M.E.E.T.I.N.G.

Mitigation of the Earthquake Effects in Towns
and in
INdustrial reGional districts

- Final Conference -

Earthquake engineering
Presentation of the book
"Strategies for reduction of the seismic risk"
Termoli, July 14th 2008
College of Engineering, via Duca degli Abruzzi

Design of flexible retaining structures under seismic loadings

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University of Molise

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Adriatic New Neighbourhood Programme INTERREG/CARDS-PHARE
MITIGATION OF THE EARTHQUAKE EFFECTS
IN TOWNS AND IN INDUSTRIAL REGIONAL DISTRICTS

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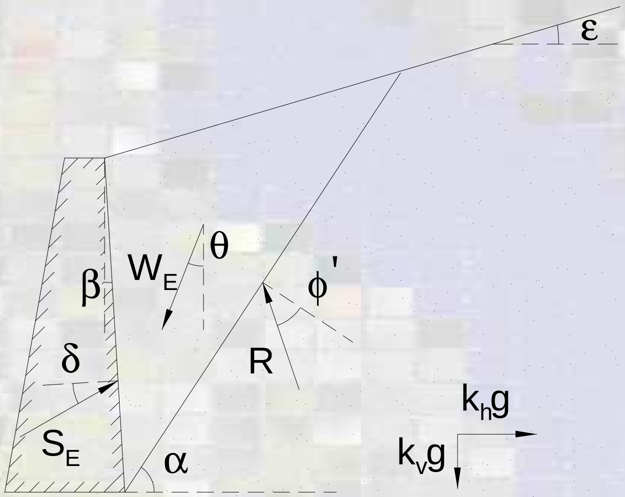
DYNAMIC EARTH PRESSURE THEORIES

1. Limit equilibrium method: Mononobe & Okabe Theory



$$S_{AE} = \frac{1}{2} K_{AE} \gamma H^2 (1 - k_v)$$

$$S_{PE} = \frac{1}{2} K_{PE} \gamma H^2 (1 - k_v)$$

Active conditions

Seismic earth pressure coefficient

$$K_{AE} = \frac{\cos^2(\phi' - \beta - \theta)}{\cos\theta \cos^2\beta \cos(\delta + \beta + \theta)} \times$$

$$\times \frac{1}{\left[1 + \sqrt{\frac{\sin(\delta + \phi')\sin(\phi' - \varepsilon - \theta)}{\cos(\delta + \beta + \theta)\cos(\varepsilon - \beta)}}\right]^2}$$

Critical failure surface

$$\alpha_{AE} = \phi' - \theta + \tan^{-1}\left[\frac{-\tan(\phi' - \theta - \varepsilon) + C_{1E}}{C_{2E}}\right]$$

$$C_{1E} = \sqrt{\tan(\phi' - \theta - \varepsilon)[\tan(\phi' - \theta - \varepsilon) + \cot(\phi' - \theta - \beta)]} \times$$
$$\times \sqrt{[1 + \tan(\delta + \theta + \beta)\cot(\phi' - \theta - \beta)]}$$
$$C_{2E} = 1 + \{\tan(\delta + \theta + \beta)[\tan(\phi' - \theta - \varepsilon) + \cot(\phi' - \theta - \beta)]\}$$

Passive conditions

Seismic earth pressure coefficient

$$K_{PE} = \frac{\cos^2(\phi' + \beta - \theta)}{\cos\theta \cos^2\beta \cos(\delta - \beta + \theta)} \times$$

$$\times \frac{1}{\left[1 + \sqrt{\frac{\sin(\delta + \phi')\sin(\phi' + \varepsilon - \theta)}{\cos(\delta - \beta + \theta)\cos(\varepsilon - \beta)}}\right]^2}$$

Critical failure surface

$$\alpha_{PE} = \theta - \phi' + \tan^{-1}\left[\frac{-\tan(\phi' + \theta + \varepsilon) + C_{3E}}{C_{4E}}\right]$$

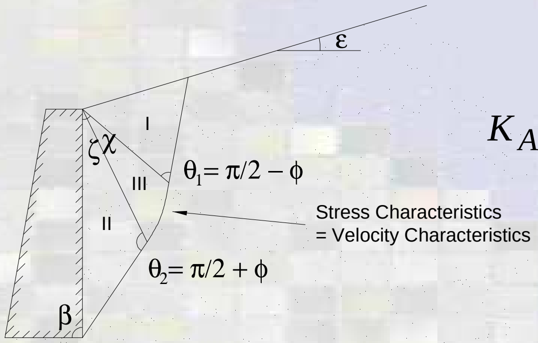
$$C_{3E} = \sqrt{\tan(\phi' - \theta + \varepsilon)[\tan(\phi' - \theta + \varepsilon) + \cot(\phi' - \theta + \beta)]} \times$$
$$\times \sqrt{[1 + \tan(\delta - \theta + \beta)\cot(\phi' - \theta + \beta)]}$$

$$C_{4E} = 1 + \{\tan(\delta + \theta - \beta)[\tan(\phi' - \theta + \varepsilon) + \cot(\phi' - \theta + \beta)]\}$$

DYNAMIC EARTH PRESSURE THEORIES

2. *Limit analysis solutions: Upper Bound Method (Chang, 1981; Chen & Liu, 1990)*

