Motorway exit bridge
3D pushover analysis

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with the collaboration of **BG ingénieurs conseils SA**

Contents

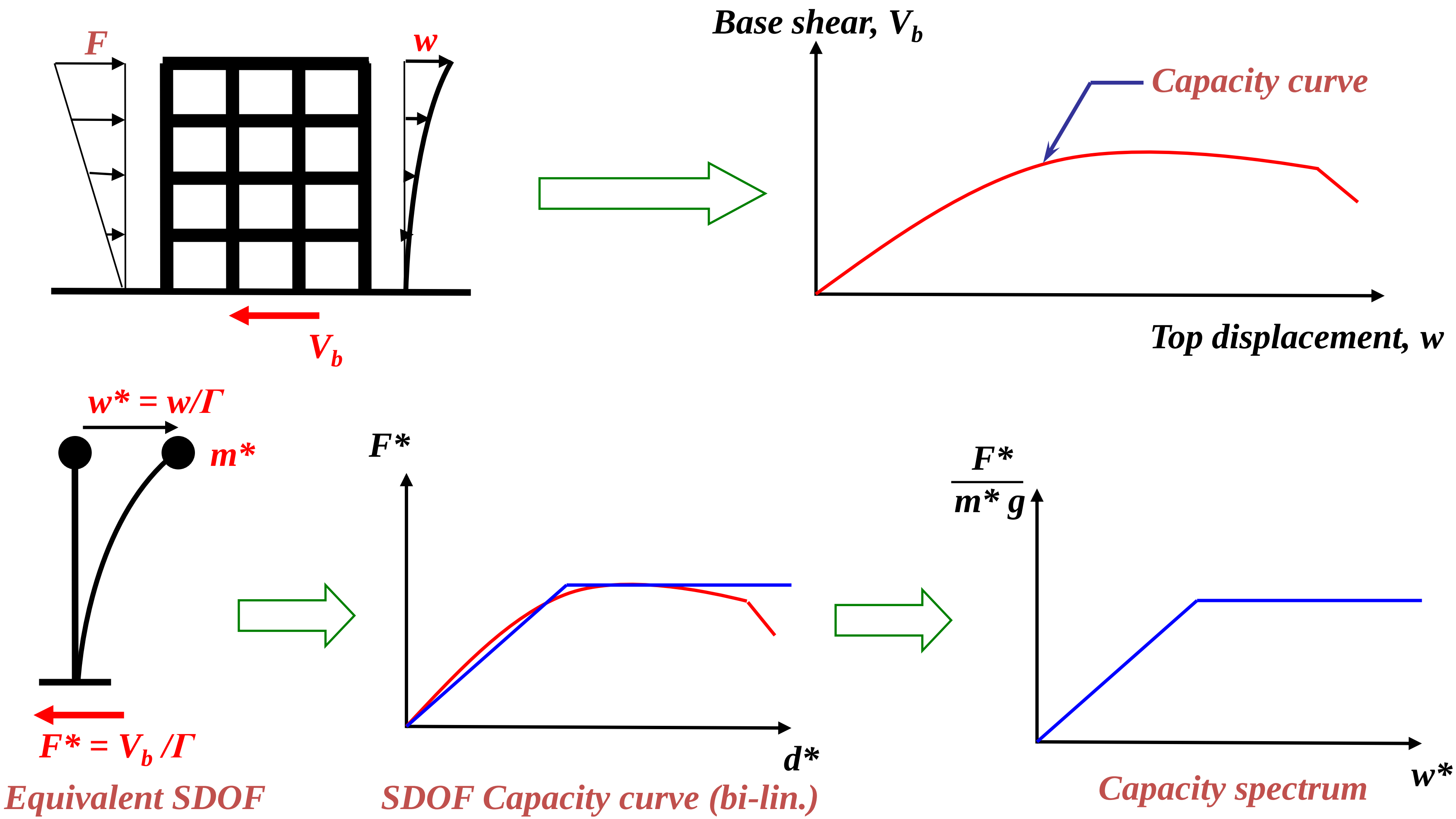
Contents

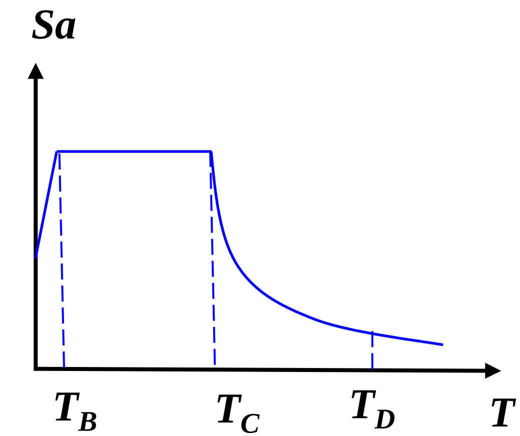
- **Recall: push-over or displacement-based method**
- 3D model of motorway exit
- Target displacement computation
- Deformation capacity
- Seismic assessment
- Conclusion

Seismic assessment of existing structures in Switzerland

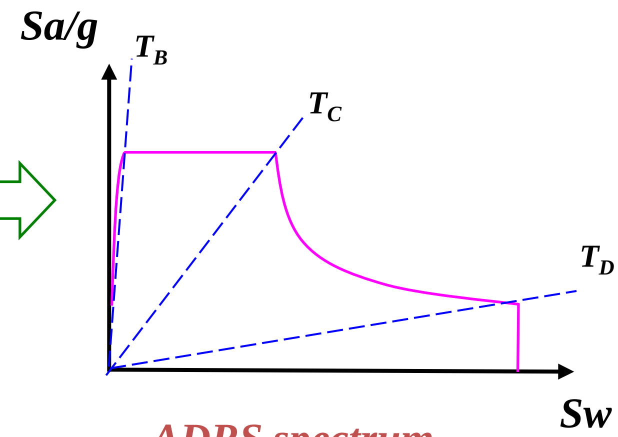
- Classical methods: replacement forces, response spectra

- Since 2004: displacement-based method (push-over), documented in CT SIA 2018

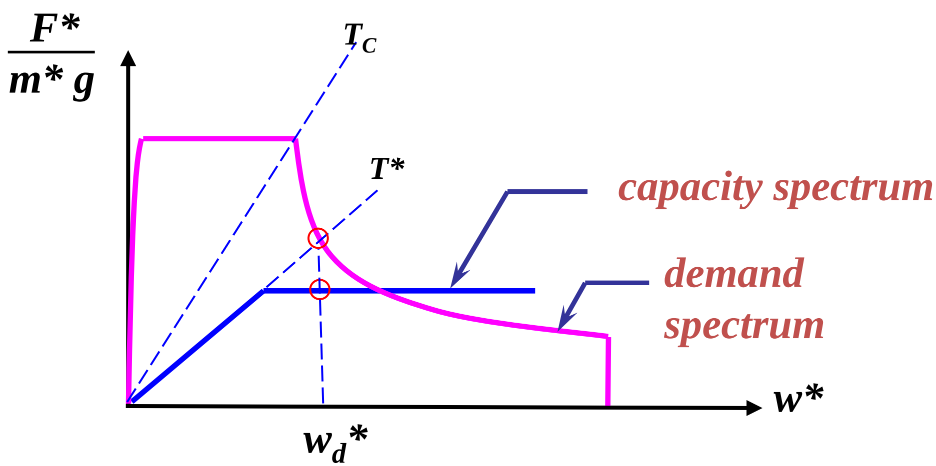

F
w
V_b
Base shear, V_b
Capacity curve
Top displacement, w
w* = w/Γ
m*
F* = V_b /Γ
Equivalent SDOF
F*
d*
SDOF Capacity curve (bi-lin.)
F*
m* g
w*
Capacity spectrum

