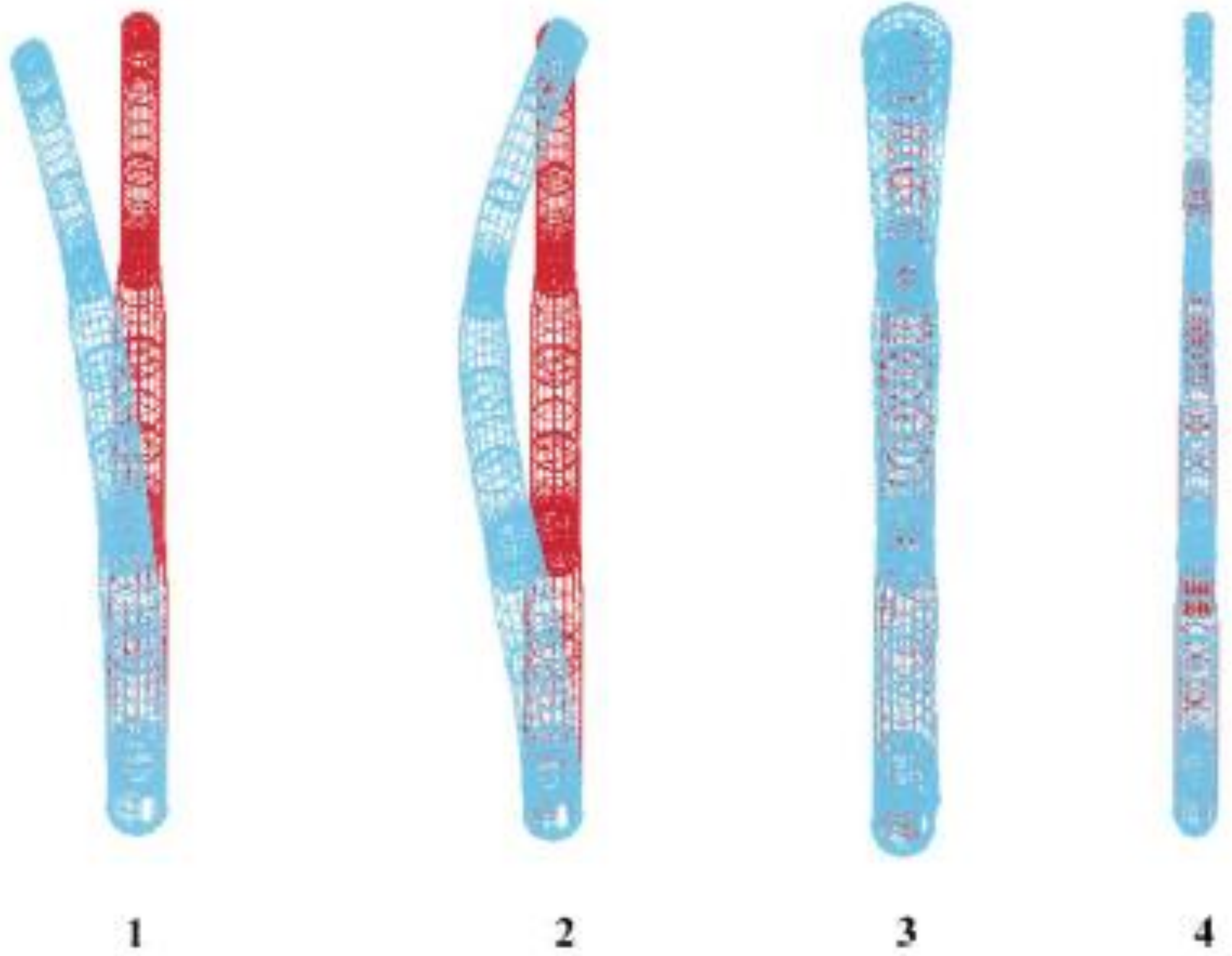
(a) Earthquake Loading (b) Elastic Response (c) Inelastic Response



Tower



Simplified concentrated masses model for seismic analysis



The first four eigenmodes of a steel tower (finite element model)

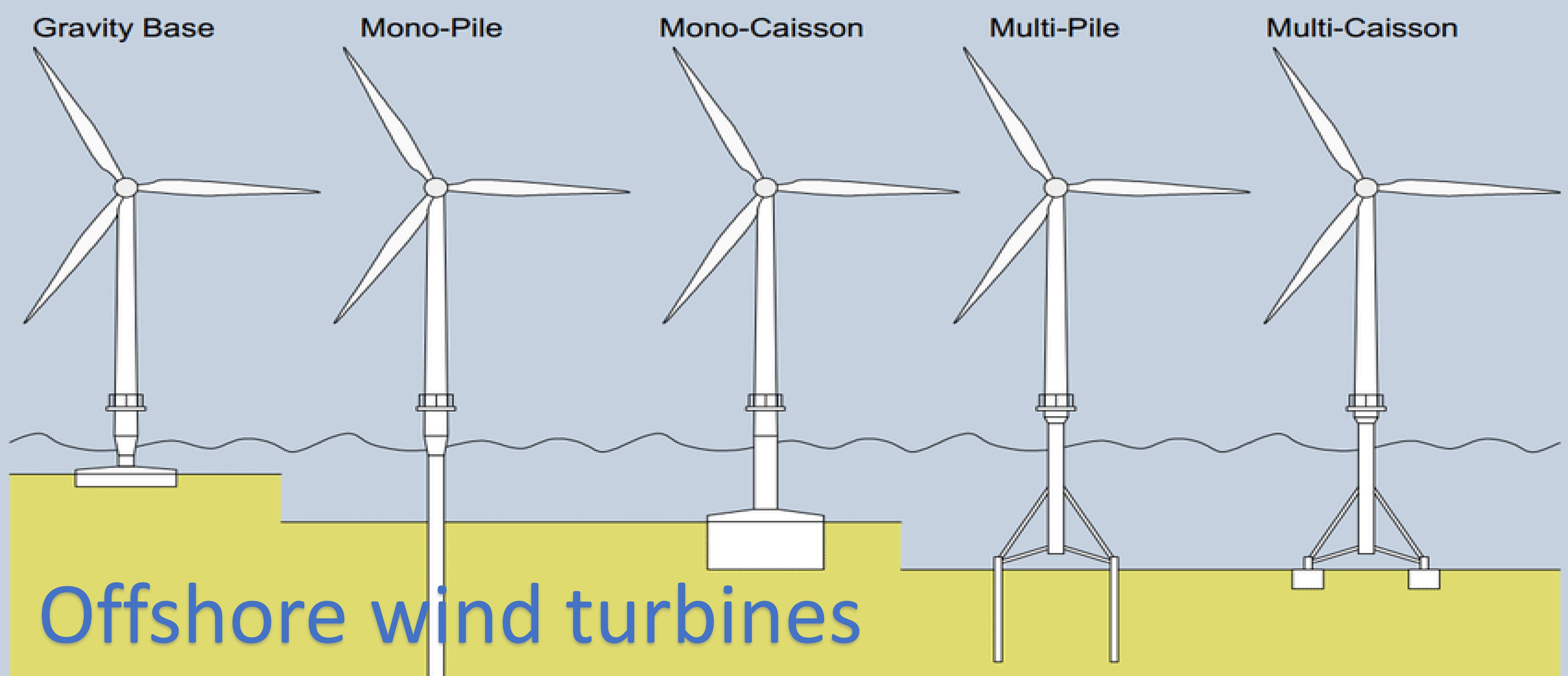
Brief description of critical parts behave nonlinearly

Inelastic Analysis of Foundation Structures

The earthquake, wind or wave (for offshore) wind turbines response of shallow and deep foundations is having a significant importance due to its complex behavior because of the semi-infinite soil media. The nonlinear response of wind turbines resting on this improved foundation model can be analyzed by assuming that the foundation resists compression and tension. In reality, soil is weak in tension and its tension capacity needs to be neglected, which leads to lift-off regions at different locations. This phenomenon becomes much more complicated by considering the inelastic soil structure behavior, which leads to a highly nonlinear problem.

Brief description of critical parts behave nonlinearly

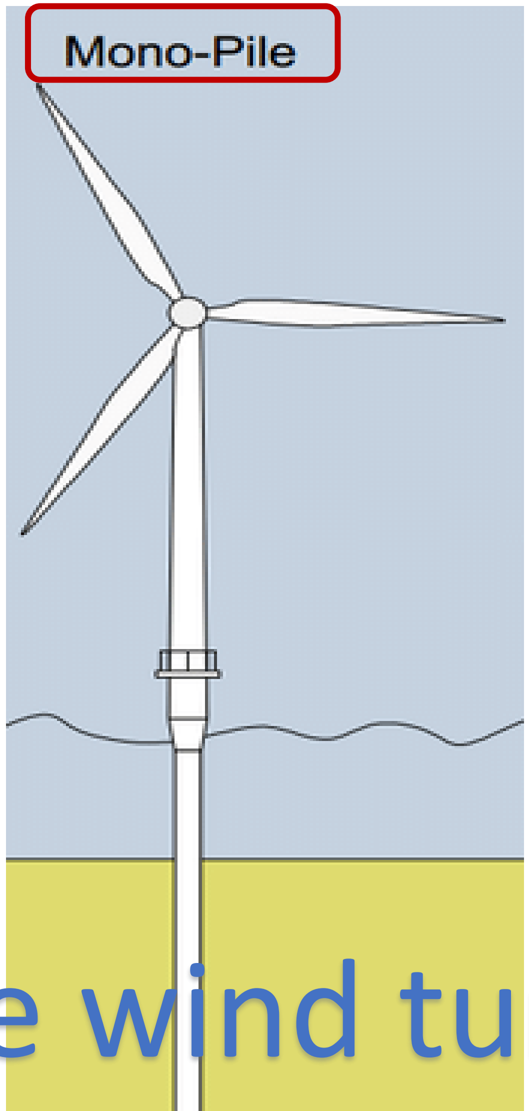
Inelastic Analysis of Foundation Structures

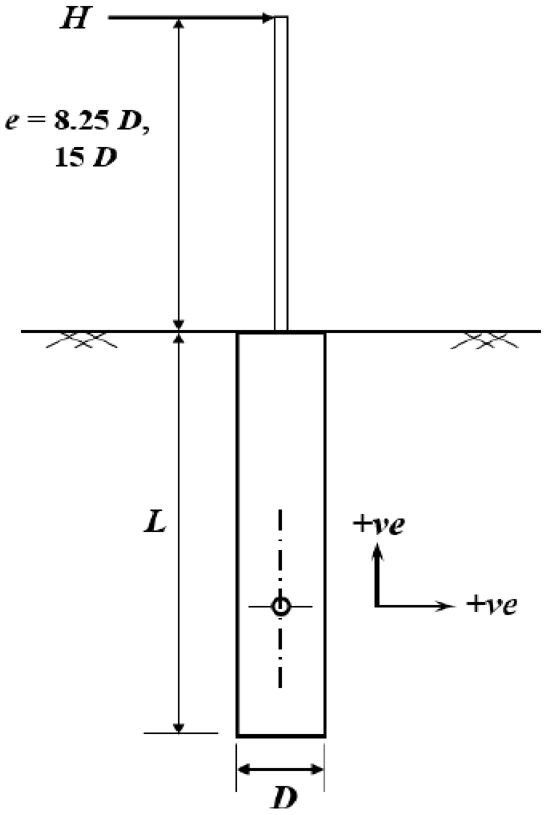


Brief description of critical parts behave nonlinearly

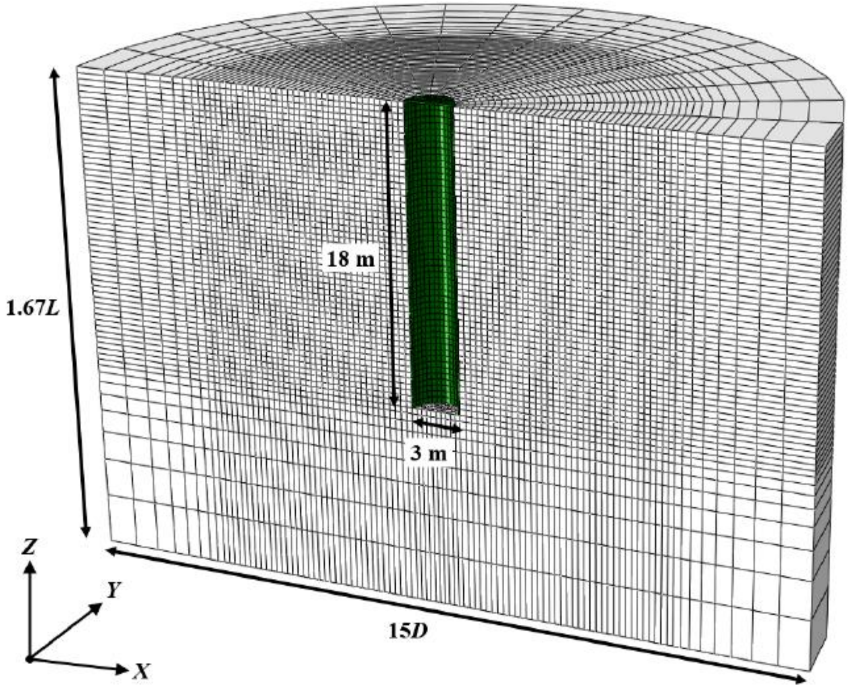
Inelastic Analysis of Foundation Structures

Case study





The schematic of the model monopile



Finite element mesh

Offshore wind turbines

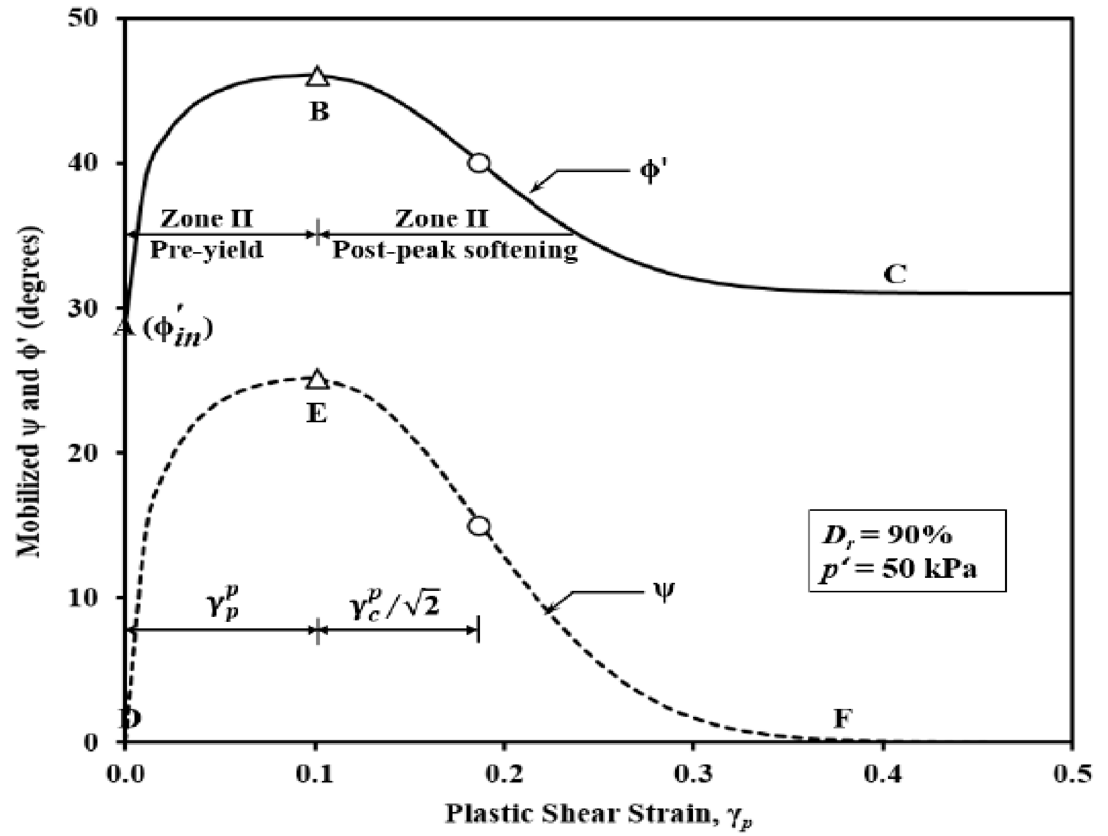
Brief description of critical parts behave nonlinearly