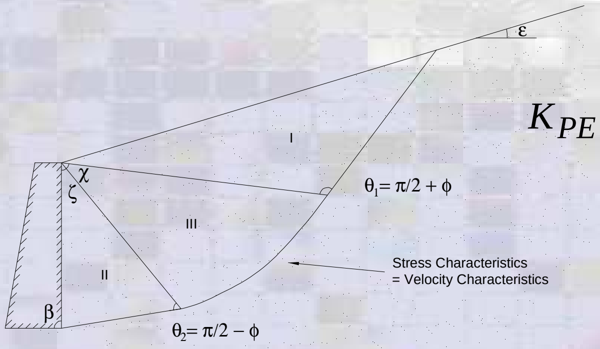
Active conditions



$$K_{AE} = N_{A\gamma} + \frac{2q}{\gamma H} N_{Aq} + \frac{2c}{\gamma H} N_{Ac}$$

β	φ	20°			30°			40°			50°		
	δ	0°	10°	20°	0°	15°	30°	0°	20°	40°	0°	25°	50°
-30°		0.77	0.74	0.76	0.62	0.61	0.67	0.49	0.50	0.62	0.38	0.42	0.65
-15°		0.60	0.56	0.56	0.45	0.42	0.44	0.33	0.32	0.36	0.23	0.23	0.31
0°	$k_h = 0$	0.49	0.45	0.43	0.33	0.30	0.30	0.22	0.20	0.21	0.13	0.13	0.15
15°		0.41	0.37	0.34	0.24	0.21	0.21	0.13	0.12	0.12	0.06	0.06	0.06
30°		0.34	0.29	0.27	0.17	0.14	0.13	0.07	0.05	0.05	0.01	0.01	0.01
-30°		0.84	0.84	0.89	0.69	0.70	0.81	0.56	0.59	0.79	0.44	0.50	0.53
-15°		0.68	0.65	0.66	0.51	0.50	0.53	0.39	0.33	0.45	0.28	0.29	0.41
0°	$k_h = 0.1$	0.57	0.53	0.52	0.40	0.37	0.37	0.27	0.25	0.26	0.17	0.17	0.21
15°		0.49	0.45	0.43	0.31	0.27	0.27	0.18	0.16	0.17	0.09	0.09	0.10
30°		0.44	0.38	0.36	0.23	0.20	0.18	0.10	0.09	0.09	0.04	0.03	0.03
-30°		0.96	1.00	1.12	0.78	0.83	1.02	0.63	0.71	1.07	0.51	0.62	1.58
-15°		0.78	0.78	0.82	0.59	0.60	0.66	0.45	0.47	0.58	0.34	0.37	0.55
0°	$k_h = 0.2$	0.67	0.65	0.65	0.47	0.45	0.47	0.33	0.32	0.36	0.22	0.22	0.28
15°		0.61	0.56	0.55	0.38	0.35	0.35	0.23	0.21	0.23	0.13	0.13	0.15
30°		0.56	0.51	0.48	0.31	0.27	0.26	0.15	0.13	0.14	0.06	0.06	0.06
-30°		1.16	1.30	1.54	0.90	1.01	1.38	0.73	0.87	1.53	0.60	0.77	2.31
-15°		0.95	1.00	1.10	0.70	0.73	0.86	0.53	0.57	0.77	0.40	0.46	0.78
0°	$k_h = 0.3$	0.83	0.84	0.88	0.57	0.56	0.61	0.40	0.40	0.47	0.28	0.29	0.39
15°		0.77	0.75	0.75	0.48	0.45	0.46	0.30	0.28	0.31	0.13	0.17	0.21
30°		0.75	0.70	0.68	0.40	0.36	0.36	0.21	0.19	0.20	0.10	0.09	0.10

Passive conditions



$$K_{PE} = N_{P\gamma} + \frac{2q}{\gamma H} N_{Pq} + \frac{2c}{\gamma H} N_{Pc}$$

β	φ	20°			30°			40°			50°		
	δ	0°	10°	20°	0°	15°	30°	0°	20°	40°	0°	25°	50°
-30°		1.74	2.00	2.29	2.15	2.82	3.77	2.71	4.23	7.45	3.48	7.39	20.18
-15°		1.78	2.16	2.56	2.38	3.42	4.57	3.26	6.08	11.67	4.63	13.12	41.27
0°	$k_h = 0$	2.04	2.58	3.17	3.00	4.71	7.10	4.60	10.09	20.91	7.55	28.68	98.06
15°		2.61	3.45	4.39	4.35	7.42	11.79	7.80	19.67	43.09	15.98	75.20	267.69
30°		3.79	5.27	6.96	7.38	13.67	22.70	16.15	45.47	103.16	43.72	234.22	848.58
-30°		1.66	1.86	2.10	2.09	2.67	3.52	2.66	4.10	7.04	3.45	7.12	19.25
-15°		1.68	1.98	2.33	2.28	3.20	4.52	3.16	5.76	10.97	4.52	12.56	39.42
0°	$k_h = 0.1$	1.89	2.35	2.86	2.82	4.37	6.55	4.38	9.49	19.66	7.27	27.37	93.61
15°		2.38	3.11	3.92	4.04	6.82	10.81	7.36	18.40	40.44	15.27	71.53	255.47
30°		3.39	4.68	6.16	6.77	12.51	20.74	15.11	42.60	96.72	41.63	223.34	809.77
-30°		1.56	1.70	1.87	2.01	2.49	3.24	2.59	3.90	6.61	3.40	6.85	18.32
-15°		1.56	1.78	2.06	2.16	2.96	4.13	3.04	5.41	10.25	4.41	12.01	37.52
0°	$k_h = 0.2$	1.71	2.08	2.50	2.63	4.00	5.95	4.15	8.86	18.33	7.00	25.95	89.09
15°		2.11	2.71	3.39	3.71	6.20	9.78	6.90	17.12	37.57	14.51	67.81	243.13
30°		2.95	4.01	5.24	6.15	11.24	18.66	14.02	39.57	89.78	39.41	211.94	770.53
-30°		1.39	1.46	1.56	1.91	2.30	2.94	2.51	3.68	6.16	3.35	6.56	17.53
-15°		1.37	1.51	1.71	2.02	2.69	3.71	2.91	5.06	9.50	4.29	11.42	35.54
0°	$k_h = 0.3$	1.48	1.73	2.04	2.42	3.59	5.30	3.91	8.20	16.97	6.69	24.51	84.32
15°		1.77	2.21	2.71	3.34	5.50	8.64	6.42	15.73	34.61	13.75	64.09	230.04
30°		2.40	3.19	4.10	5.45	9.89	16.41	12.94	36.27	82.68	37.13	200.35	729.04