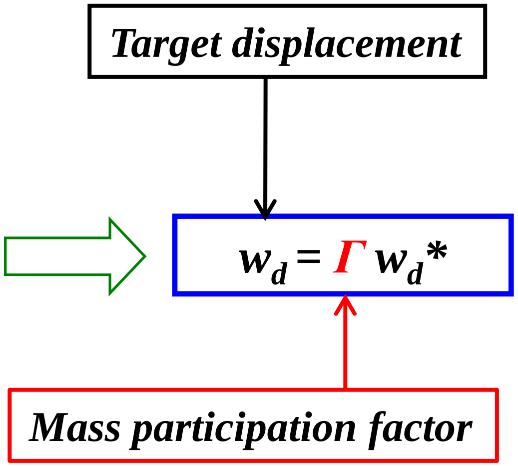


Acceleration Response Spectrum



ADRS spectrum





$$\alpha_{eff} = w_{Rd} / w_d$$ (SIA CT 2018)

α_{eff}	**compliance factor**
w_{Rd}	allowable displacement (capacity of deformation)
w_d	target displacement

$\alpha_{eff} < \alpha_{min}$	intervention **necessary**
$\alpha_{min} \leq \alpha_{eff} \leq \alpha_{adm}$	intervention **necessary, if proportionate**
$\alpha_{adm} \leq \alpha_{eff}$	**no intervention**

α_{min}, α_{adm} = f(structure type, lifetime)

Here, for class II and T = 50 years: $\alpha_{min} = 0.25$ et $\alpha_{adm} = 0.76$