Inelastic Analysis of Foundation Structures

Description	Constitutive Equation	Soil Parameters
Relative density index	$I_R = I_D(Q - \ln p') - R$	$I_D = \frac{D_r(\%)}{100}$, $R = 1$ [24], $Q = 7.4 + 0.6\ln(\sigma'_c)$ & $7.4 \leq Q \leq 10$ [25], $\sigma'_c = p'\left(1 - \frac{2\sin\phi'_c}{3 - \sin\phi'_c}\right)$
Peak friction angle	$\phi'_p = \phi'_c + A_\psi I_R$	ϕ'_c, A_ψ
Peak dilation angle	$\psi_p = \left(\frac{\phi'_p - \phi'_c}{k_\psi}\right)$	k_ψ
Strain softening parameter	$\gamma^p_c = C_1 + C_2 I_D$	C_1, C_2
Plastic strain at ϕ'_p	$\gamma^p_p = \gamma^p_c \left(\frac{p'}{p'_a}\right)^m$	p'_a, m

Brief description of critical parts behave nonlinearly

Inelastic Analysis of Foundation Structures

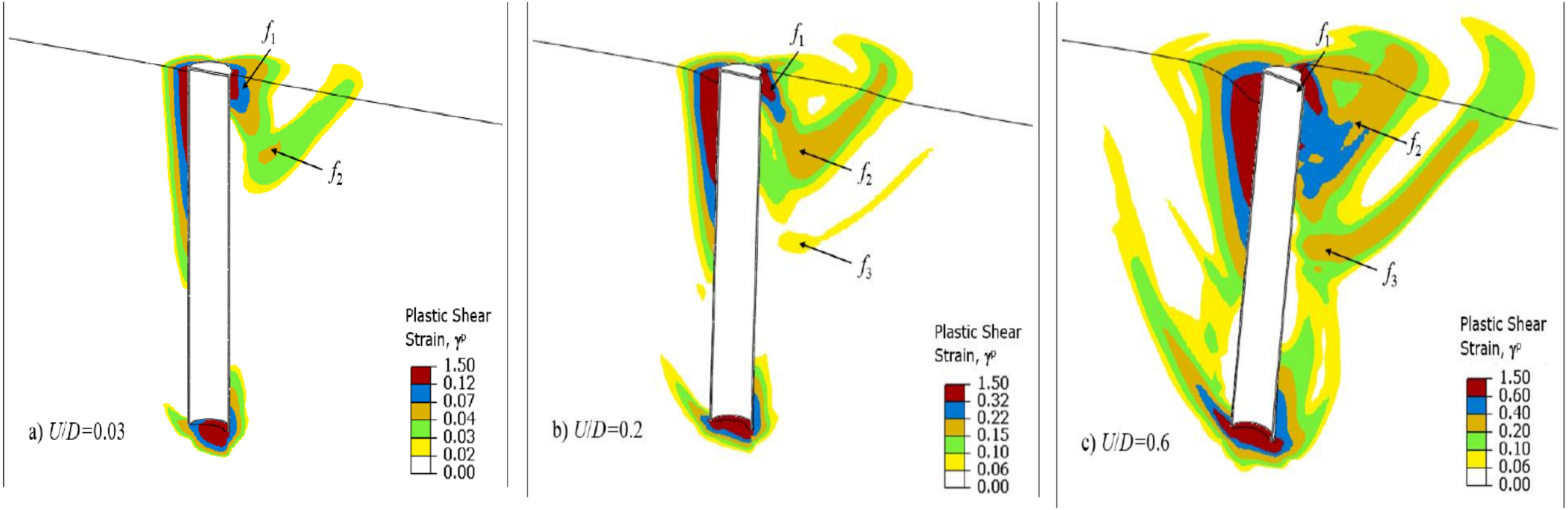
Description	Constitutive Equation	Soil Parameters
Mobilized friction angle at zone-II	$\phi' = \phi'_{in} + \sin^{-1}\left[\left(\frac{2\sqrt{\gamma^p \gamma^p_p}}{\gamma^p + \gamma^p_p}\right)\sin(\phi'_p - \phi'_{in})\right]$	
Mobilized dilation angle at Zone-II	$\psi = \sin^{-1}\left[\left(\frac{2\sqrt{\gamma^p \gamma^p_p}}{\gamma^p + \gamma^p_p}\right)\sin(\psi_p)\right]$	
Mobilized friction angle at zone-III	$\phi' = \phi'_c + \exp\left[-\left(\frac{\gamma^p - \gamma^p_p}{\gamma^p_c}\right)^2\right](\phi'_p - \phi'_c)$	
Mobilized dilation angle at Zone-III	$\psi = \exp\left[-\left(\frac{\gamma^p - \gamma^p_p}{\gamma^p_c}\right)^2\right]\psi_p$	

Symbols: A_ψ: slope of $(\phi'_p - \phi'_c)$ vs. I_R; m, C_1, C_2: soil parameters; I_R: relative density index; k_ψ: slope of $(\phi'_p - \phi'_c)$ vs. ψ_p; ϕ'_{in}: ϕ' at the start of plastic deformation; ϕ'_c: critical state friction angle; γ^p: engineering plastic shear strain

Brief description of critical parts behave nonlinearly

Inelastic Analysis of Foundation Structures

Modified Mohr-Coulomb criterion

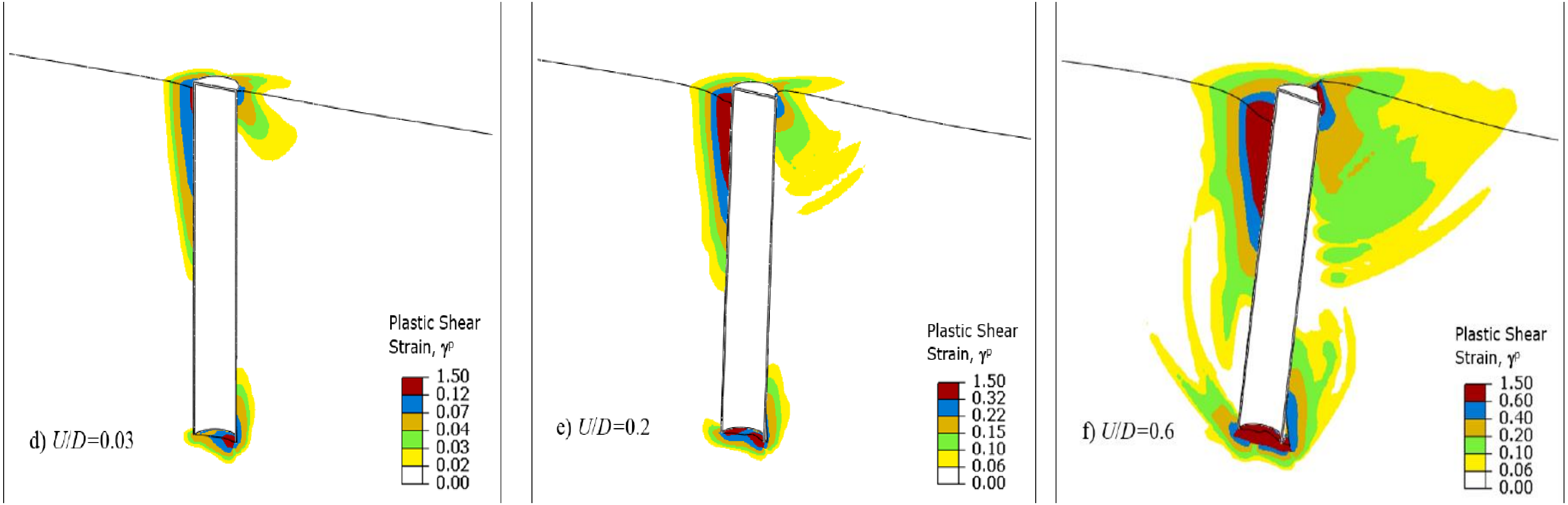


U/D: Normalized maximum displacement

Brief description of critical parts behave nonlinearly

Inelastic Analysis of Foundation Structures

Mohr-Coulomb criterion



U/D: Normalized maximum displacement

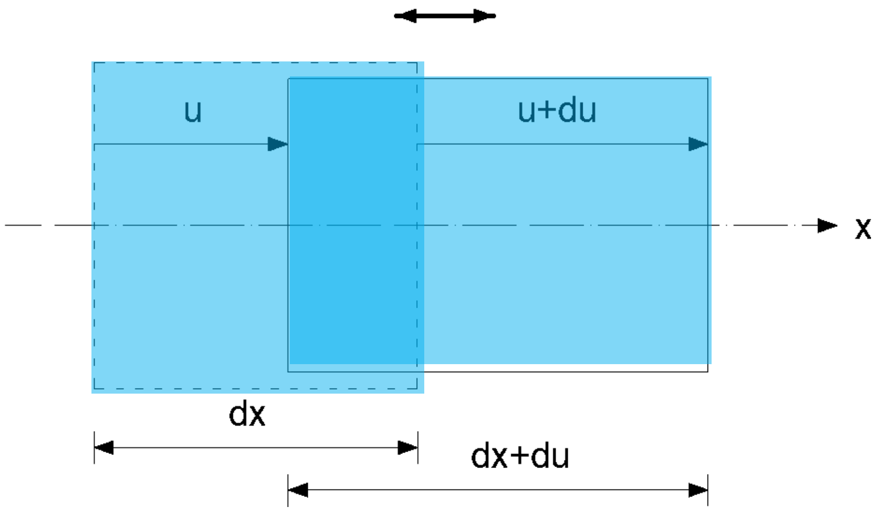
Brief description of critical parts behave nonlinearly

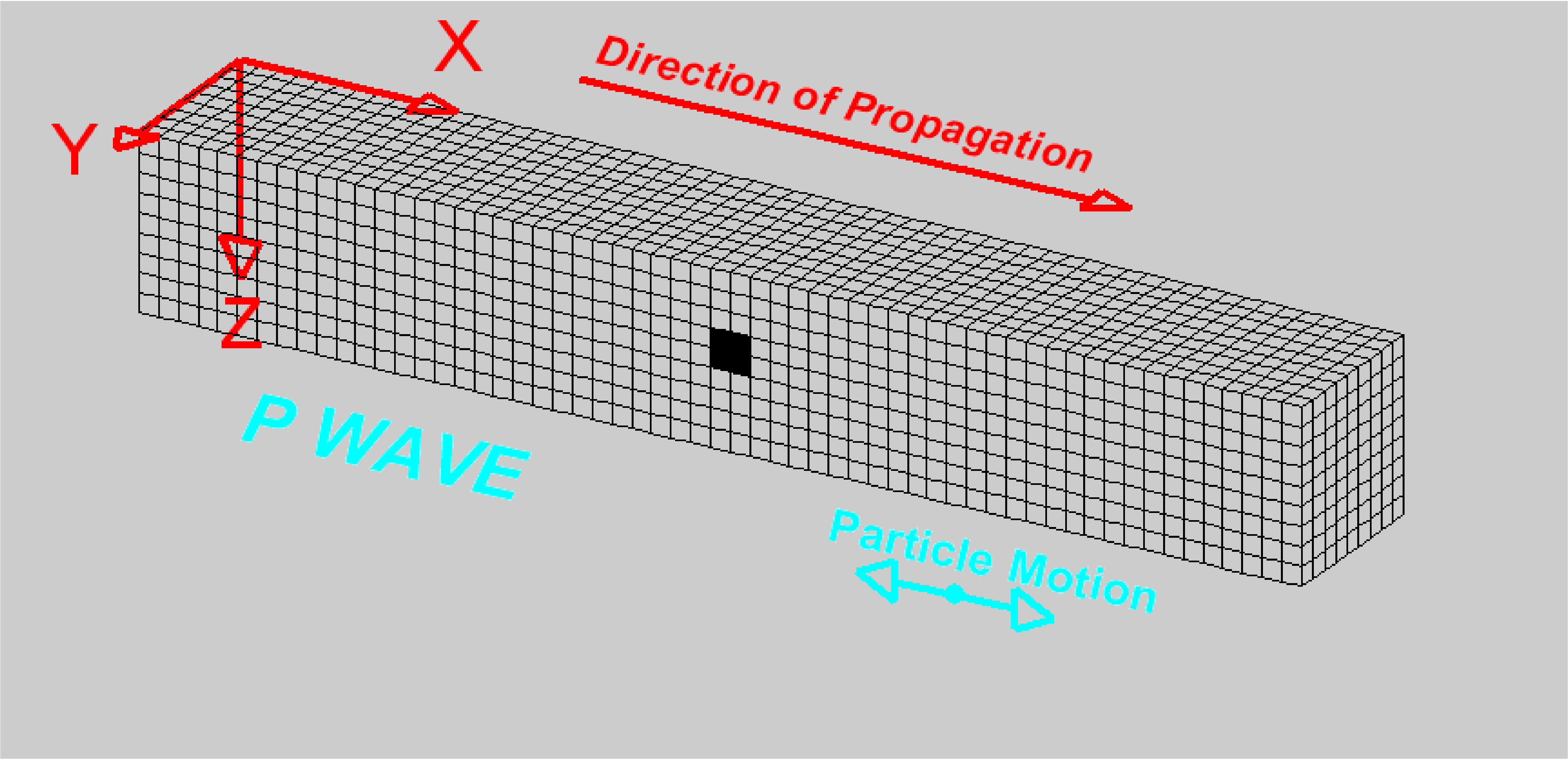
Seismic Inelastic Behavior of Soil

Wave propagation

- Principal or volume waves P
- Motion parallel to wave propagation.
- Compression or decompression: $\varepsilon = \dfrac{\partial u}{\partial x}$

- Velocity of propagation: $C = C_p = V_p = \alpha = \sqrt{\dfrac{\lambda + 2G}{\rho}}$