DYNAMIC EARTH PRESSURE THEORIES

3. Limit analysis solutions: Lower Bound Method for Passive earth pressure (Lancellotta, 2007)

The problem of deriving the passive resistance acting on a rough vertical wall in seismic conditions can be dealt with the wall tilted from the vertical by the angle $\theta = \tan^{-1}(k_h/1 \pm k_v)$ and interacting with a backfill of slope $\varepsilon^* = \varepsilon - \theta$.

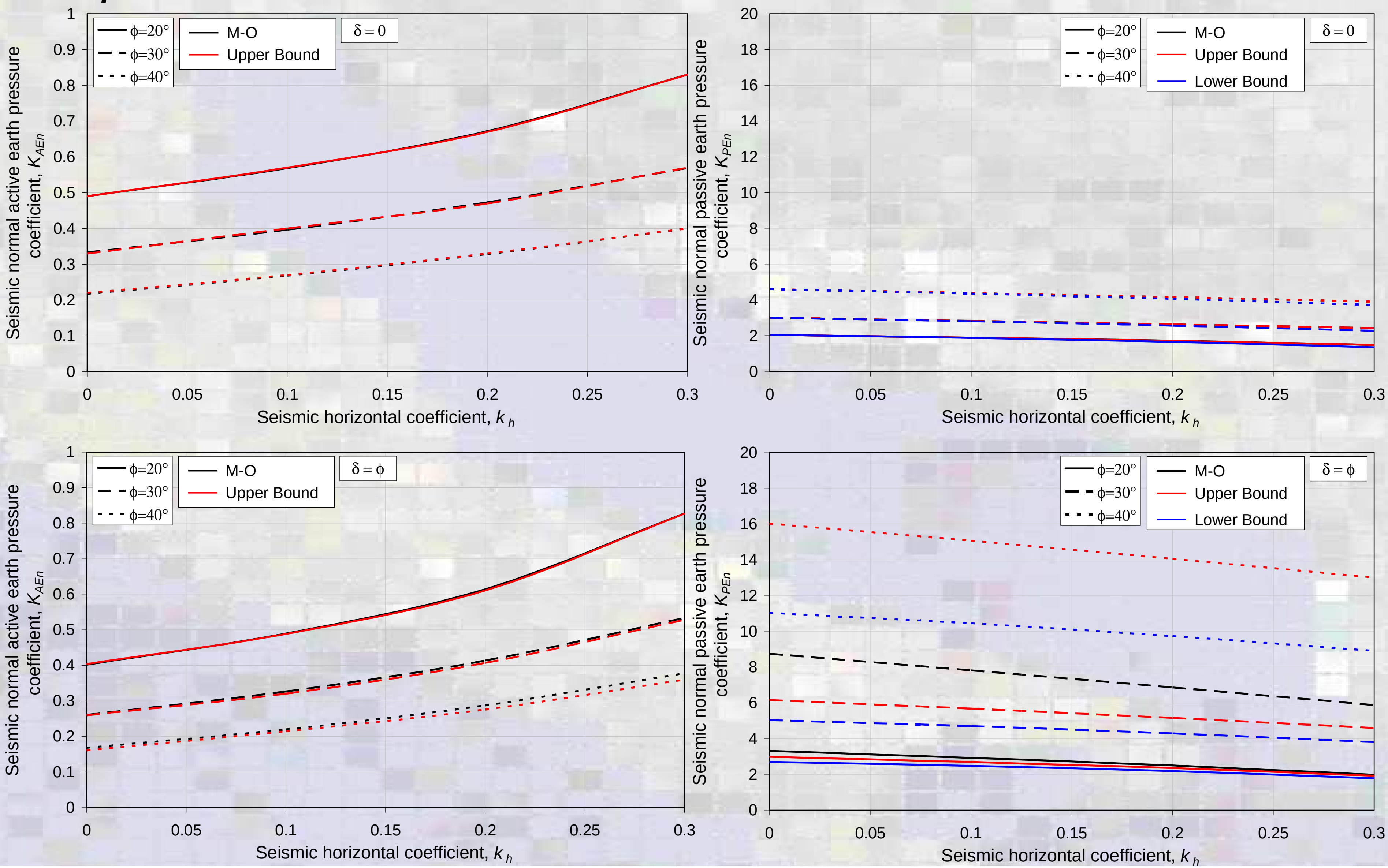
$$K_{PE} = \left[\frac{\cos\delta}{\cos(\varepsilon-\theta) - \sqrt{\sin^2\phi' - \sin^2(\varepsilon-\theta)}} \times \times\left(\cos\delta + \sqrt{\sin^2\phi' - \sin^2\delta}\right) \right] e^{a\cdot\tan\phi'}$$

where

$$a = \sin^{-1}\left(\frac{\sin\delta}{\sin\phi'}\right) + \sin^{-1}\left[\frac{\sin(\varepsilon-\theta)}{\sin\phi'}\right] + \delta + (\varepsilon-\theta) + 2\theta$$