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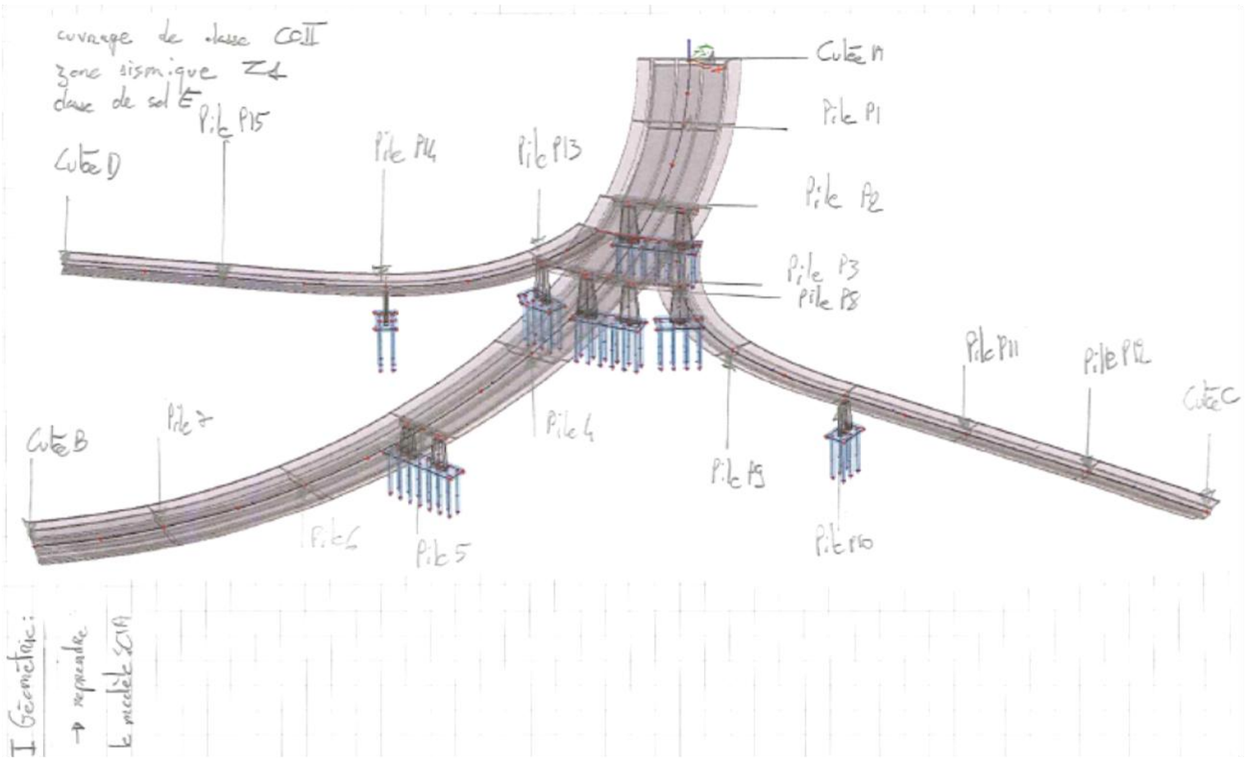
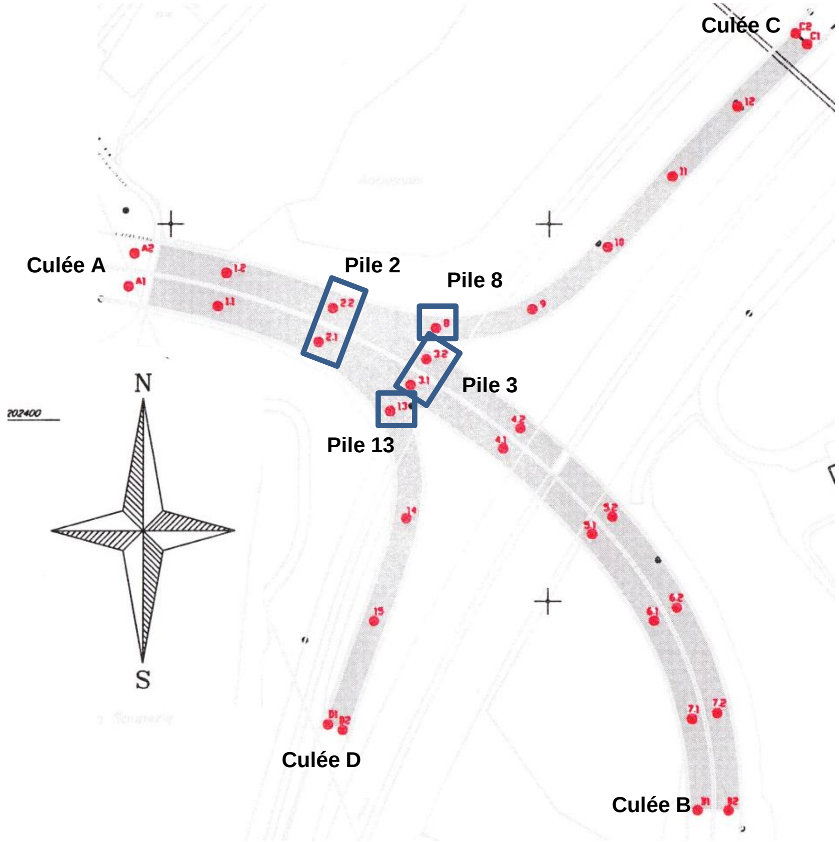
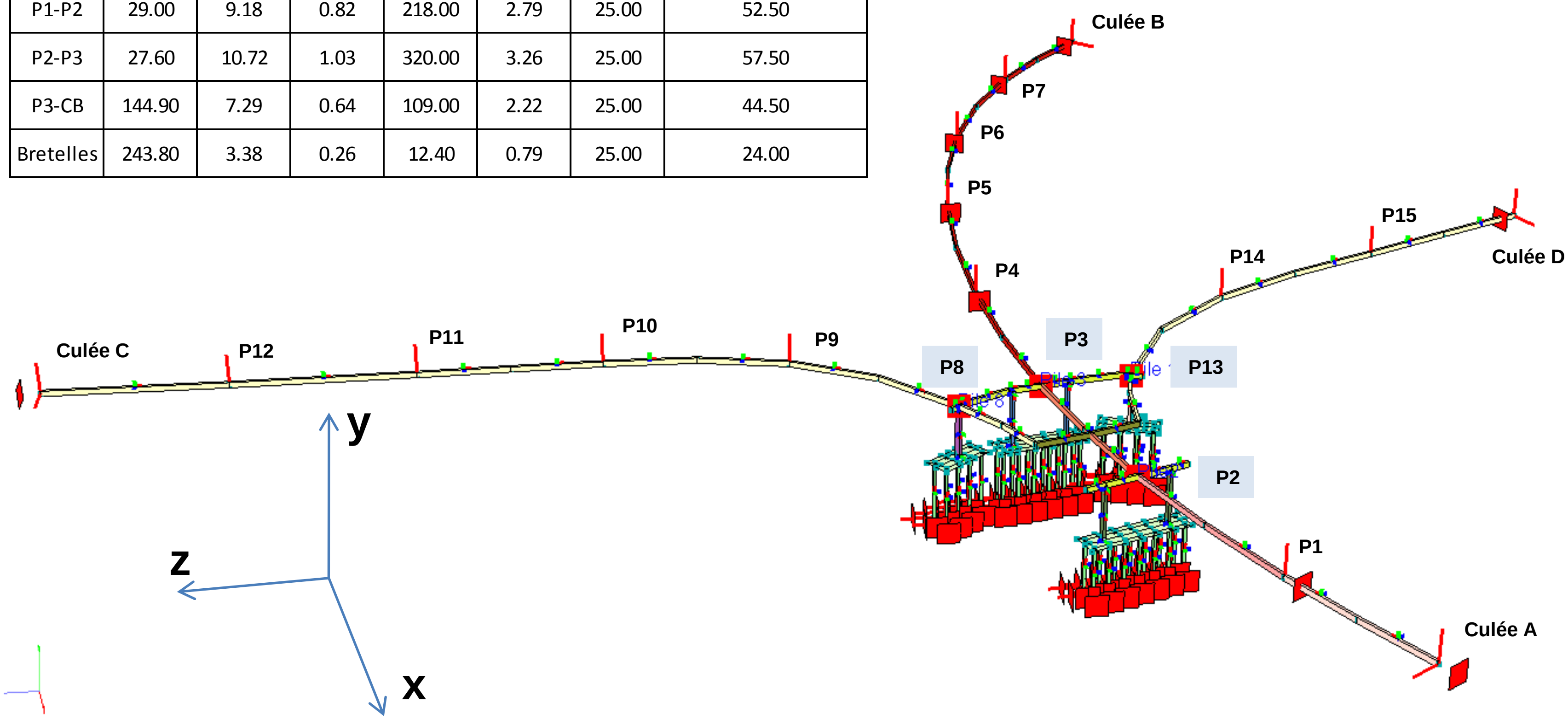
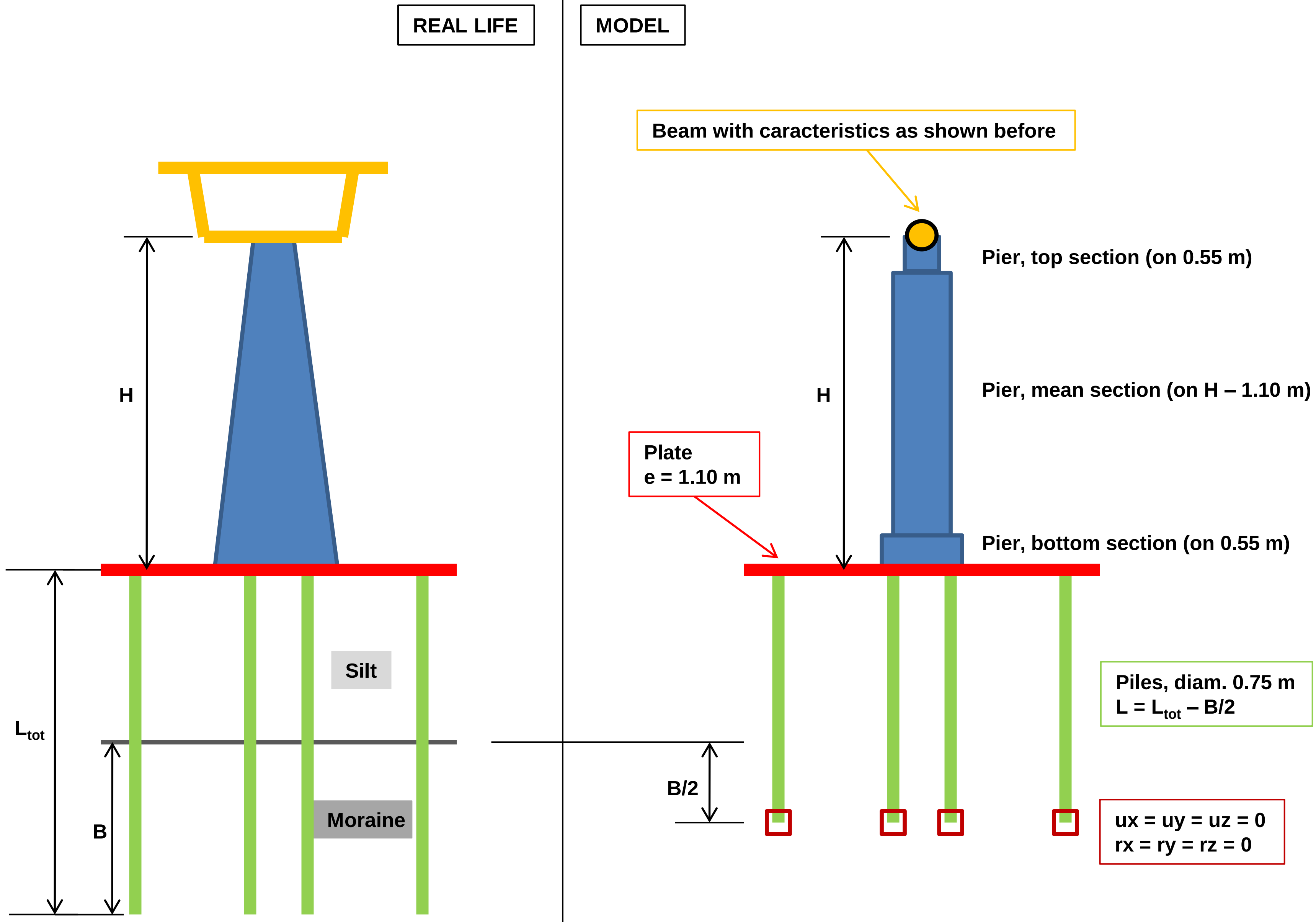