X
Y
Z
Direction of Propagation
P WAVE
Particle Motion

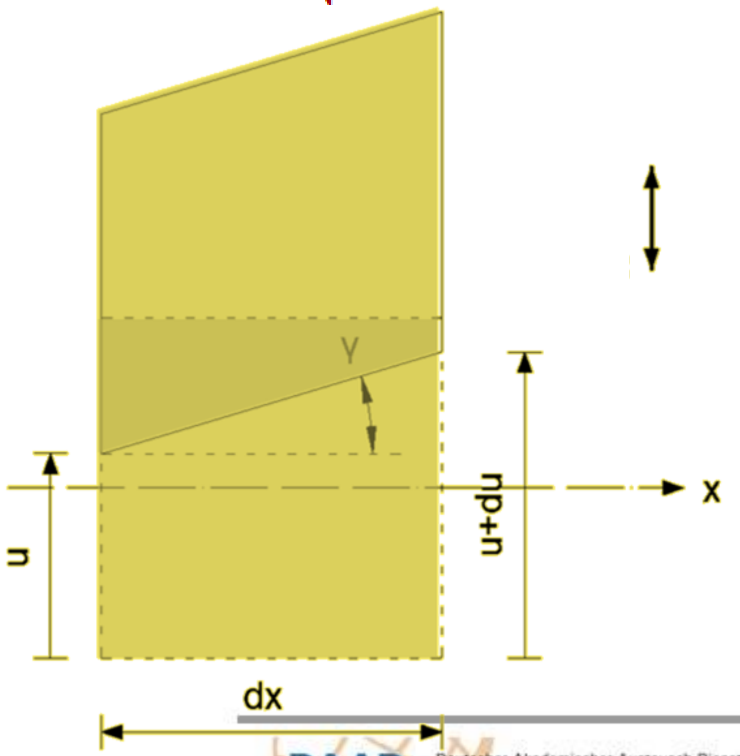
Transverse or shear waves S

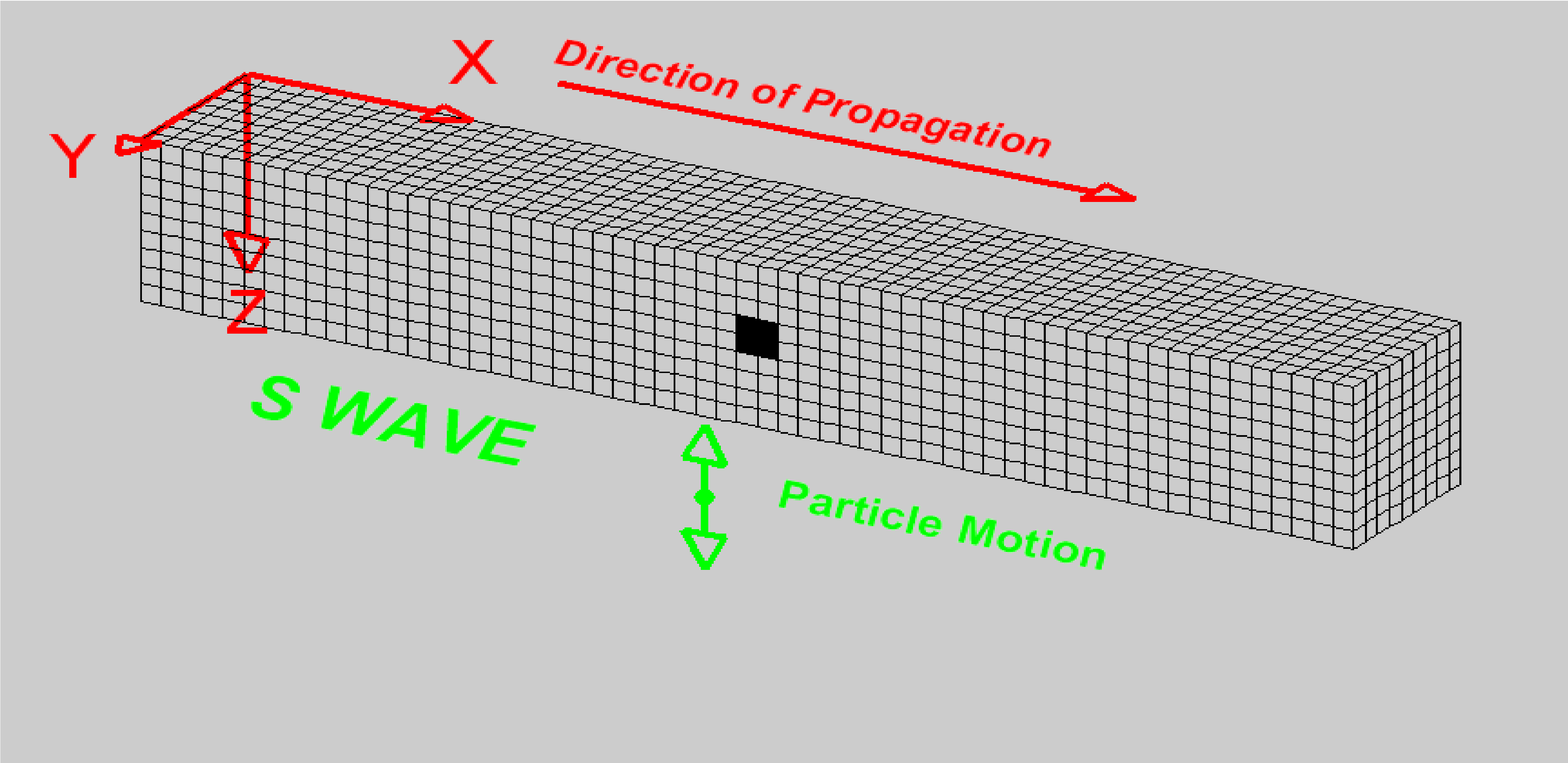
Transverse motion vs. wave propagation.

Shear stresses and strains: $\gamma = \dfrac{\partial u}{\partial x}$

Wave propagation

Propagation velocity: $C = C_s = V_s = \beta = \sqrt{\dfrac{G}{\rho}}$




X
Y
Z
Direction of Propagation
S WAVE
Particle Motion

One has:

$$C = V = \sqrt{\frac{N}{\rho}}$$

where:

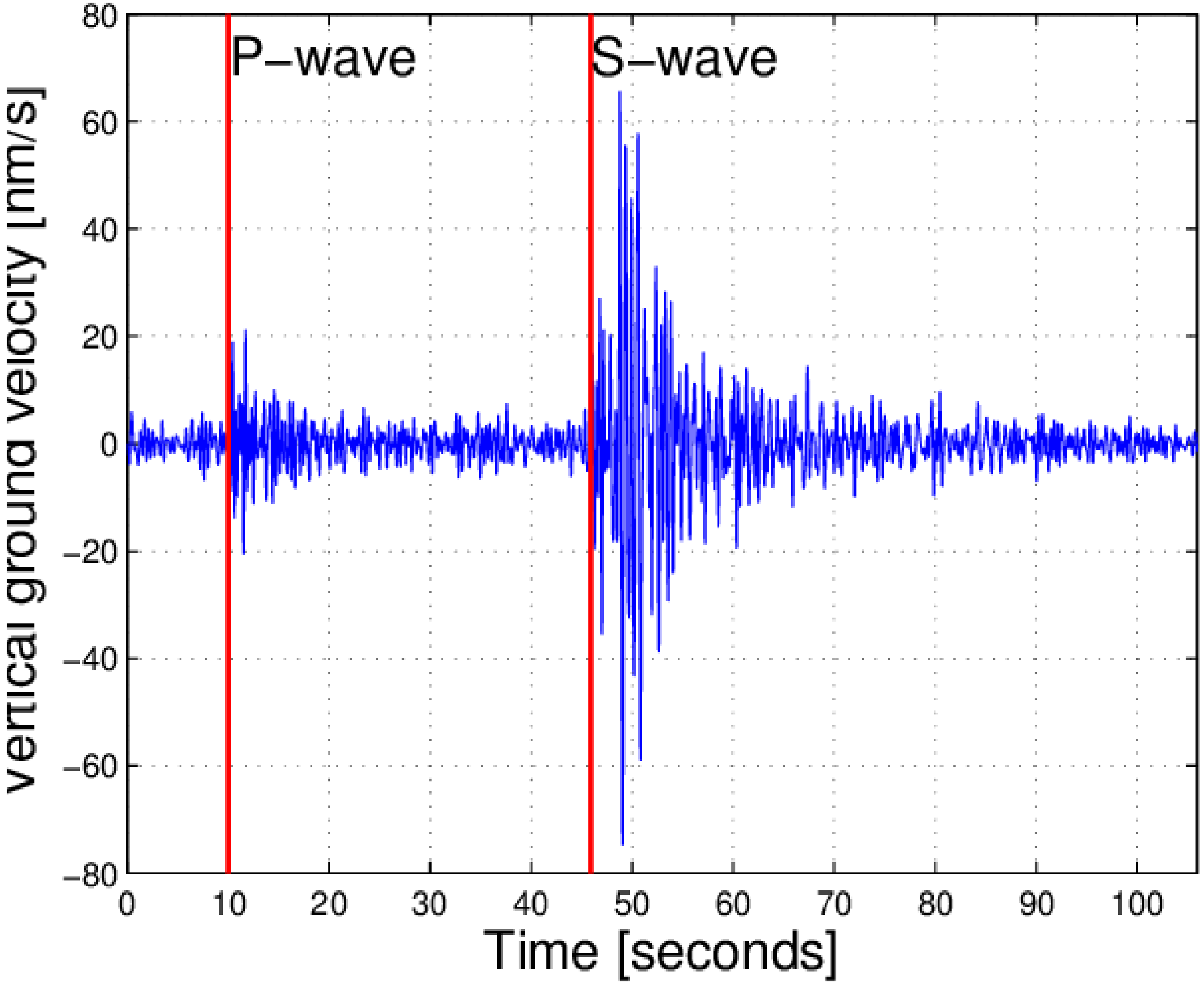
$N = D = \lambda + 2G$ P-wave

$N = G$ S-wave

Furthermore:

$\sigma = (\lambda + 2G) \cdot \varepsilon$ P-wave

$\tau = G \cdot \gamma$ S-wave



Earthquake with P-wave and S-wave arrivals record

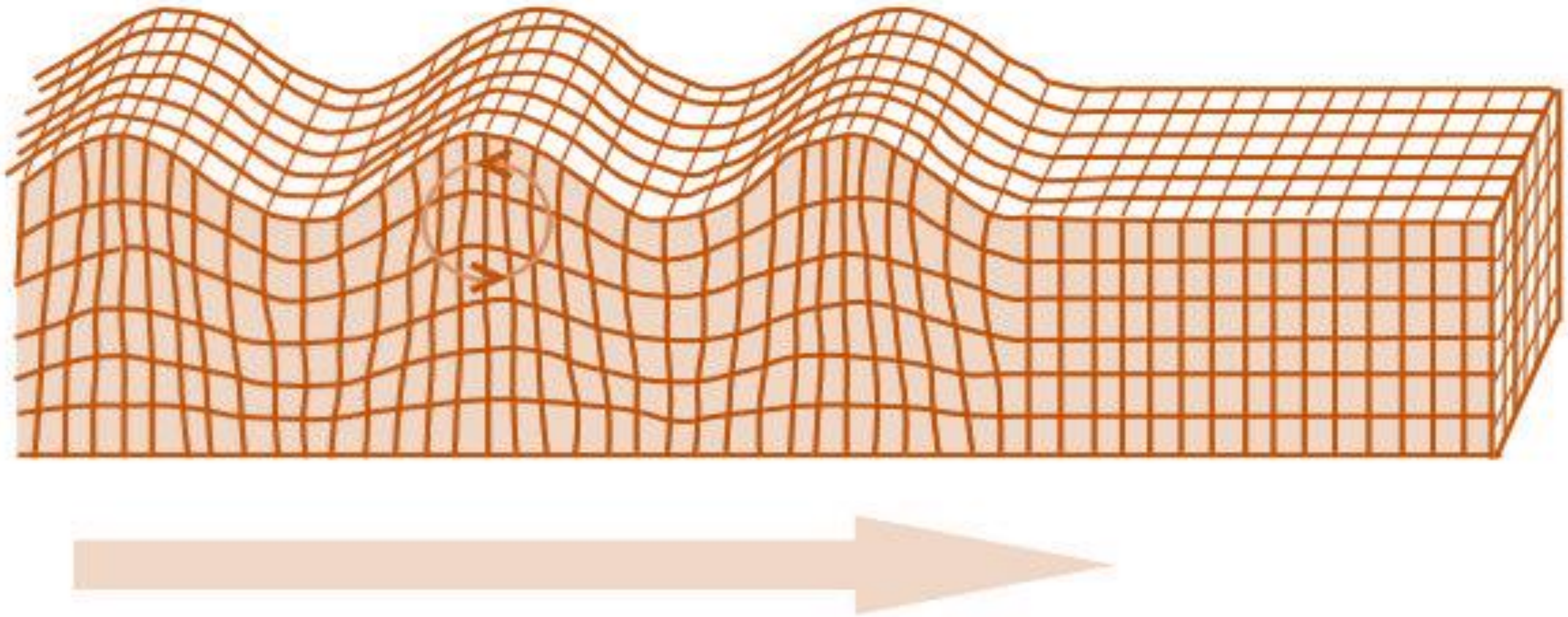
Rayleigh Surface Waves

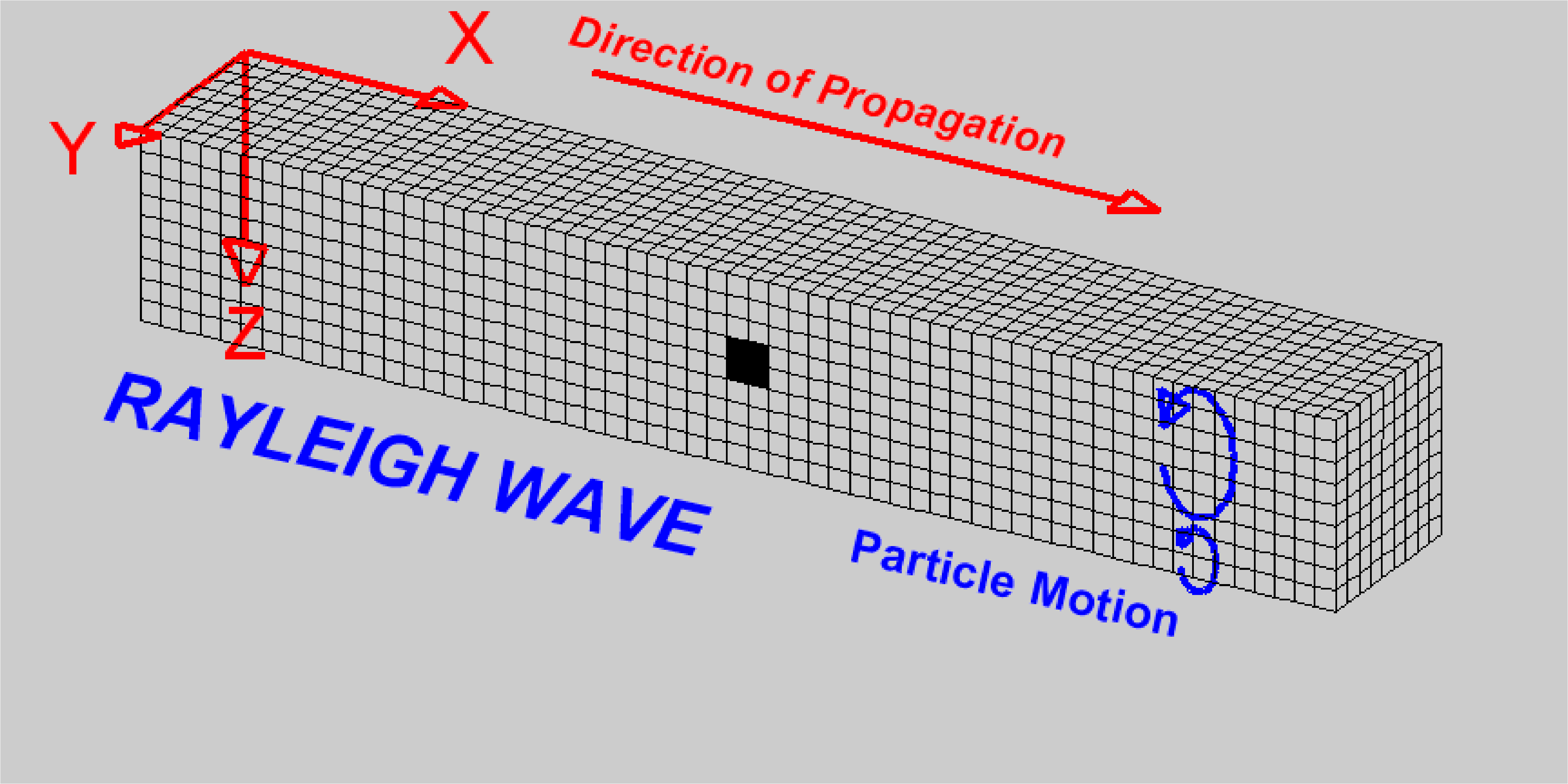
They are created and spread on the surface of the earth.