DYNAMIC EARTH PRESSURE THEORIES

Comparisons between the seismic methods



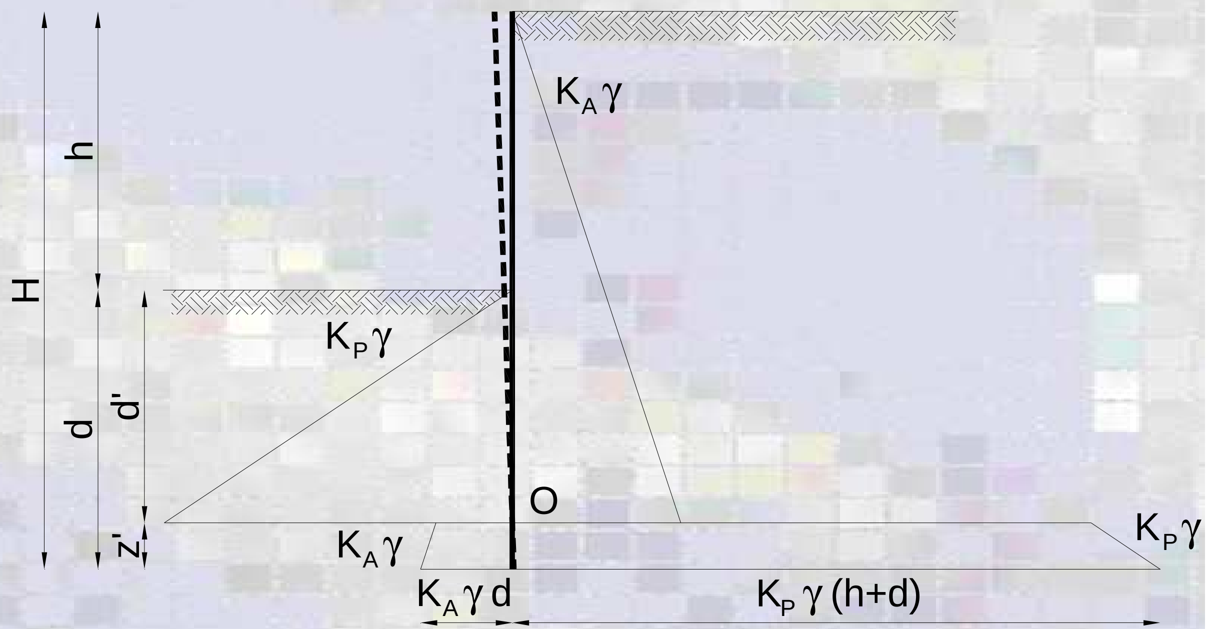
DESIGN OF FERW WITH LE METHOD

Static conditions

Hypotheses:

- Plane strain conditions
- Rigid-perfectly plastic soil behavior
- Rigid wall
- Kinematical mechanism is constituted by a wall rotation around a point placed near to the bottom