ouvrage de classe COII
zone sismique Z1
classe de sol E
Culée A
Pile P1
Pile P2
Pile P3
Pile P8
Pile P15
Culée D
Pile P14
Pile P13
Pile P11
Pile P12
Culée C
Culée B
Pile 7
Pile 4
Pile P9
Pile P10
Pile 6
Pile 5
I Géométrie:



Only P2 P3 P8 P13 are modeled explicitely

Caisson	L	A	Ix	Iy	Iz	γ	q superstruct.
	[m]	[m^2]	[m^4]	[m^4]	[m^4]	[kN/m^3]	[kN/m]
CA-P1	23.50	8.59	0.69	196.20	2.75	25.00	52.50
P1-P2	29.00	9.18	0.82	218.00	2.79	25.00	52.50
P2-P3	27.60	10.72	1.03	320.00	3.26	25.00	57.50
P3-CB	144.90	7.29	0.64	109.00	2.22	25.00	44.50
Bretelles	243.80	3.38	0.26	12.40	0.79	25.00	24.00



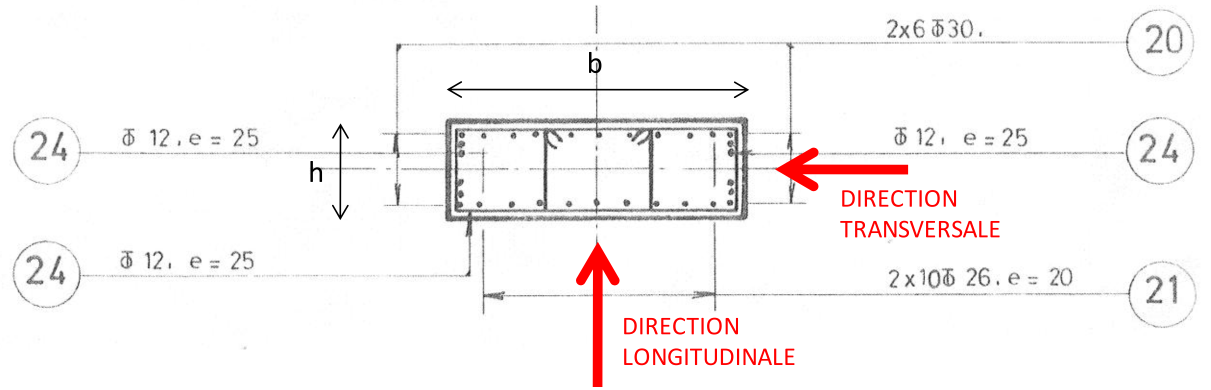

REAL LIFE
MODEL
Beam with caracteristics as shown before
H
Pier, top section (on 0.55 m)
H
Pier, mean section (on H – 1.10 m)
Plate
e = 1.10 m
Pier, bottom section (on 0.55 m)
Silt
Ltot
Piles, diam. 0.75 m
L = Ltot – B/2
B/2
Moraine
B
ux = uy = uz = 0
rx = ry = rz = 0

Piers' characteristics

Pile	modèle	H	b top	h top	b moy	h moy	b bottom	h bottom
		[m]	[mm]	[mm]	[mm]	[mm]	[mm]	[mm]
P2	double	8.05	2150	800	2825	800	3500	800
P3	double	8.50	2150	800	2875	800	3600	800
P8	simple	7.70	2050	800	2750	800	3450	800
P13	simple	7.70	2050	800	2675	800	3300	800

Elément	Modèle	E	ν	γ	fc	ft
		[MPa]	[-]	[kN/m3]	[kN/m2]	[kN/m2]
Pile (béton)	non linéaire	21'000	0.2	25	30'000	2'500
Pile (armatures)	non linéaire	210'000	0.3	78	500'000	500'000
Caissons, entretoises, pieux, dalles	élastique linéaire	21'000	0.2	25	-	-

Piers' characteristics (cont.)



	Direction longitudinale				Direction transversale			
Pile	top	moy	bottom	étriers	top	moy	bottom	étriers
P2	8phi26	9phi26	13phi26	2xphi12e25	6phi30	6phi30	6phi30	phi12e25
P3	9phi26	10phi26	13phi30	2xphi12e25	6phi30	6phi30	6phi30	phi12e25
P8	9phi26	11phi26	13phi26	2xphi12e25	6phi26	6phi26	6phi26	phi12e25
P13	9phi26	10phi26	13phi26	2xphi12e25	6phi26	6phi26	6phi26	phi12e25

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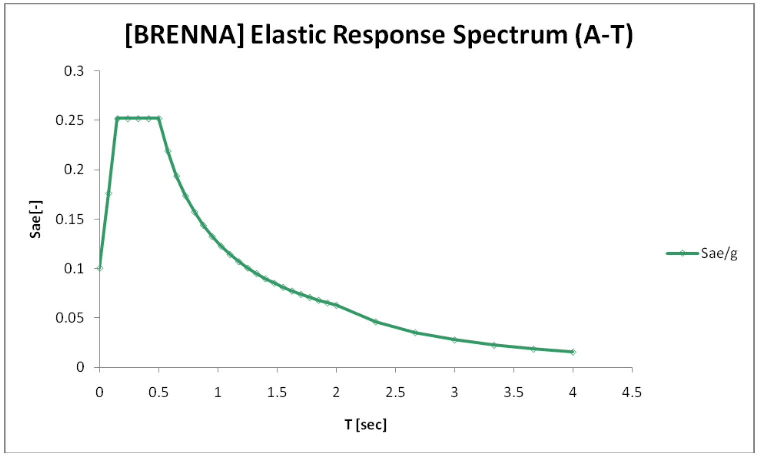
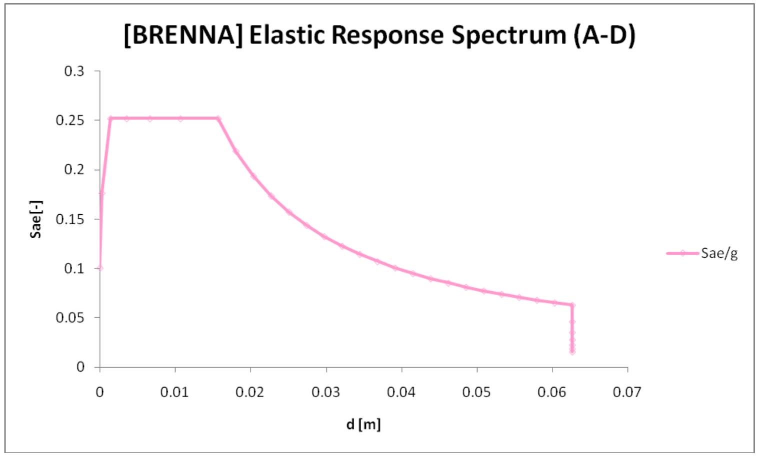
Demand spectrum