The motion of the particles is elliptical in the direction of propagation.

The motion of the particles decreases with depth.

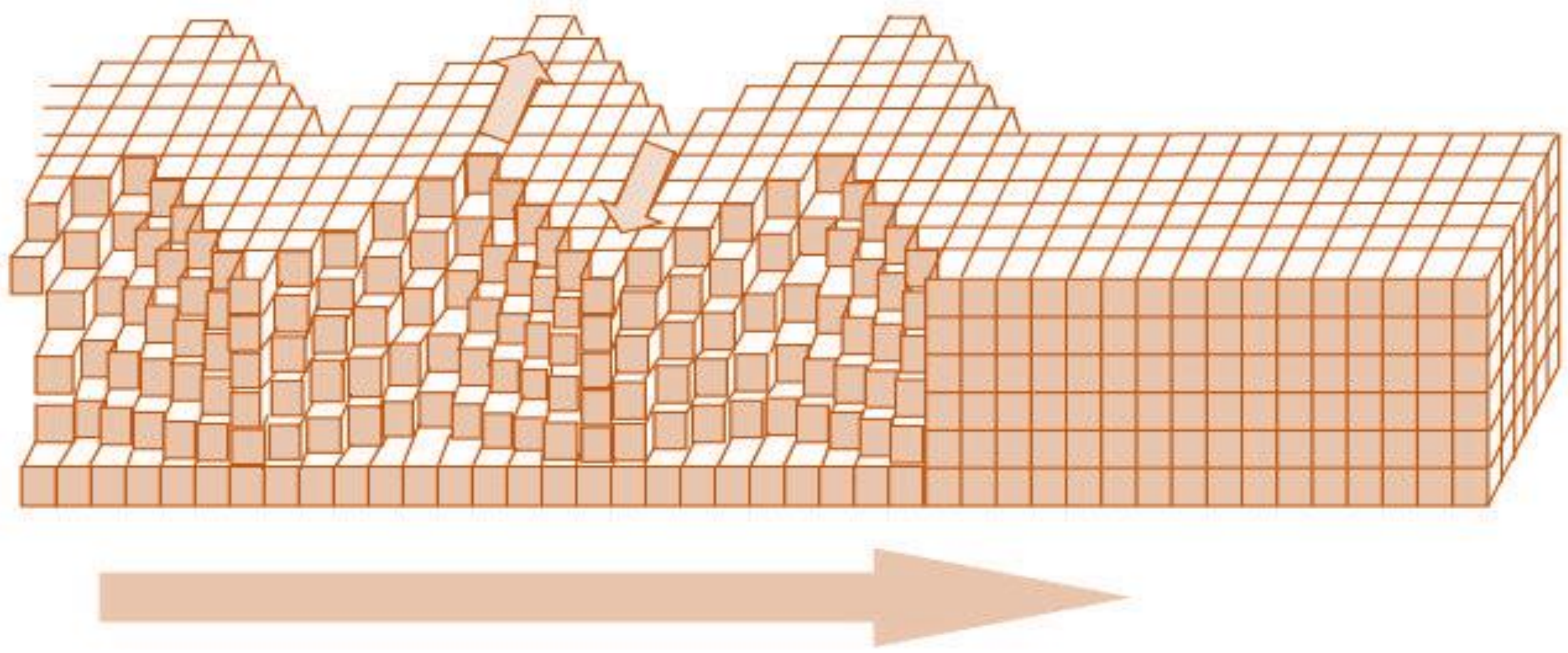
Wave propagation

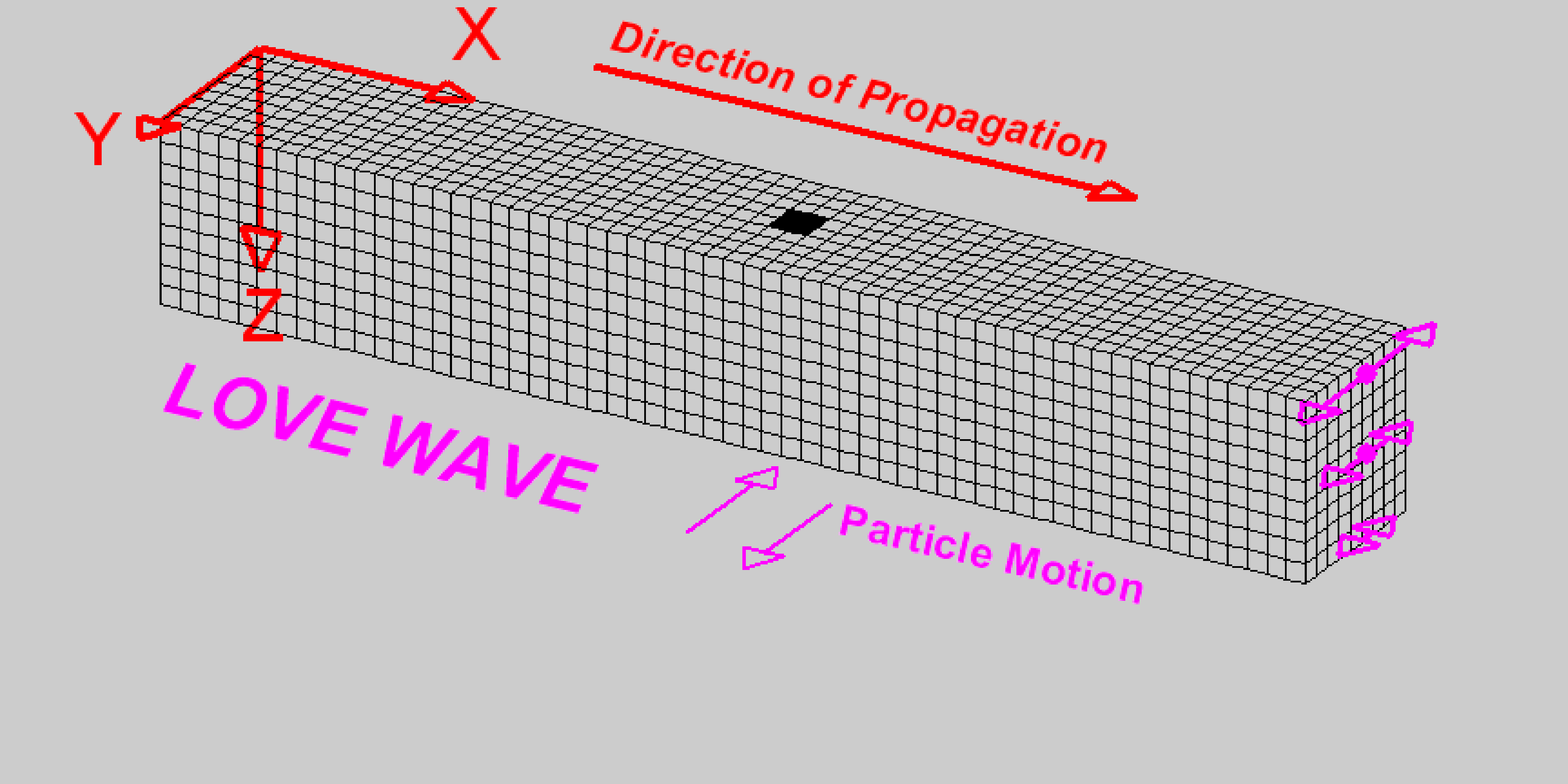



X
Y
Z
Direction of Propagation
RAYLEIGH WAVE
Particle Motion

Love Waves
They are created and spread on the surface of the earth.
The motion of the particles is horizontal/shear.
The motion of the particles decreases with depth.

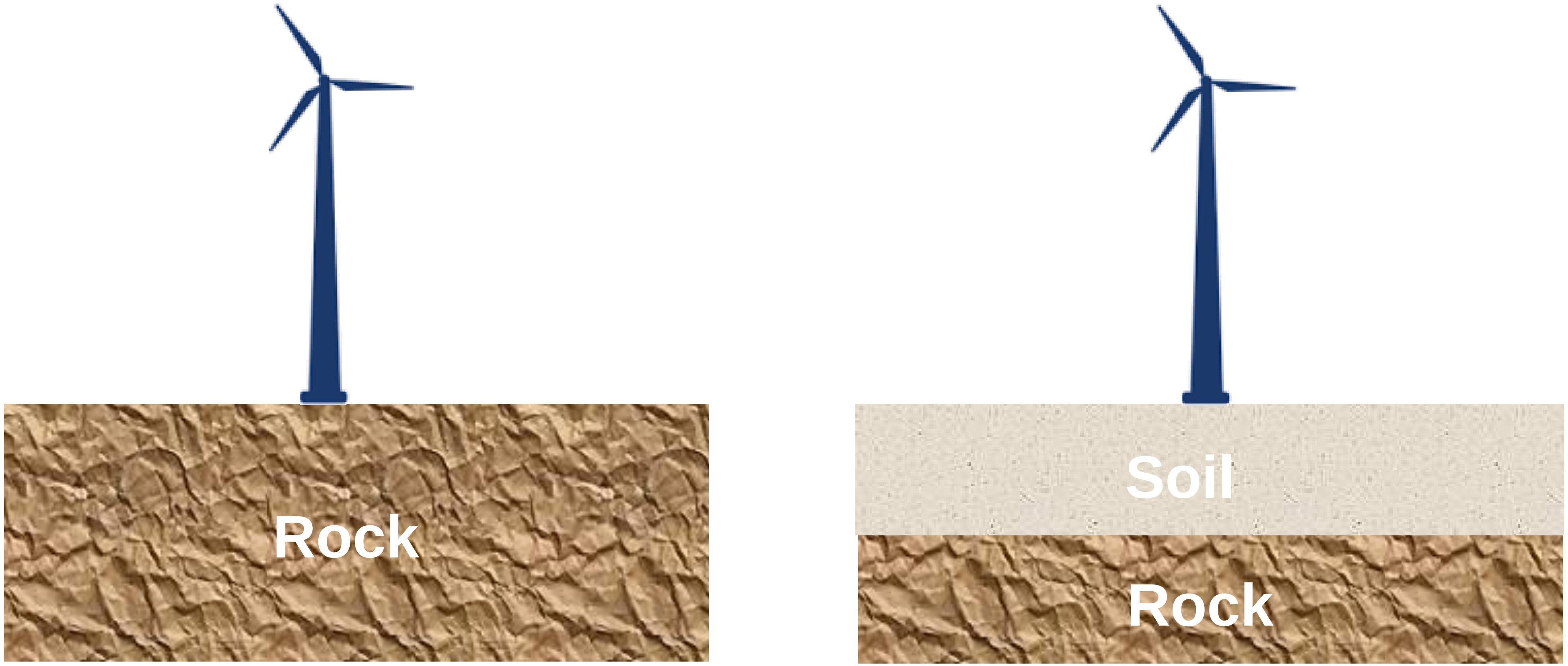
Wave propagation




X
Y
Z
Direction of Propagation
LOVE WAVE
Particle Motion

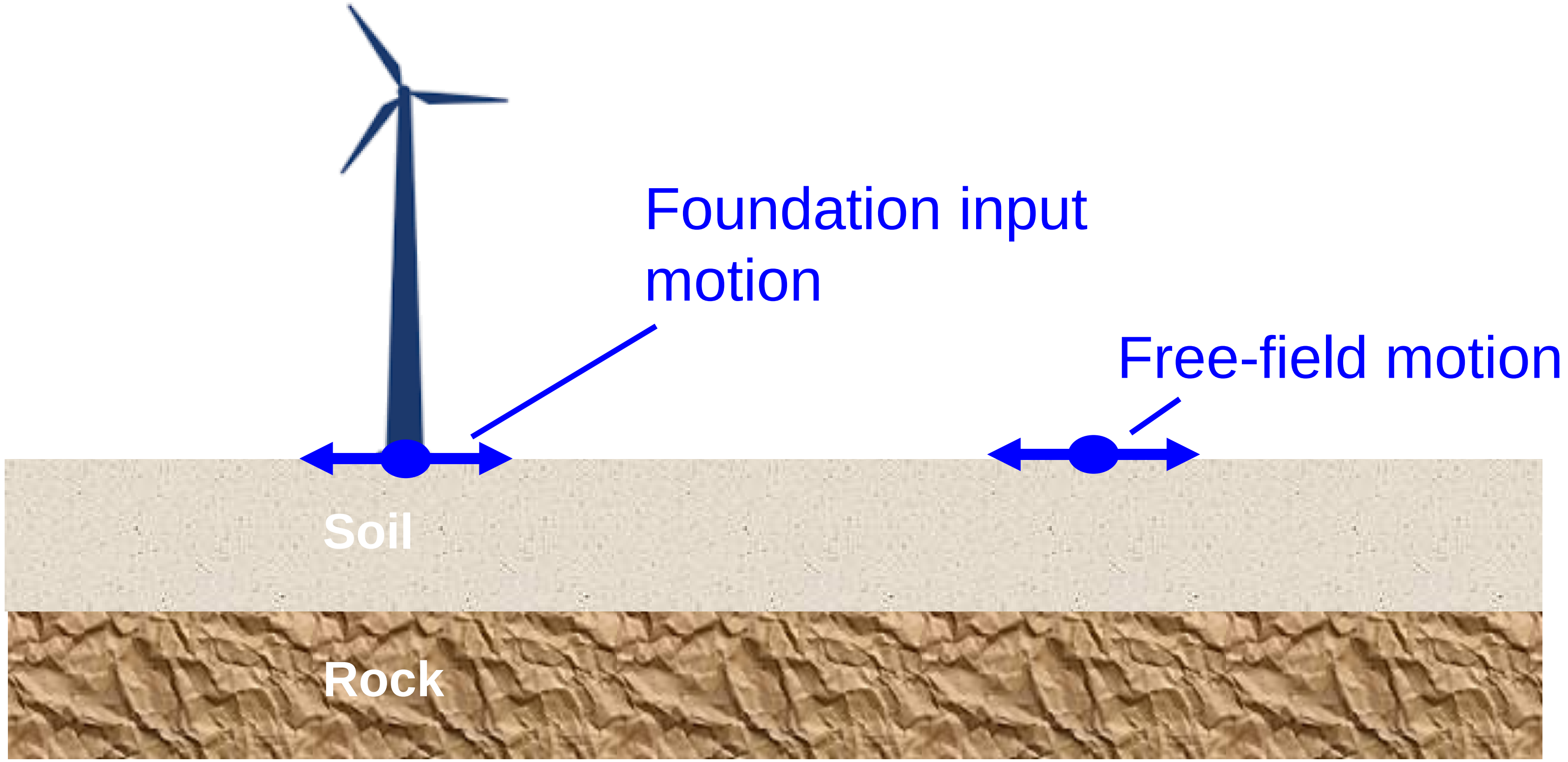
Soil-Tower Interaction

How does the presence of soil affect the response of the tower?