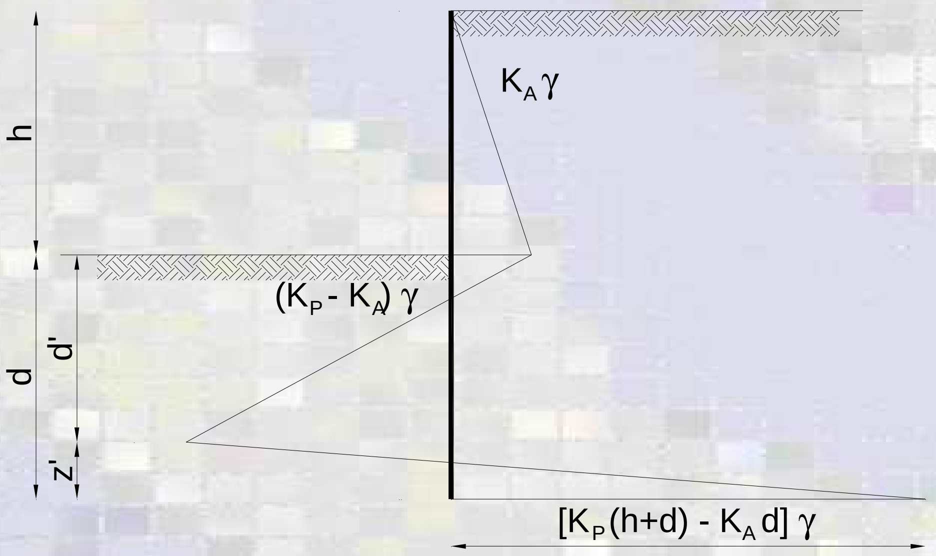
Earth pressures distribution



DESIGN OF FERW WITH LE METHOD

Static conditions

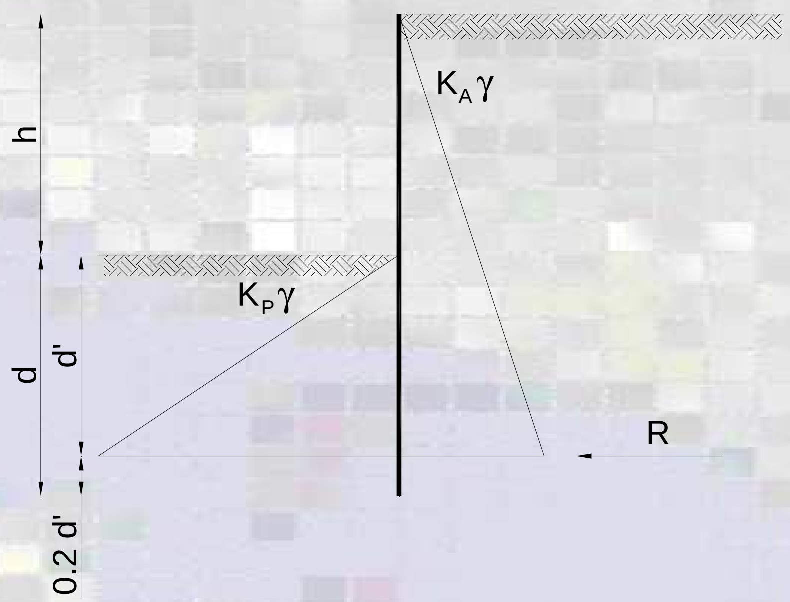
Full method (Krey, 1936)



$$\frac{z'}{h} = \frac{\frac{K_P}{K_A}\left(\frac{d}{h}\right)^2 - \left(1+\frac{d}{h}\right)^2}{\left(\frac{K_P}{K_A}-1\right)\left(1+2\frac{d}{h}\right)}$$

$$\frac{z'}{h} = \sqrt{\frac{\frac{K_P}{K_A}\left(\frac{d}{h}\right)^3 - \left(1+\frac{d}{h}\right)^3}{\left(\frac{K_P}{K_A}-1\right)\left(1+2\frac{d}{h}\right)}}$$

Blum method (Blum, 1931)



$$d = \frac{1.2h}{\sqrt[3]{K_P/K_A} - 1}$$

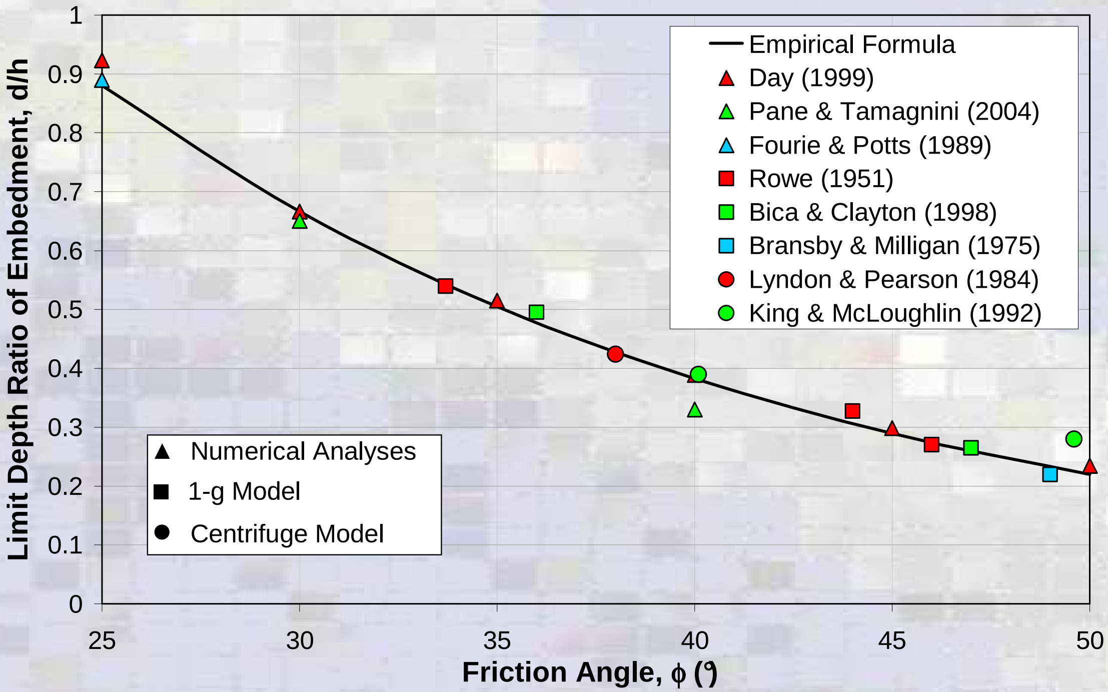
DESIGN OF FERW WITH LE METHOD

Soil-wall friction angle δ

- Current practice and EC8-5: $\delta_A = 2/3\ \varphi$; $\delta_P = 0$
- Padfield & Mair, 1984 (Report CIRIA No. 104): $\delta_A = 2/3\ \varphi$; $\delta_P = 1/2\ \varphi$

$$\frac{d}{h} = FS \cdot \frac{2}{3} e^{-\left[\frac{\phi' - 30°}{18}\right]}$$

Empirical formula (Bica & Clayton, 1992)