- Horizontal ground acceleration in Z1 : a_{gd} = 0.6 m/s^2
- Structure importance factor : γ_f = 1.2
- Spectrum coefficient S = 1.4
- Damping : 5 %

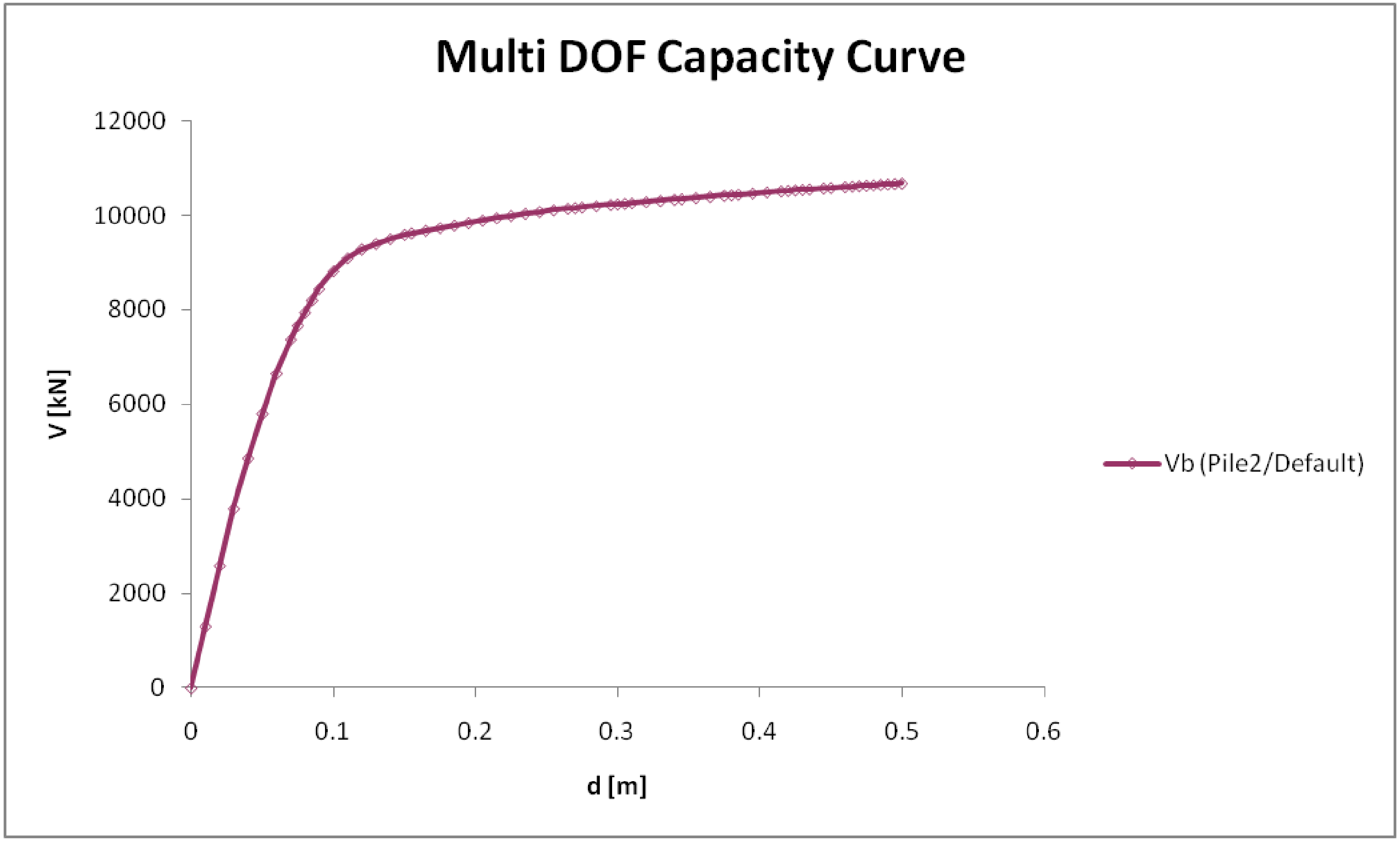


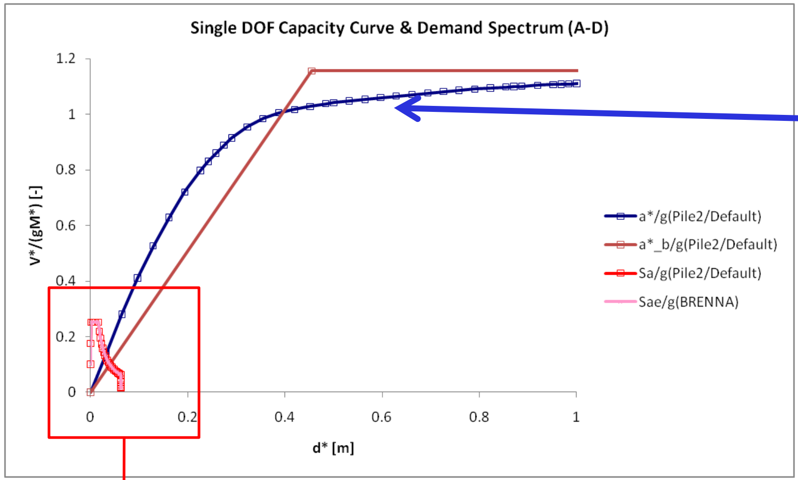
Acceleration response spectrum

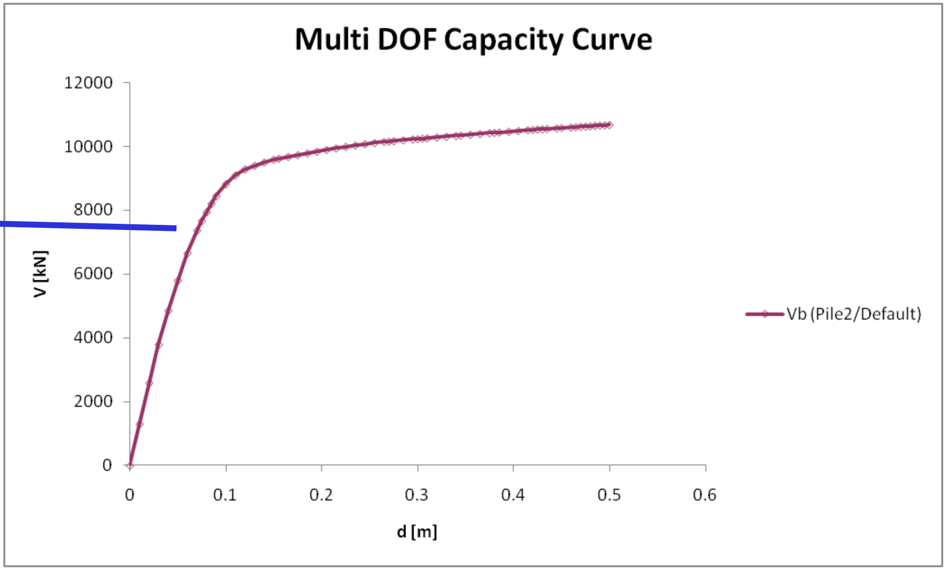


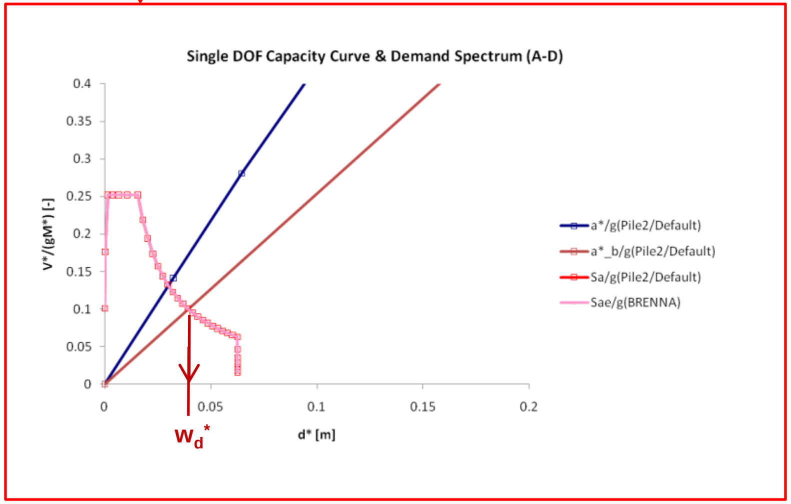
ADRS spectrum

Capacity curve

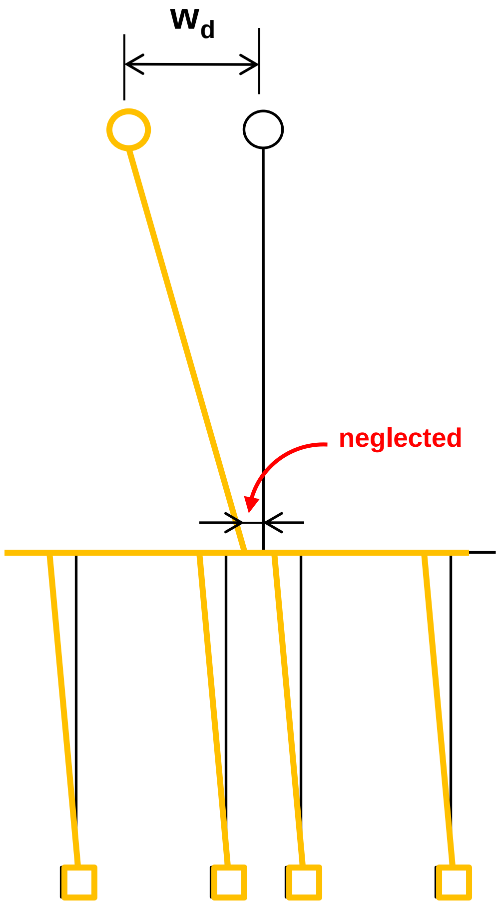








	Pushover analysis report		
Item	Unit	Pile2/Default	
MDOF Free vibr. period........T	[s]	1.64318	
SDOF Free vibr. period.......T*	[s]	1.258785	
SDOF equivalent mass.........M*	[kg]	3039220	
Mass participation factor Gamma	-	0.310006	
Bilinear yield force value..Fy*	[kN]	34449.4	