Does the structure founded on rock respond differently than when founded on soil?

Soil-Tower Interaction



How does the motion at the base of the tower differ from the free-field motion?

Soil-Tower Interaction

In reality, the response of the soil affects the response of the tower, and the response of the tower affects the response of the soil

Soil-Tower Interaction

<u>Kinematic interaction</u>

Presence of stiff foundation elements on or in soil cause foundation motions to deviate from free-field motions.

<u>Inertial interaction</u>

Inertial response of tower causes base shear and moments which cause displacements of foundation relative to free-field.

Soil-Tower Interaction (STI)

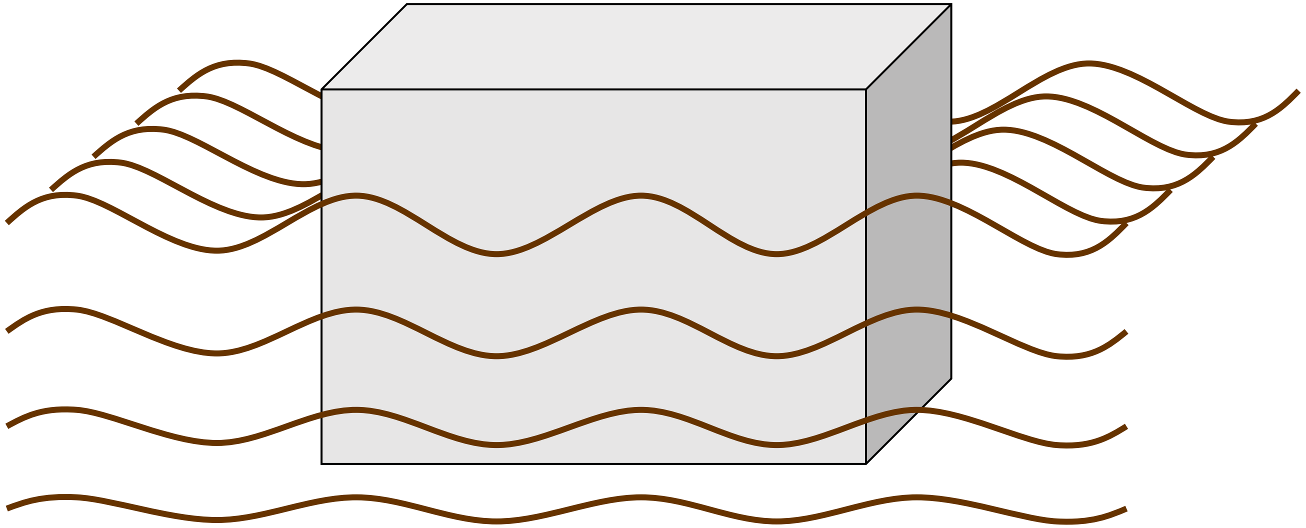
Kinematic STI has three primary causes:

Base slab averaging – results from stiffness of foundation

Embedment – reduction of ground motion with depth

Wave scattering – scattering off corners and edges

Ground motion amplitude decreases with depth

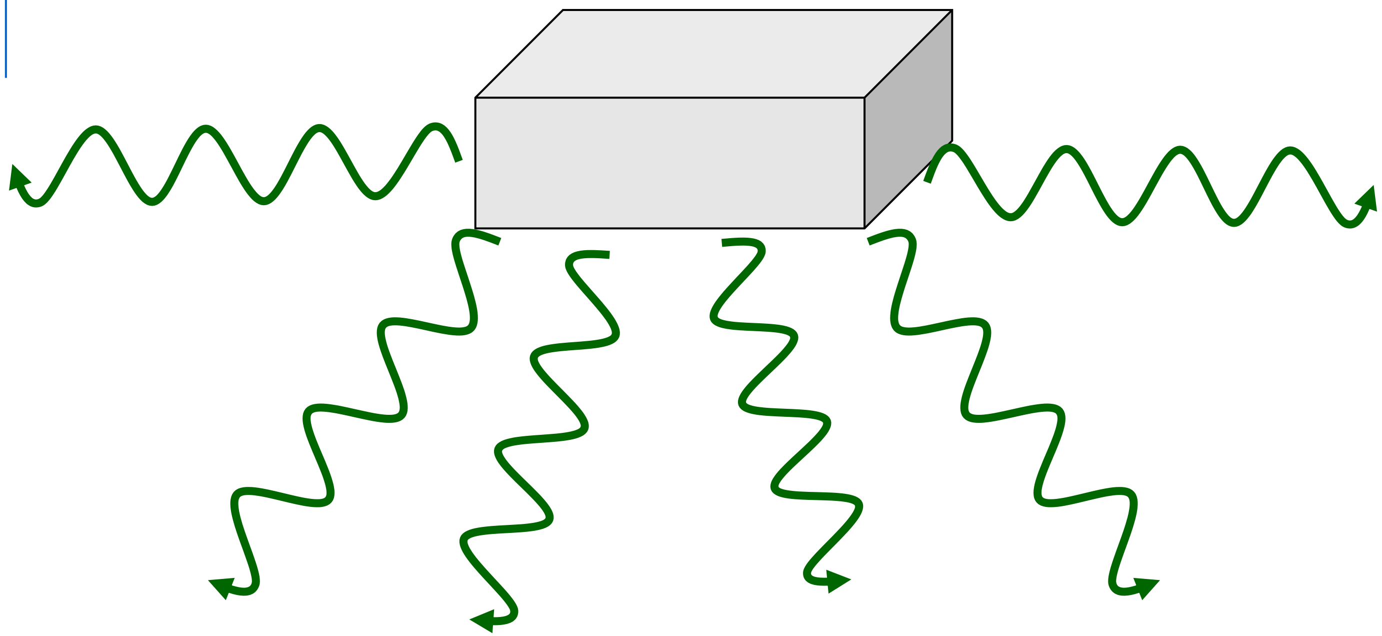


Soil-Tower Interaction (STI)

Inertial STI results from compliance of soil

Soil is not rigid – will deform due to loads from structure

Deformations resulting from structural forces will propagate away from structure



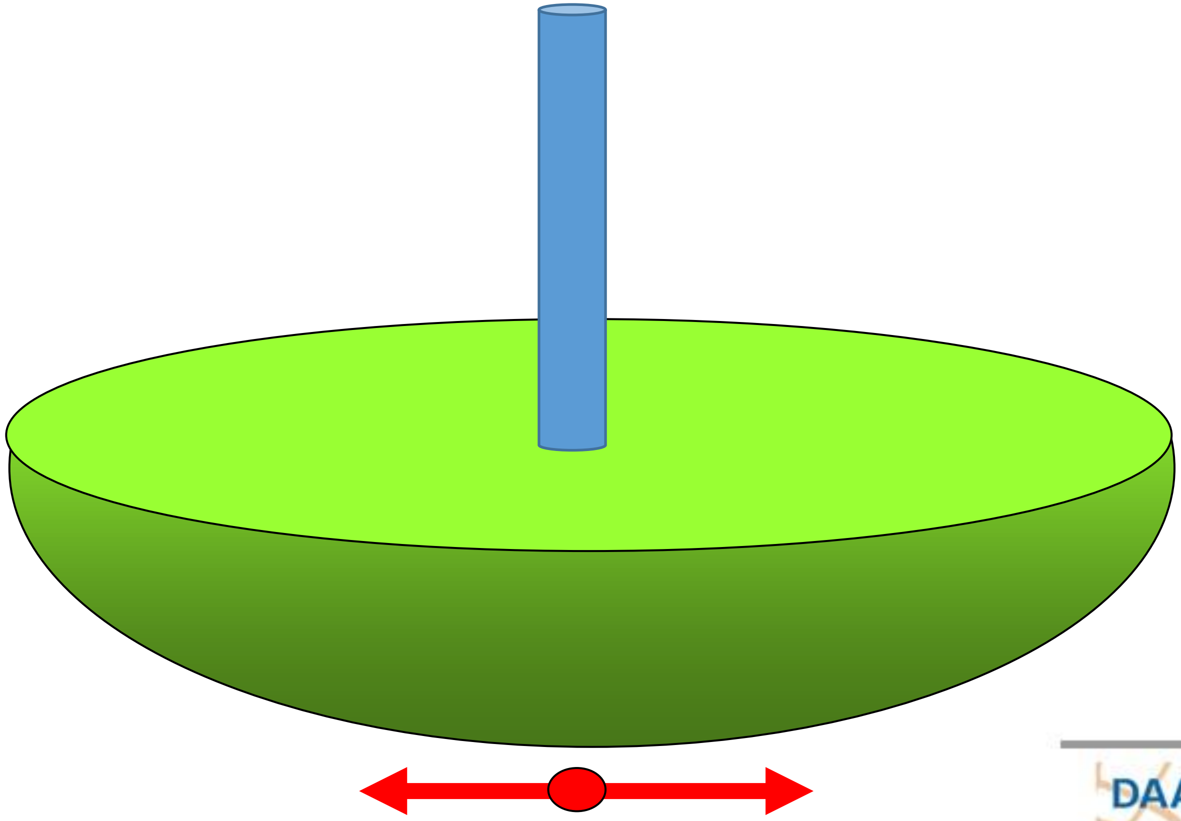
Energy “removed” from structure – radiation damping

Soil-Tower Interaction (STI)

Analysis of soil-tower interaction

Two approaches

Direct approach – model soil and tower together



Requires detailed model of tower and soil in one computer program

Can handle nonlinear soil and tower responses

Soil-Tower Interaction

Analysis of soil-tower interaction

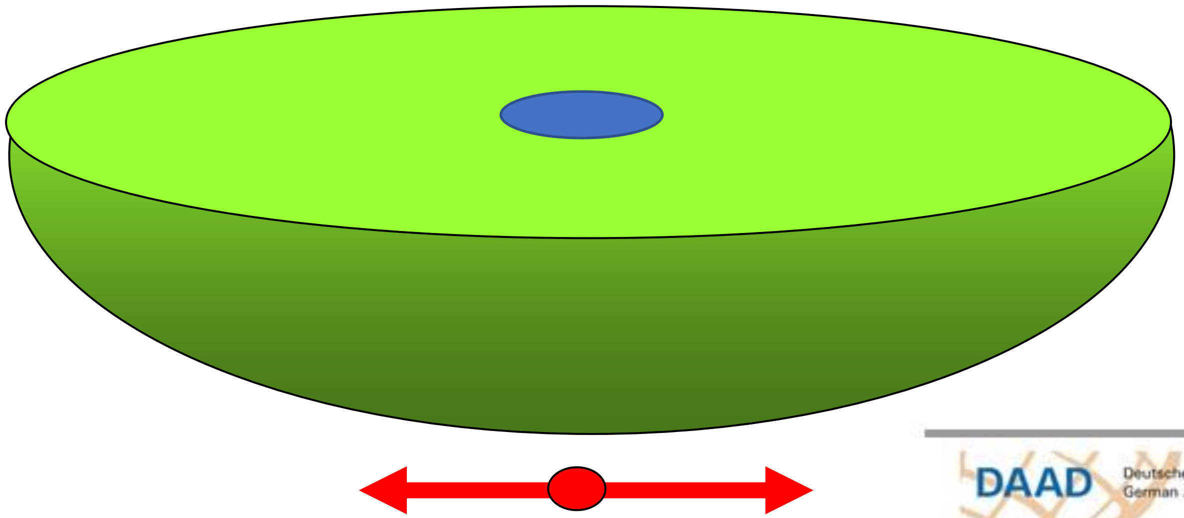
Two approaches

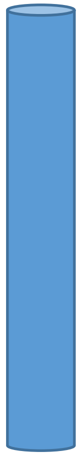
Direct approach – model soil and tower together