Experimental and numerical limit depth ratios collected by the literature

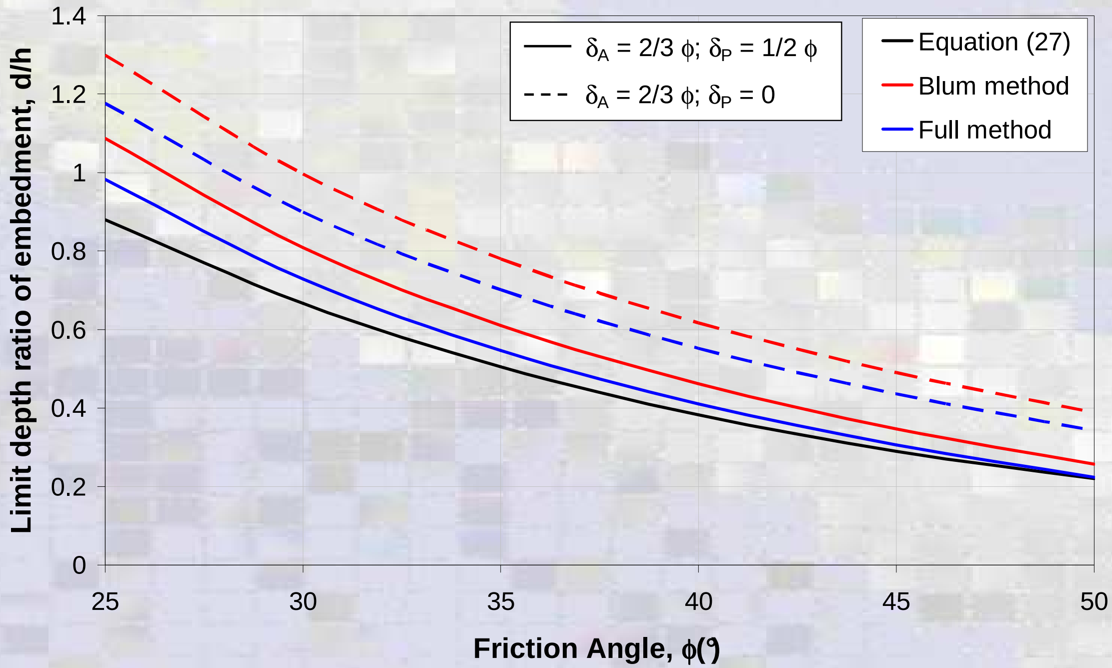
DESIGN OF FERW WITH LE METHOD

Effects of δ-value on limit depth ratio d/h

- Current practice and EC8-5: $\delta_A = 2/3\ \varphi$; $\delta_P = 0$
- Padfield & Mair, 1984 (Report CIRIA No. 104): $\delta_A = 2/3\ \varphi$; $\delta_P = 1/2\ \varphi$

$$\frac{d}{h} = FS \cdot \frac{2}{3} e^{-\left[\frac{\phi' - 30^\circ}{18}\right]}$$

Empirical formula (Bica & Clayton, 1992)



Comparisons between the empirical formula and the LE methods

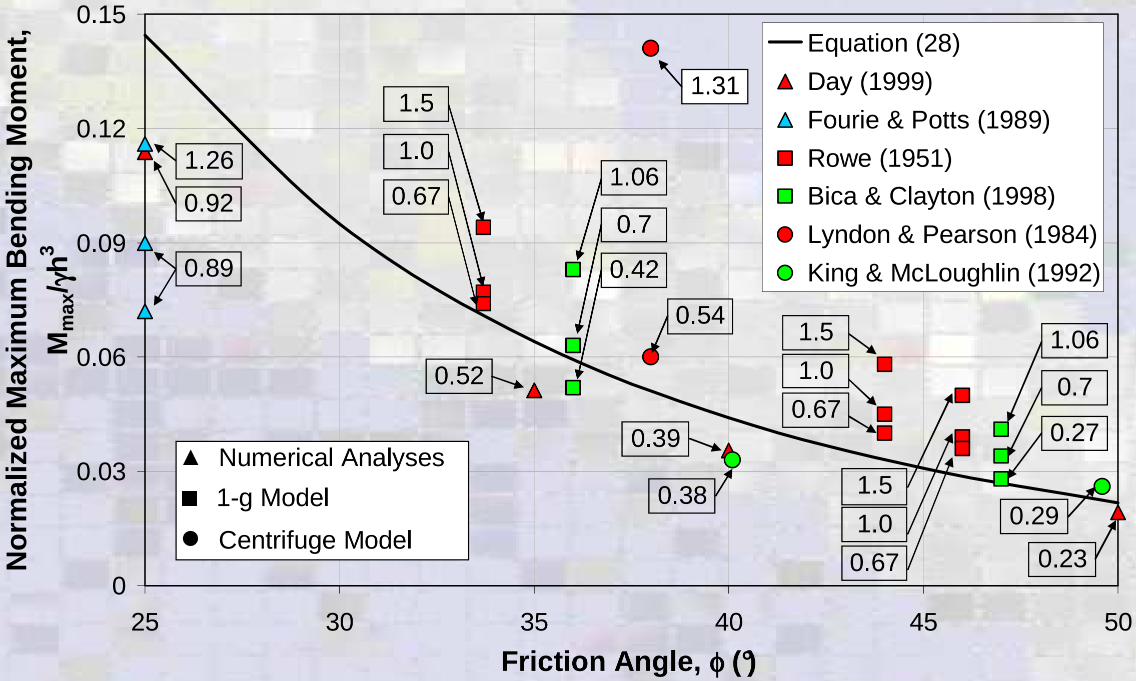
DESIGN OF FERW WITH LE METHOD

Effects of depth ratio on normalized maximum bending moment $M_{max}/\gamma h^3$

- Current practice and EC8-5: $\delta_A = 2/3\ \varphi$; $\delta_P = 0$
- Padfield & Mair, 1984 (Report CIRIA No. 104): $\delta_A = 2/3\ \varphi$; $\delta_P = 1/2\ \varphi$

$$\frac{M_{\max}}{\gamma h^3} = 0.095 \cdot e^{-\left[\frac{\phi' - 30^\circ}{16}\right]} \cdot e^{\frac{\left[\frac{d}{h} - \frac{2}{3}\right]}{2}}$$