Bilinear displ. at yield....Dy*	[m]	0.454949	
Target displacement.........Dm*	[m]	1.612872	
SDOF displacement demand....Dt*	[m]	0.039413	← w_d^*
Energy.....................Em*	[kN*m]	47726.1	
Reduction factor.............qu	-	1	
Demand ductility factor......mi	-	40.9227	
Capacity ductility factor...miC	-	3.545169	
MDOF displacement demand.....Dt	[m]	0.012218	← w_d



w_d
neglected

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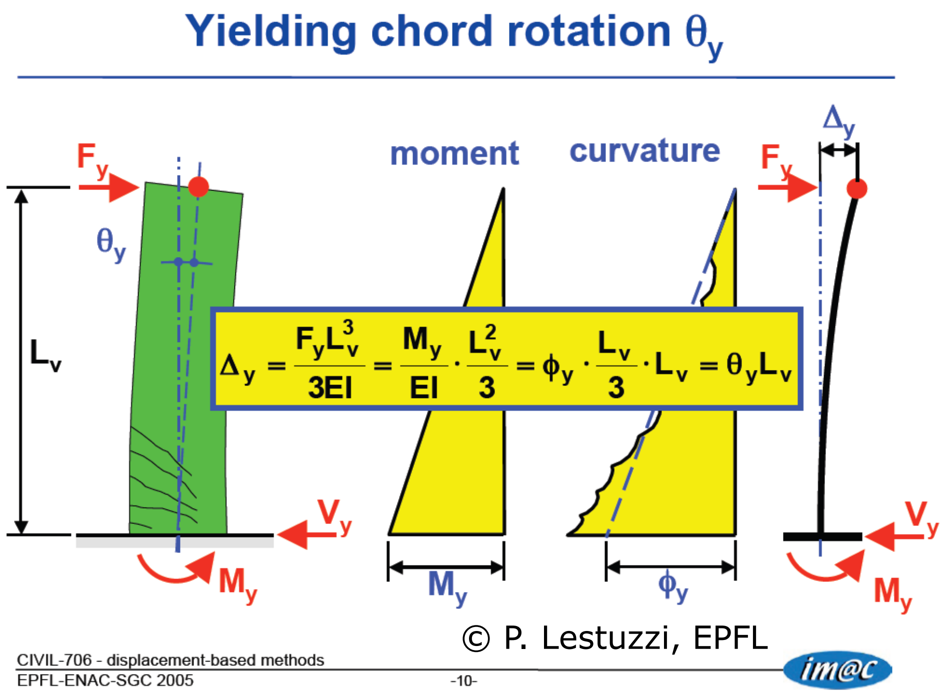
$w_{Rd} = \theta_{max} * L_V$

L_V : shear length = H/2 for a fixed ended beam
Rotation capacity (simplified) : $\theta_{max} = 3 * \theta_y$
Yielding chord rotation : $\theta_y = \phi_y * L_V/3$