Substructure approach – model separately and combine

Can use different codes for soil and tower response

Kinematic STI



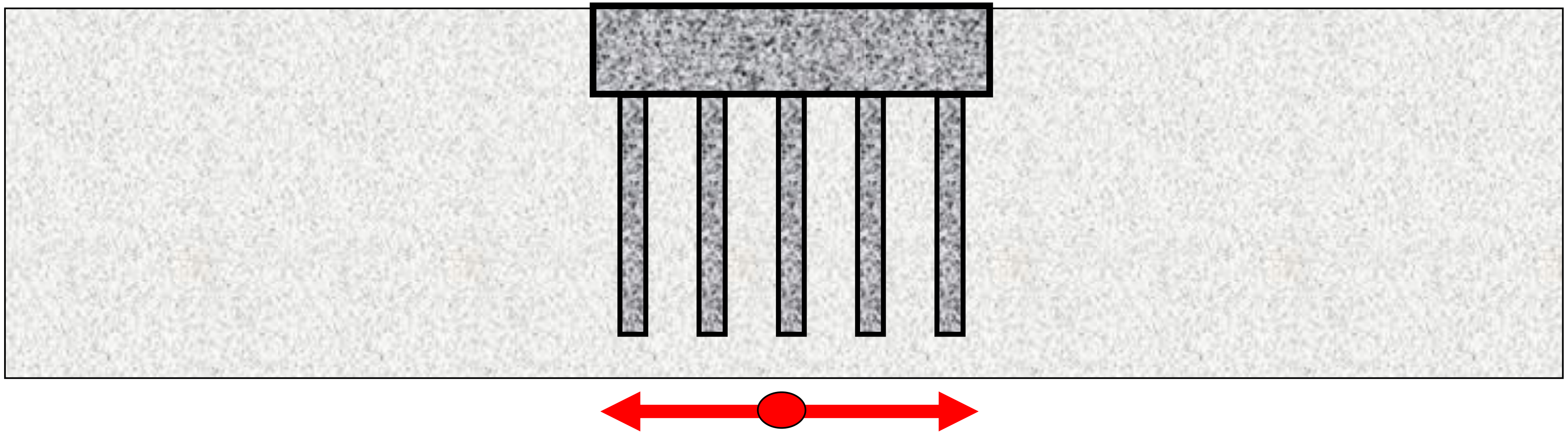


Inertial STI

Superposition requires linearity

Soil-Tower Interaction

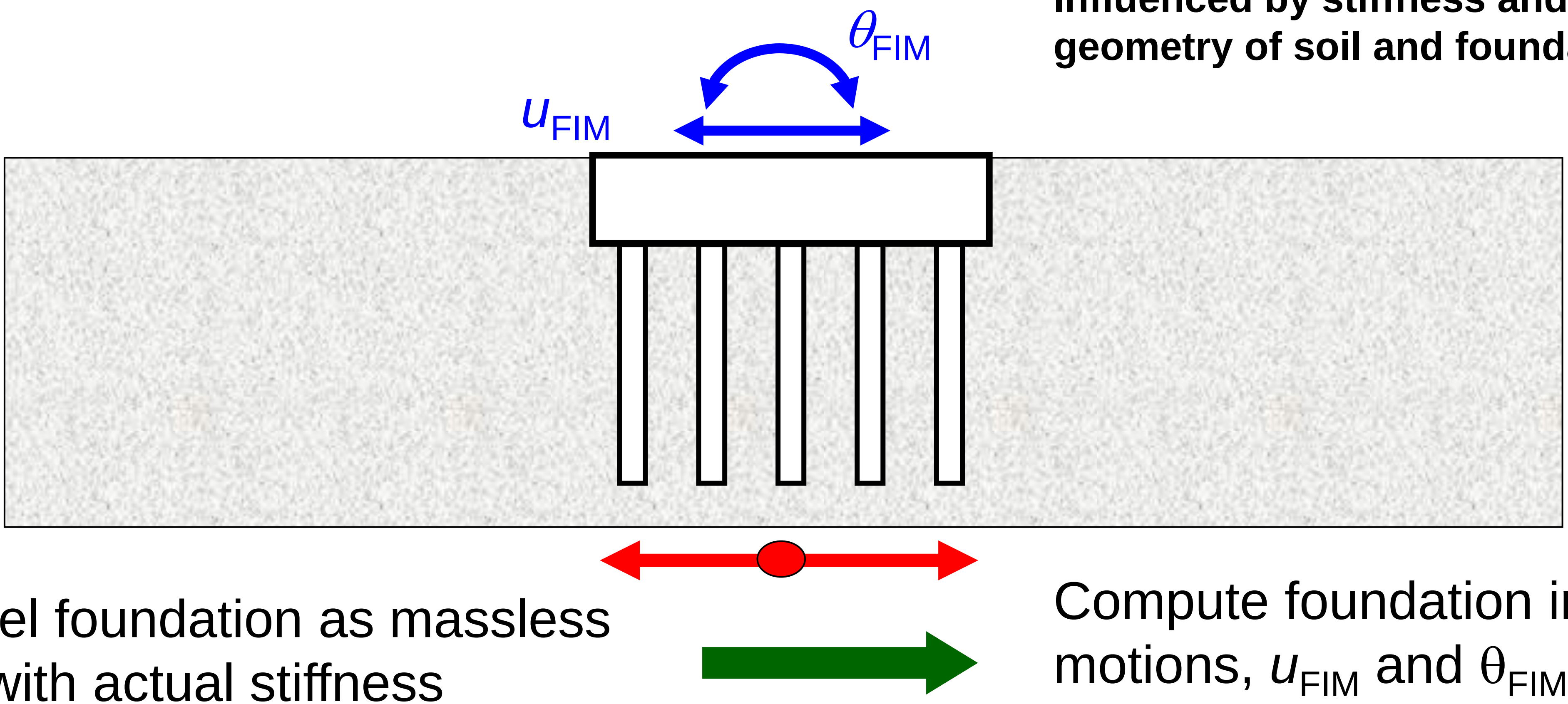
Analysis of kinematic soil-tower interaction



Soil-Tower Interaction

Analysis of kinematic soil-tower interaction

Influenced by stiffness and geometry of soil and foundation

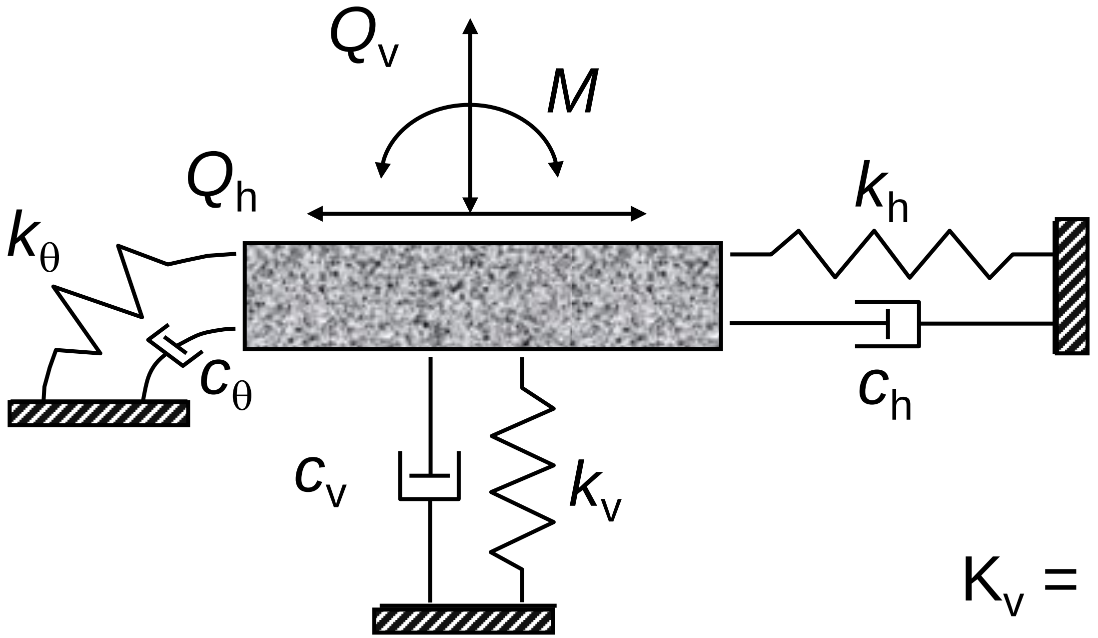


Model foundation as massless but with actual stiffness

Compute foundation input motions, u_{FIM} and θ_{FIM}

Soil-Tower Interaction

Impedance function – foundation stiffness and damping



$K_v = k_v + ic_v\omega$

6 x 6 matrix of complex impedance coefficients

3 translational coefficients

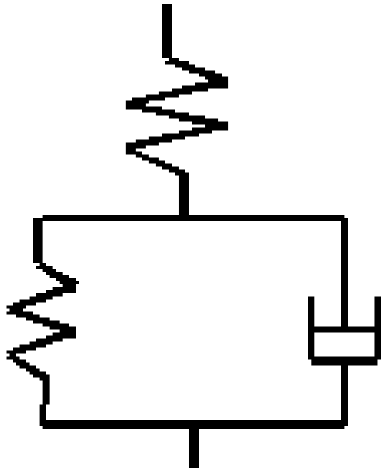
3 rotational coefficients

Cross-coupling (off-diagonal) coefficients

Nonlinear soil behavior

Three elements viscoelastic model

(Voigt model + linear elastic spring)



- Kondner, R. L., & Ho, M. M. (1965). Viscoelastic response of a cohesive soil in the frequency domain. Transactions of the Society of Rheology, 9(2), 329-342.
- Cox, W. R., Reese, L. C., & Grubbs, B. R. (1974, January). Field testing of laterally loaded piles in sand. In Offshore Technology Conference. Offshore Technology Conference.
- Oka, F., Kodaka, T., & Kim, Y. S. (2004). A cyclic viscoelastic–viscoplastic constitutive model for clay and liquefaction analysis of multi-layered ground. International journal for numerical and analytical methods in geomechanics, 28(2), 131-179.

3. Cyclic Viscoelastic-Viscoplstic Model

Viscoelastic - Viscoplastic Model

Infinitesimal

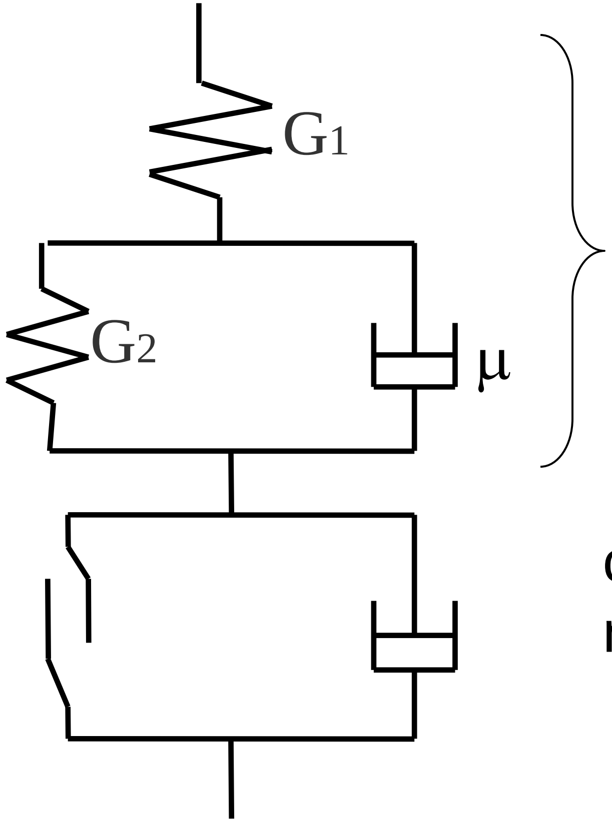
viscoelastic

Small

Strain level

viscoplastic

Large

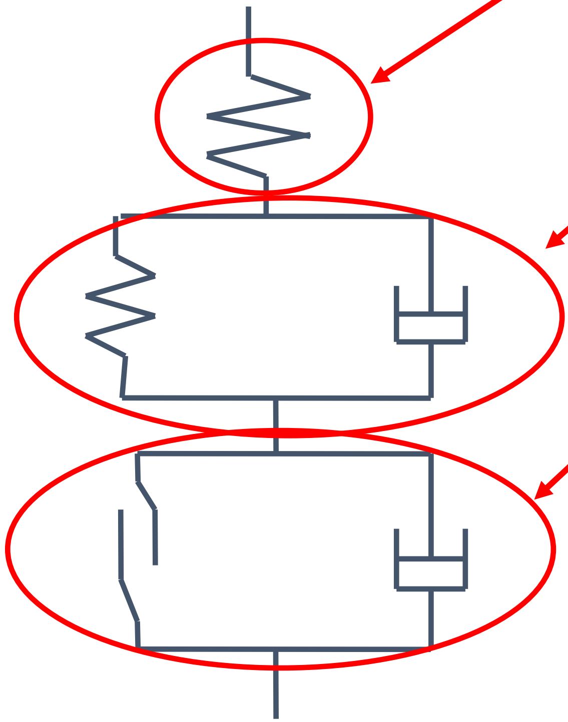


viscoelastic3 parameter model

cyclic viscoplastic model

Deviatric strain rate tensor: $\dot{e}_{ij}$

$$\dot{e}_{ij} = \dot{e}_{ij}^{e} + \dot{e}_{ij}^{vev} + \dot{e}_{ij}^{vp} = \dot{e}_{ij}^{ve} + \dot{e}_{ij}^{vp}$$



$\dot{e}_{ij}^{e}$: elastic component

$\dot{e}_{ij}^{vev}$: viscoelastic Voigt component

$\dot{e}_{ij}^{vp}$: viscoplastic component

Elastic Component

$$\dot{e}_{ij}^{e} = \frac{1}{2G_1}\dot{S}_{ij}$$

where

G_1: first elastic shear modulus

$\dot{S}_{ij}$: deviatoric stress rate tensor

Voigt Viscoelastic Component

$$\dot{e}_{ij}^{vev} = \frac{1}{\mu}(S_{ij} - 2G_2 \cdot e_{ij}^{vev})$$

where

μ: viscosity coefficient

G_2: second elastic shear modulus of Voigt element

S_{ij}: deviatoric stress tensor

3 Elements Viscoelastic Component

$$\dot{e}_{ij}^{ve} = \frac{1}{2G_1}\dot{S}_{ij} + \frac{1}{\mu}(S_{ij} - 2G_2 \cdot e_{ij}^{vev})$$

A Proposed Cyclic Viscoelastic and Viscoplastic Constitutive Model

$$\dot{\varepsilon}_{ij} = \frac{1}{2G_1}\dot{S}_{ij} + \frac{1}{\mu}\left(S_{ij} - 2G_2 \cdot e_{ij}^{vev}\right) + \frac{\kappa}{3(1+e)}\frac{\dot{\sigma}'_m}{\sigma'_m}\delta_{ij}$$
$$+ C_{01}\frac{< \Phi'_1(F) >}{\sigma'_m}\frac{\left(\eta^*_{ij} - \chi^*_{ij}\right)}{\bar{\eta}^*_x}$$
$$+ C_{02}\frac{< \Phi'_1(F) >}{\sigma'_m}\{\tilde{M}^* - \frac{\eta^*_{mn}\left(\eta^*_{mn} - \chi^*_{mn}\right)}{\bar{\eta}^*_x}\}\frac{1}{3}\delta_{ij}$$

Three elements viscoelastic model

+

Cyclic viscoplastic model

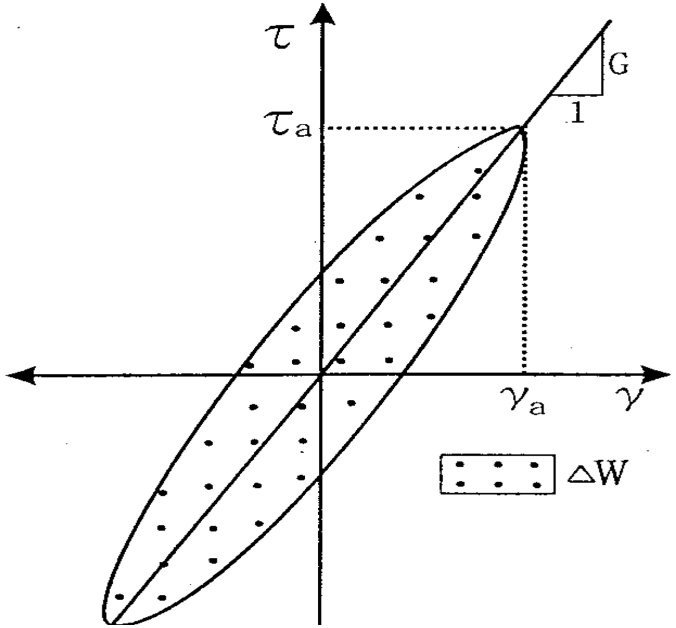
Cyclic Triaxial Deformation Tests

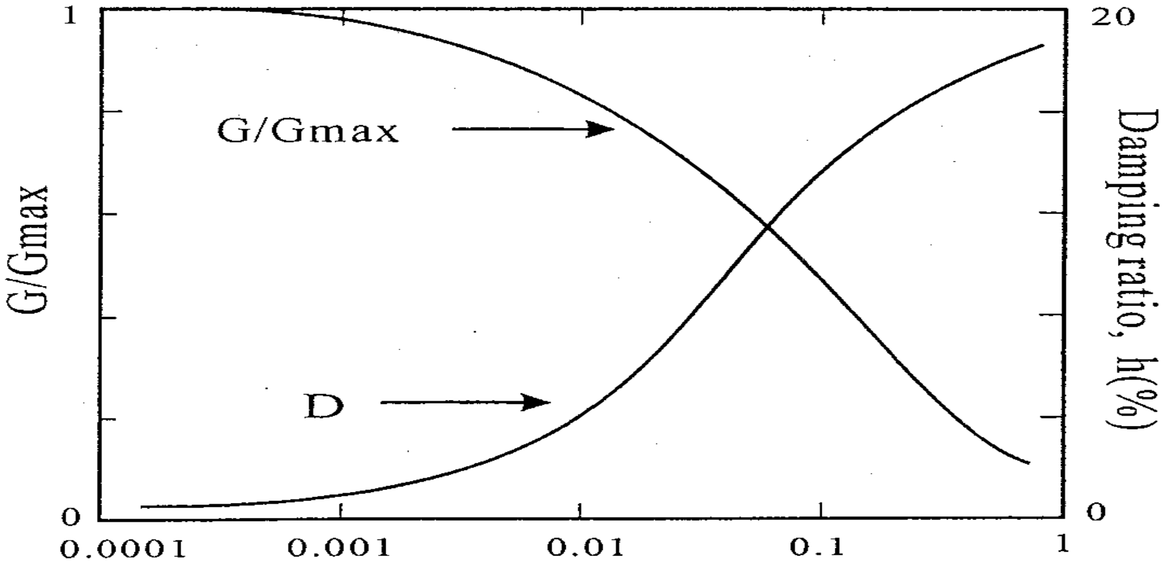
The equivalent shear modulus, G;