Empirical formula (Bica & Clayton, 1992)



Experimental and numerical normalized maximum bending moment collected by the literature

DESIGN OF FERW WITH LE METHOD

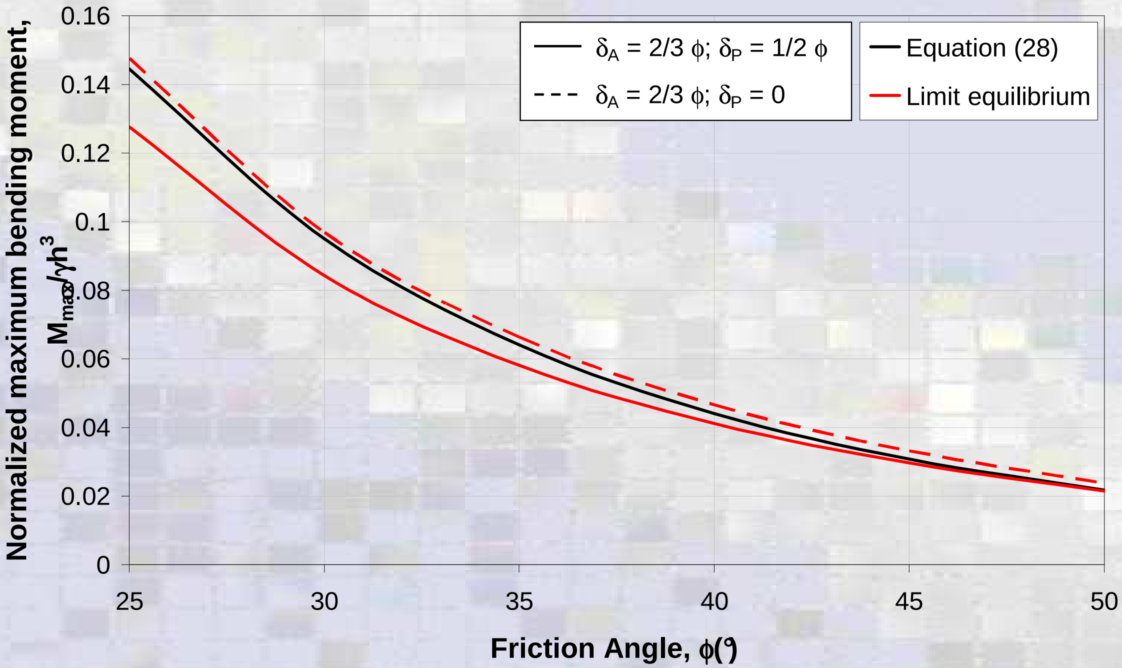
Empirical formula
(Bica & Clayton, 1992)

$$\frac{M_{\max}}{\gamma h^3} = 0.095 \cdot e^{-\left[\frac{\phi' - 30^\circ}{16}\right]} \cdot e^{\frac{\left[\frac{d}{h} - \frac{2}{3}\right]}{2}}$$

Limit Equilibrium

$$M_{\max} = \frac{\gamma}{6}\left[K_A (h+x)^3 - K_P x^3\right]$$

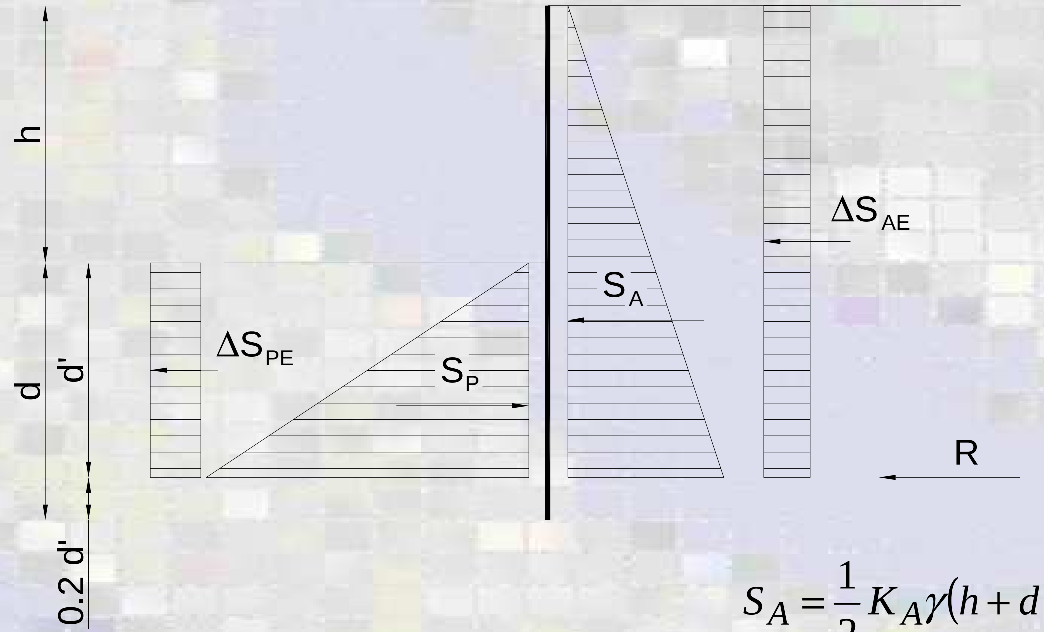
$$\frac{x}{h} = \frac{1}{\sqrt{K_P / K_A} - 1}$$