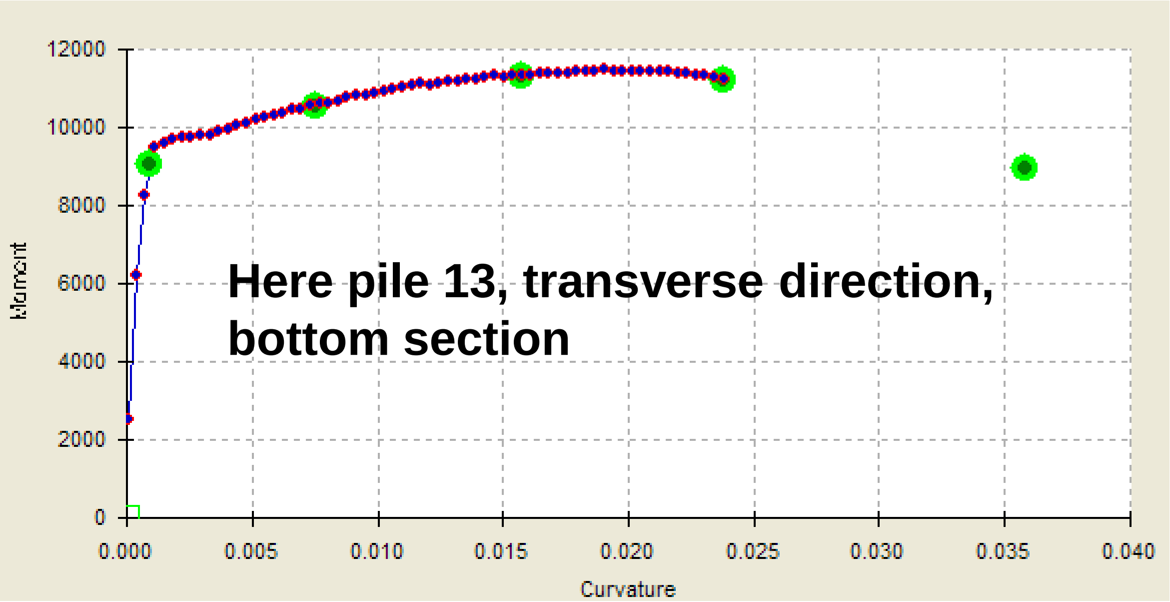
Plastification nominal curvature (simplified) : $\phi_y = 2.1 * \varepsilon_{sk}/h_b$
ε_{sk} : steel plastification strain= 0.2 %
h_b : rectangular beam height

(see SIA CT 2018, 6.2)



Shear stress verification

$M^{+}_{Rd,1}$ et $M^{+}_{Rd,2}$ obtained with moment- curvature analysis



$$V_d^{+} = (M^{+}_{Rd,1} + M^{+}_{Rd,2}) / H$$

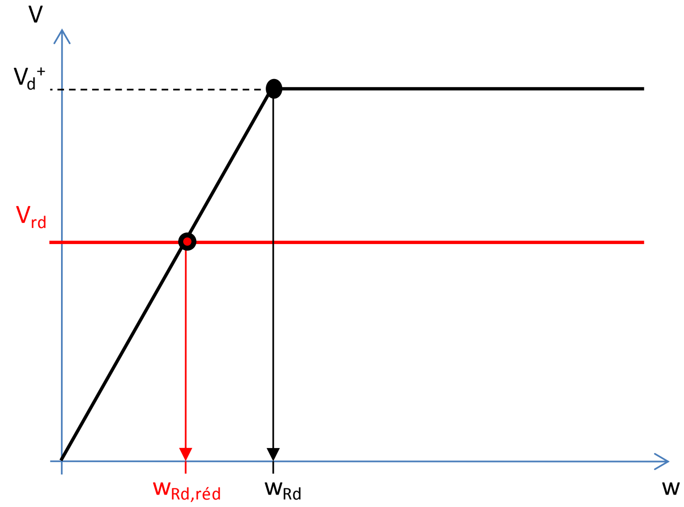
Shear stress verification

Means that pier will fail due to shear before it reaches its maximal bending curvature

$$\text{When } V_d^+ > V_{Rd} \Rightarrow \alpha_{eff,réd} = w_{Rd,réd}/w_d$$

Nominal shear resistance
$V_d^+ = (M^+_{Rd,1} + M^+_{Rd,2}) / H$

Maximal shear resistance
$V_{rd} = A_{sw}/s * z * f_{sd} * \cot \alpha$



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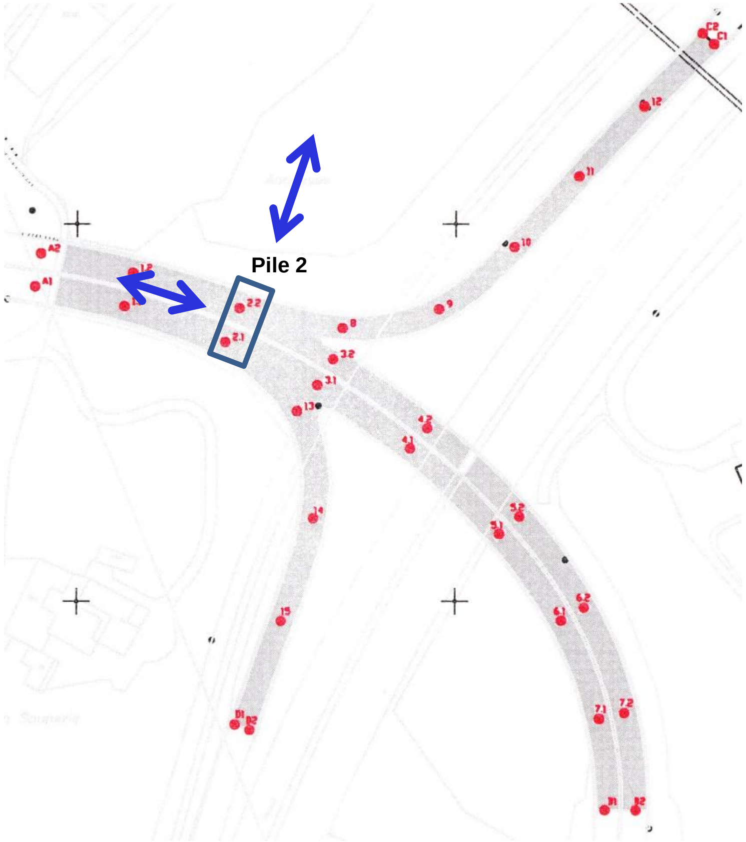
For each pile (here pile 2), verification must be made:

- in **four directions** (+/- longitudinal, +/- transversal)
- for **two load distributions** (modal and unitary)



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w_d	target displacement

$\alpha_{eff} < \alpha_{min}$	intervention **necessary**
$\alpha_{min} \leq \alpha_{eff} \leq \alpha_{adm}$	intervention **necessary, if proportionate**
$\alpha_{adm} \leq \alpha_{eff}$	**no intervention**

α_{min}, α_{adm} = f(structure type, lifetime)

Here, for class II and T = 50 years: $\alpha_{min} = 0.25$ et $\alpha_{adm} = 0.76$