$$G = \frac{\tau_a}{\gamma_a}$$

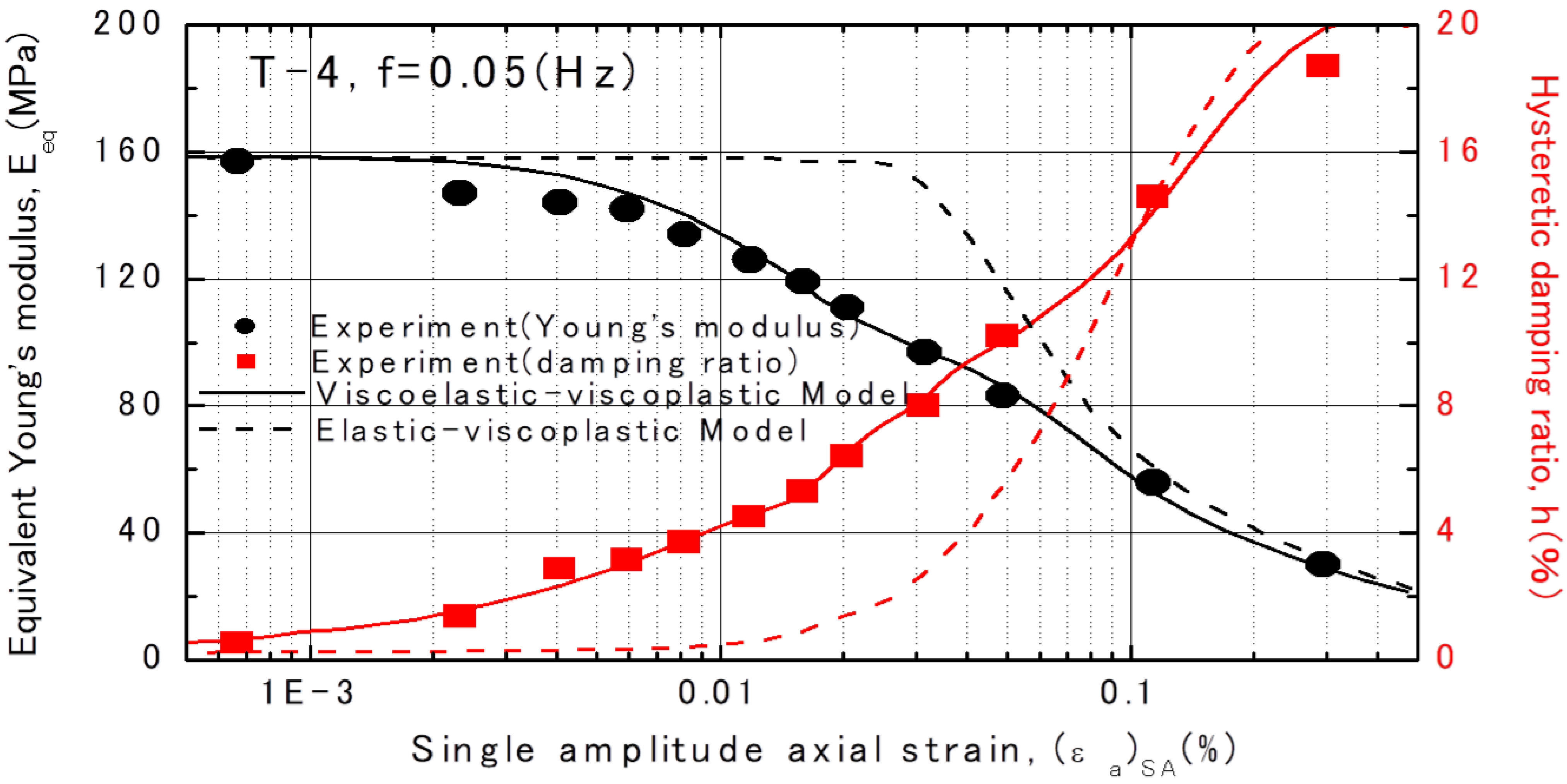
The hysteretic or equivalent viscous damping ratio, D

$$D = \frac{1}{2\pi}\frac{\Delta W}{W} = \frac{1}{2\pi}\frac{\Delta W}{G\gamma_a^2}$$

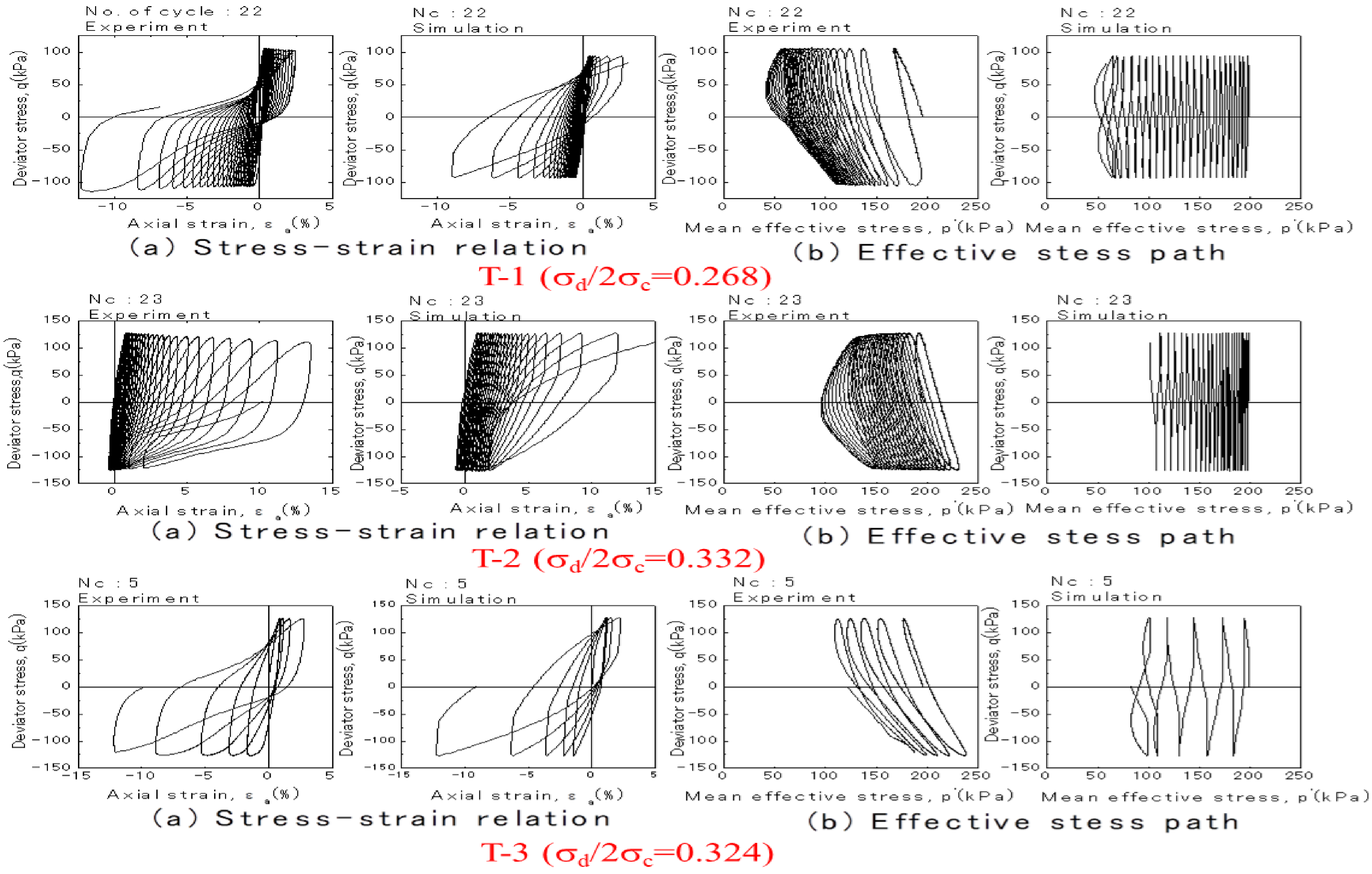




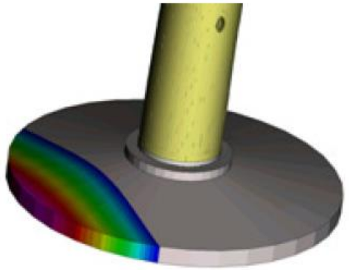
The results of the Cyclic Triaxial Deformation Test

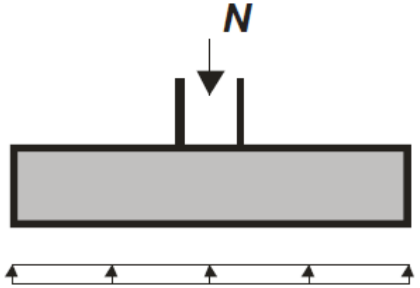


Soil behavior under cyclic loads

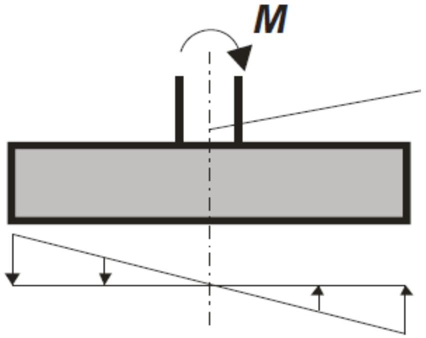


Soil behavior under large deformations



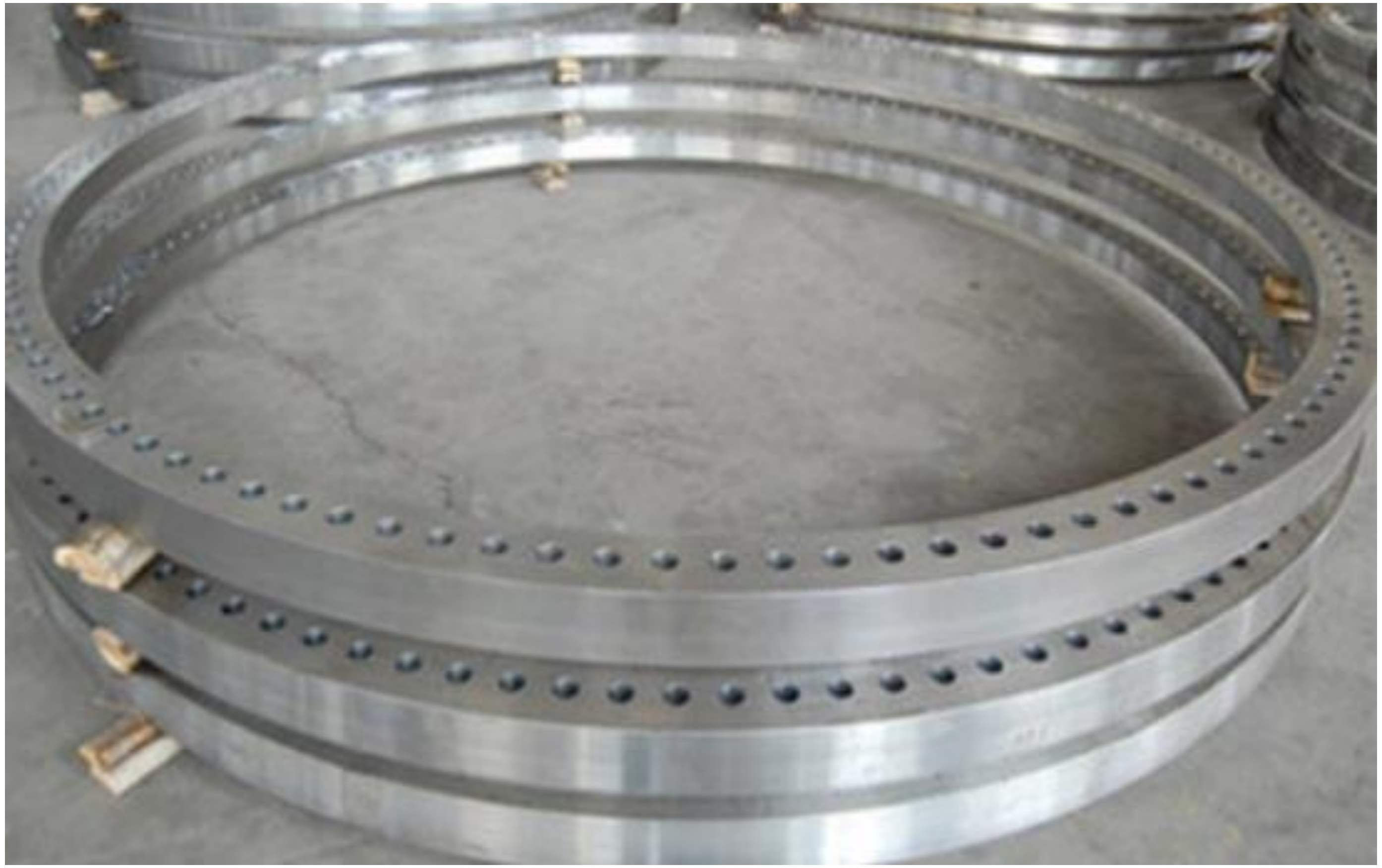


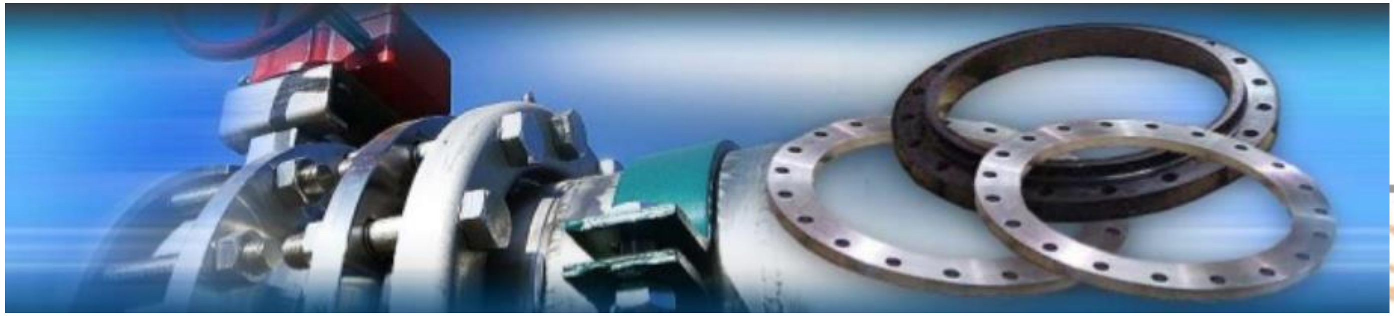
Soil pressure from symmetric load case



Fictitious soil pressure from asymmetric load case

NONLINEAR BEHAVIOR OF BOLTED L-FLANGED CONNECTIONS



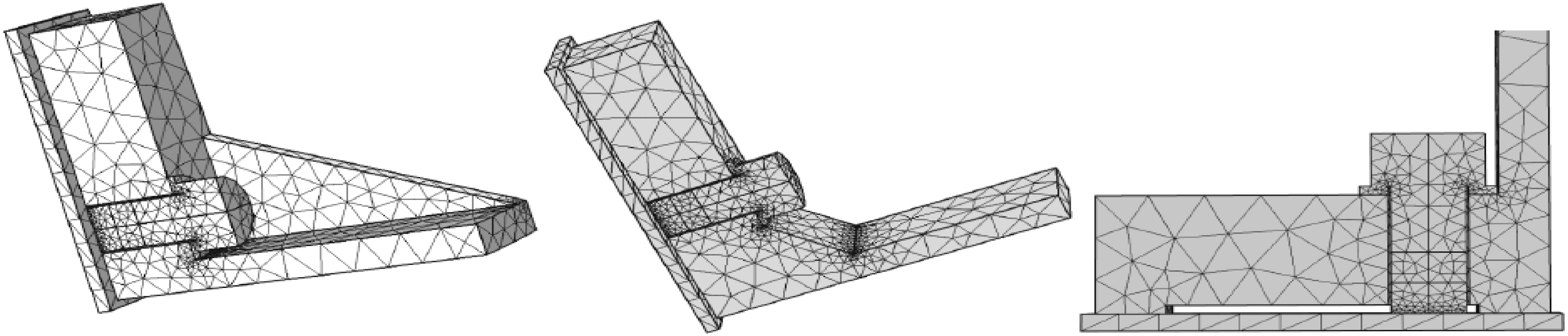


NONLINEAR BEHAVIOR OF BOLTED L-FLANGED CONNECTIONS

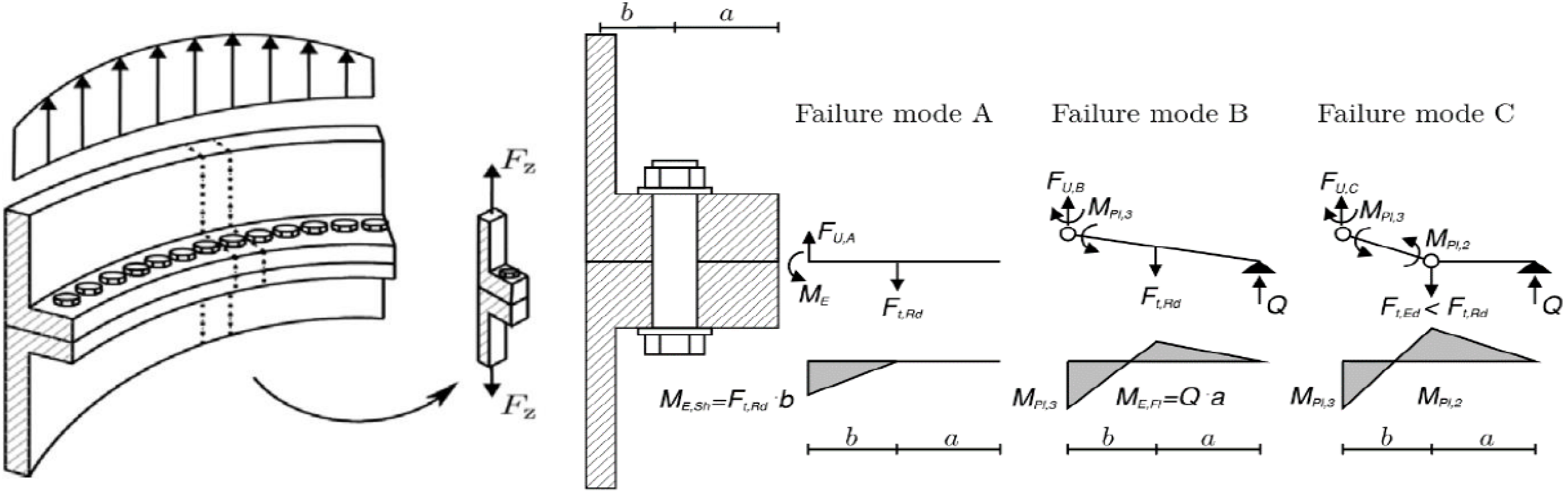
In wind turbine towers the preferred design is circular tubes that are connected to each other by a bolted flange joint.

The design is typically that of an L-flange resulting in an eccentrically loaded bolted connection.

The eccentricity results in **a non-linear relationship** between external load on the tower and the tensile force in the bolt.



NONLINEAR BEHAVIOR OF BOLTED L-FLANGED CONNECTIONS



$$F_z = \frac{4 \cdot M_{Ed}}{n_b \cdot D_{sh,m}} + \frac{N_{Ed}}{n_b}$$

$$F_{U,A} = F_{t,Rd}$$

$$F_{t,Rd} = \min\left(\frac{f_{y,bolt} \cdot A_s}{\gamma_{M2}} ; \frac{0.9 \cdot f_{u,bolt} \cdot A_s}{\gamma_{M7}} \right)$$

$$F_{U,B} = \frac{F_{t,Rd} \cdot a + M_{pl,3}}{a + b}$$

$$M_{E,Fl} \leq W_{E,Flange} \cdot f_{yd,Flange}$$

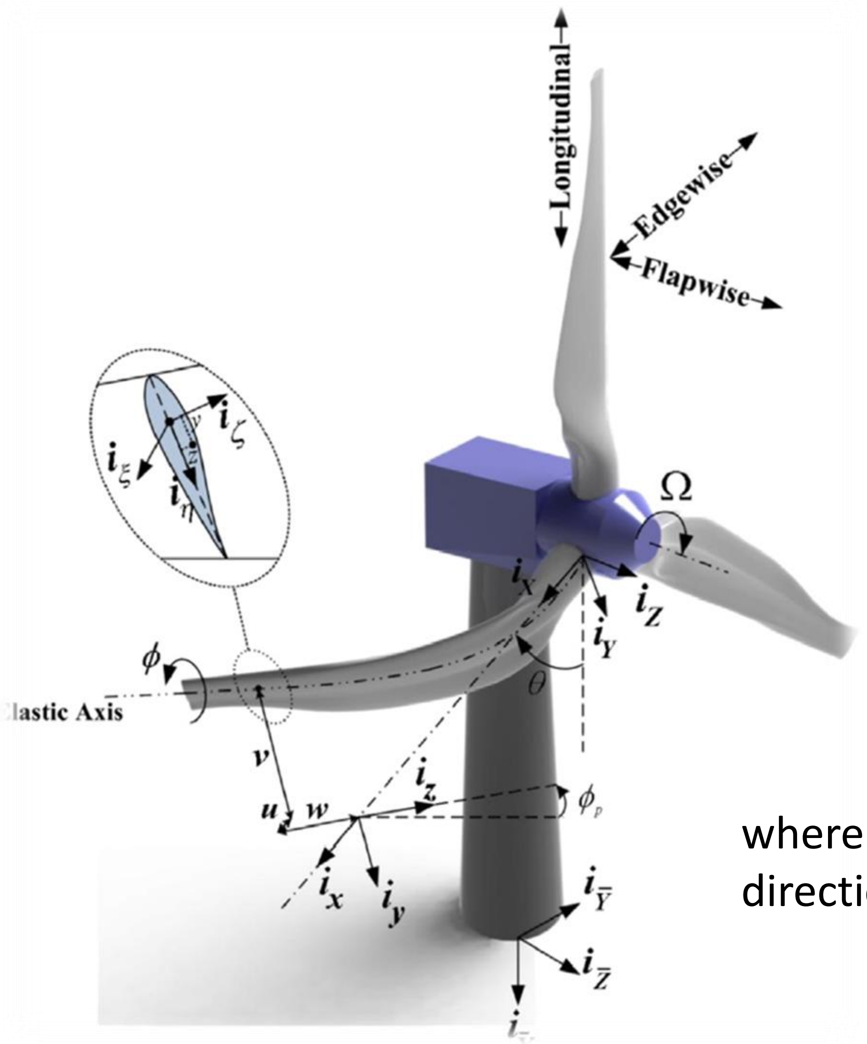
$$F_{U,C} = \frac{M_{pl,2} + M_{Pl,3}}{b}$$

Nonlinear analysis of the wind turbine blade dynamics

- Due to economical reasons, the new generation of wind turbine structures with larger and more flexible blades is observed. So, the significant large deformation of such flexible structures makes the application of nonlinear models more crucial.
- Wind turbine blades often have the specific geometry with high slenderness ratios. Therefore, the nonlinear beam theory for modeling purposes can be used.

Nonlinear analysis of the wind turbine blade dynamics

Large deformation kinematics of the blade



$$\{i_{\xi\eta\zeta}\} = T\{i_{xyz}\},$$

$$T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{pmatrix} \times \begin{pmatrix} B_{11} & B_{12} & B_{13} \\ -B_{12} & B_{11} + B_{13}^2/(1+B_{11}) & -B_{12}B_{13}/(1+B_{11}) \\ -B_{13} & B_{23} & B_{11} + B_{12}^2/(1+B_{11}) \end{pmatrix}$$

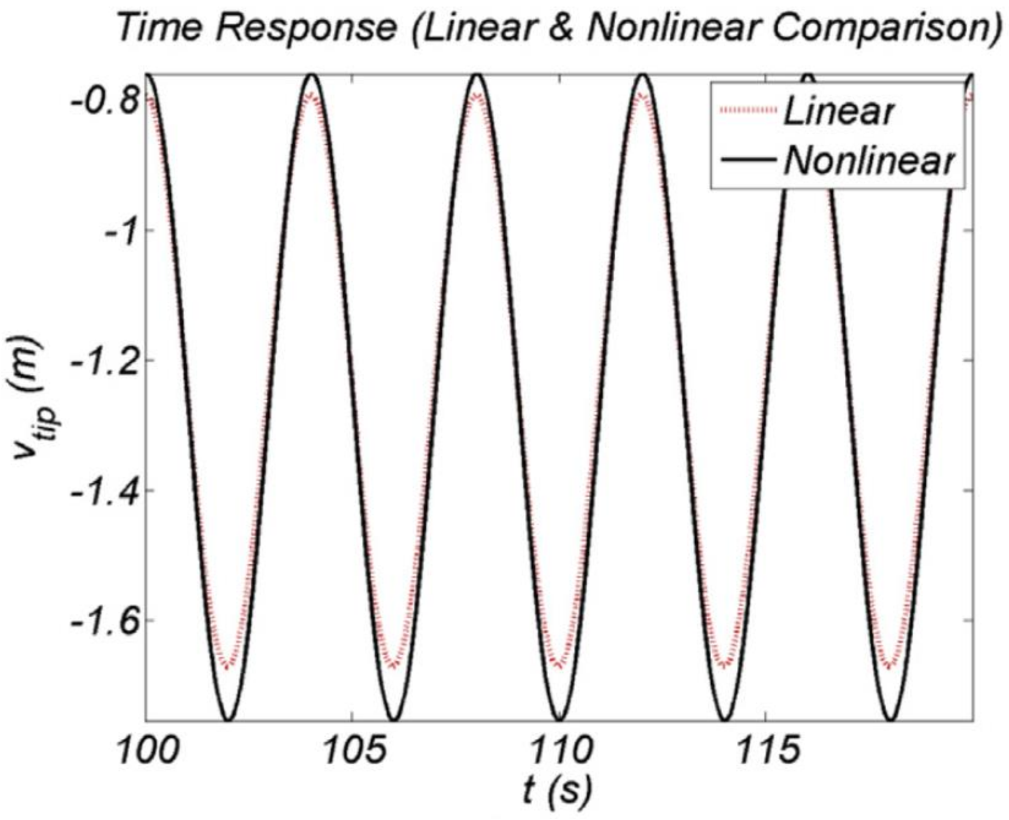
$$B_{11} = \frac{1+u'}{1+e}, \quad B_{12} = \frac{v'}{1+e}, \quad B_{13} = \frac{w'}{1+e},$$

$$e = \sqrt{(1+u')^2 + v'^2 + w'^2} - 1$$

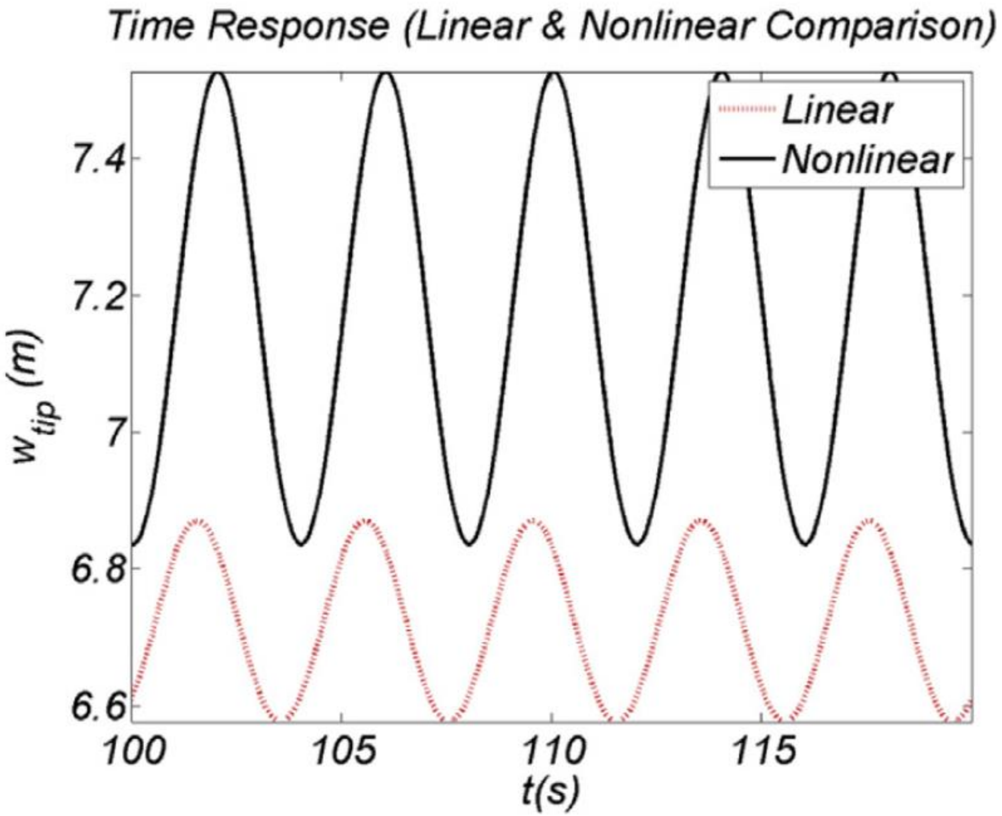
where e is the elongation of the elastic axis and u is the longitudinal deflection in i_x direction, v and w are the lateral deflections in i_y and i_z directions, respectively.

Nonlinear analysis of the wind turbine blade dynamics

Large deformation kinematics of the blade: results



edgewise direction (v_{tip})



flapwise direction (w_{tip})


Thank you for your attention