LONGI				
PILE	2	3	8	13
H [m]	8.05	8.5	7.7	7.7
Lv [m]	4.025	4.25	3.85	3.85
angle [°]	107	99	128	72
dir_push_X	-0.96	-0.99	-0.79	-0.95
dir_push_Z	0.29	0.16	0.62	-0.31
b_top [mm]	2150	2150	2050	2050
b_mid [mm]	2825	2875	2750	2675
b_bot [mm]	3500	3600	3450	3300
h [mm]	800	800	800	800
phi_L top	8phi26	9phi26	9phi26	9phi26
phi_L mid	9phi26	10phi26	11phi26	10phi26
phi_L bot	13phi26	13phi30	13phi26	13phi26
Astop [mm2]	0.0042	0.0048	0.0048	0.0048
Asmid [mm2]	0.0048	0.0053	0.0058	0.0053
Asbot [mm2]	0.0069	0.0092	0.0069	0.0069
phi_V	2xphi12e25	2xphi12e25	2xphi12e25	2xphi12e25
VRd [kN]	1139	1139	1139	1139
N top [kN]	-3950	-3550	-2750	-2850
N bot [kN]	-4400	-4100	-3150	-3200
MRd top [kNm]	2800	3200	2700	2700
MRd bot [kNm]	4200	4700	3800	3700
Vd [kN]	870	929	844	831
d target mod [m]	0.0122	0.0115	0.0117	0.0068
d target -mod [m]	0.0123	0.0116	0.0117	0.0077
d target 1 [m]	0.0120	0.0112	0.0117	0.0065
d target -1 [m]	0.0120	0.0113	0.0117	0.0075
phi_y	0.0053	0.0053	0.0053	0.0053
w_y [m]	0.0284	0.0316	0.0259	0.0259
w_Rd [m]	0.0851	0.0948	0.0778	0.0778
alpha mod	6.97	8.25	6.65	11.44
alpha -mod	6.91	8.17	6.65	10.11
alpha 1	7.09	8.47	6.65	11.97
alpha -1	7.09	8.39	6.65	10.38

TRANS				
PILE	2	3	8	13
H [m]	8.05	8.5	7.7	7.7
Lv [m]	4.025	4.25	3.85	3.85
angle [°]	107	99	128	72
dir_push_X	-0.29	-0.16	-0.62	0.31
dir_push_Z	-0.96	-0.99	-0.79	-0.95
h_top [mm]	2150	2150	2050	2050
h_mid [mm]	2825	2875	2750	2675
h_bot [mm]	3500	3600	3450	3300
b [mm]	800	800	800	800
phi_L top	6phi30	6phi30	6phi26	6phi26
phi_L mid	6phi30	6phi30	6phi26	6phi26
phi_L bot	6phi30	6phi30	6phi26	6phi26
Astop [mm2]	0.0042	0.0042	0.0032	0.0032
Asmid [mm2]	0.0042	0.0042	0.0032	0.0032
Asbot [mm2]	0.0042	0.0042	0.0032	0.0032
phi_V	phi12e25	phi12e25	phi12e25	phi12e25
VRd top [kN]	1595	1595	1519	1519
N top [kN]	-3950	-3550	-2750	-2850
N bot [kN]	-4400	-4100	-3150	-3200
MRd top [kNm]	8800	8200	6300	6400
MRd bot [kNm]	15800	16000	11600	11200
Vd [kN]	3056	2847	2325	2286
d target mod [m]	0.0018	0.0033	0.0060	0.0049
d target -mod [m]	0.0018	0.0033	0.0073	0.0049
d target 1 [m]	0.0017	0.0028	0.0052	0.0038
d target -1 [m]	0.0019	0.0028	0.0062	0.0038
phi_y bot	0.0012	0.0012	0.0012	0.0013
w_y [m]	0.0065	0.0070	0.0060	0.0063
w_y_red [m]	0.0034	0.0039	0.0039	0.0042
w_Rd_red [m]	0.0101	0.0118	0.0118	0.0125
alpha mod red	5.64	3.58	1.97	2.56
alpha -mod red	5.64	3.58	1.62	2.56
alpha 1 red	5.97	4.22	2.27	3.30
alpha -1 red	5.34	4.22	1.90	3.30

Contents

	Direction longitudinale: αeff = wRd / wd				Direction transversale: αeff = wRd,réd / wd			
distribution selon §3.6	modale	- modale	uniforme	- uniforme	modale	- modale	uniforme	- uniforme
Pile 2	6.97	6.91	7.09	7.09	5.64	5.64	5.97	5.34
Pile 3	8.25	8.17	8.47	8.39	3.58	3.58	4.22	4.22
Pile 8	6.65	6.65	6.65	6.65	1.97	1.62	2.27	1.90
Pile 13	11.44	10.11	11.97	10.38	2.56	2.56	3.30	3.30

Seismic assesment OK because $\alpha_{eff} \geq \alpha_{adm} = 0.76$ for each pile in each direction

Why use displacement-based method instead of classical replacement forces method?

Design horizontal acceleration in the 1960s-1970s: small
Verification in the 2000s: a_h >> ! => RF often fails !
RF method: behavior coefficient q => hidden reserves...

					Coefficient de conformité α (réduit à $\alpha_{réd}$ si nécessaire) pour chaque pile								
			T [s]	S_d [%]	1 VD	1 FR	2 VD	2 FR	3 VD	3 FR	4 VD	4 FR	5
Forces de remplacement	transversal	encastré	1.9	5.6	10.19	1.10	2.95	3.19	2.93	2.77	1.94	1.94	6.46
		base	2.2	4.9	-	-	-	-	-	-	-	-	-
		optimiste	2.2	4.9	-	-	-	-	-	-	-	-	-
	longitudinal	encastré	0.8	13.0	0.21	0.23	4.96	4.86	4.36	4.89	1.86	1.64	0.56
		base	1.4	7.6	0.25	0.49	6.49	8.44	7.06	8.66	1.17	1.49	3.41
		optimiste	1.8	5.2	0.46	1.53	9.53	13.14	11.00	14.36	1.48	1.91	4.41
Push-over	transversal	encastré	1.9	5.6	23.57	3.16	17.67	21.67	19.24	16.50	24.03	31.59	95.75
		base	2.2	4.9	-	-	-	-	-	-	-	-	-
		optimiste	2.2	4.9	-	-	-	-	-	-	-	-	-
	longitudinal	encastré	0.8	13.0	0.20	0.18	38.66	51.25	50.90	41.24	8.29	7.31	1.61
		base	1.4	7.6	0.38	0.36	33.20	34.19	42.58	43.83	7.58	8.42	1.77
		optimiste	1.8	5.2	0.76	0.76	29.91	30.74	38.82	39.88	6.89	7.63	2.97

Compliance factor always > α_{adm} !

encastré: encastrement de toutes les piles à la jonction pile-puits, a_gd = 1 m/s2, inclinaison des bielles à 45°

base: encastrement de toutes les piles à - 12 m sous la jonction pile-puits, a_gd = 1 m/s2, inclinaison des bielles à 45°

optimiste: encastrement de la pile 1 à - 18 m au lieu de - 12 m, a_gd = 0.83 m/s2 au lieu de 1 m/s2, inclinaison des bielles à 25°

$\alpha < \alpha_{min} = 0.25$

$\alpha_{min} = 0.25 < \alpha < \alpha_{adm,50} = 0.76$