Comparisons between the empirical formula and the LE methods

DESIGN OF FERW WITH LE METHOD

Seismic conditions



Seismic earth pressures distributions (according to EC8-5)

$$S_A = \frac{1}{2} K_A \gamma (h + d')^2$$

$$\Delta S_{AE} = \frac{1}{2} (K_{AE} - K_A) \gamma (h + d')^2$$

$$k_h = \frac{S}{r} \frac{a_g}{g}$$

$$d = \frac{1.2h}{\sqrt[3]{\dfrac{3K_{PE} - K_P}{3K_{AE} - K_A}} - 1}$$

$$S_P = \frac{1}{2} K_P \gamma d'^2$$

$$\Delta S_{PE} = \frac{1}{2} (K_{PE} - K_P) \gamma d'^2$$

Factor r takes into account the capabilities of the wall to accept displacements. For embedded walls r = 1

DESIGN OF FERW WITH LE METHOD

Seismic conditions: depth of embedment

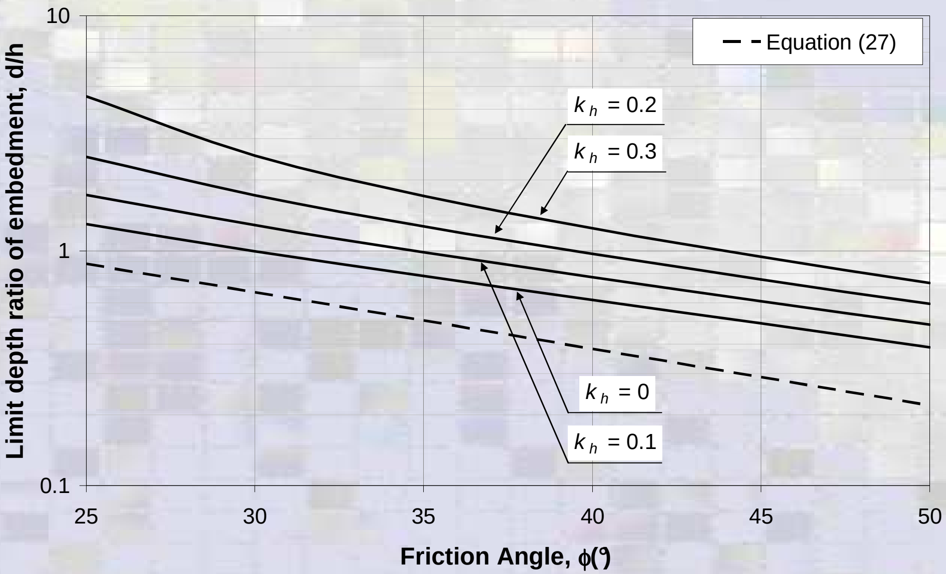
Active earth pressure coefficients:
Mononobe & Okabe method

Passive earth pressure coefficients:
Lancellotta method

$$d = \frac{1.2h}{\sqrt[3]{\frac{3K_{PE} - K_P}{3K_{AE} - K_A}} - 1}$$

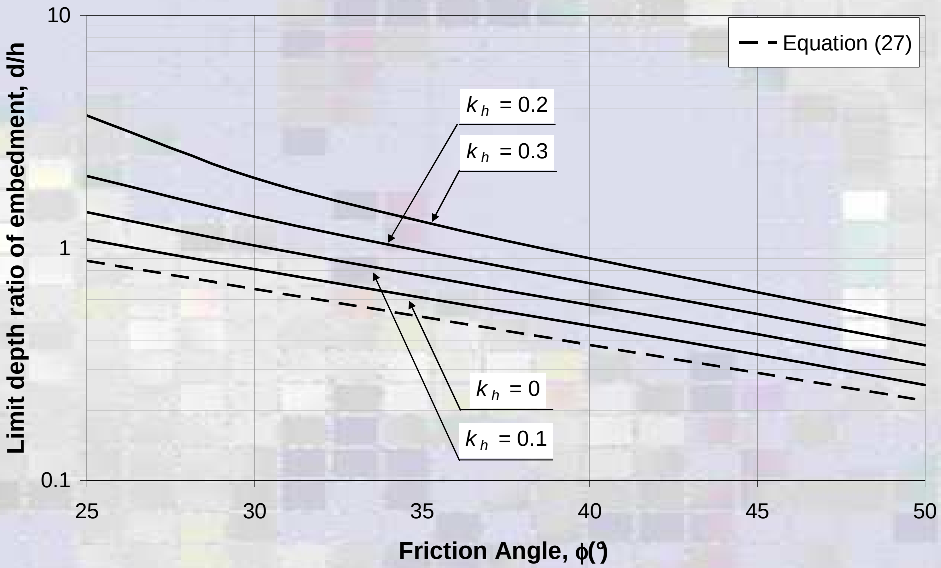
EC8-5

$\delta_A = 2/3\ \varphi;\ \delta_P = 0$



Padfield & Mair, 1984

$\delta_A = 2/3\ \varphi;\ \delta_P = 1/2\ \varphi$



DESIGN OF FERW WITH LE METHOD

Seismic conditions: maximum bending moment

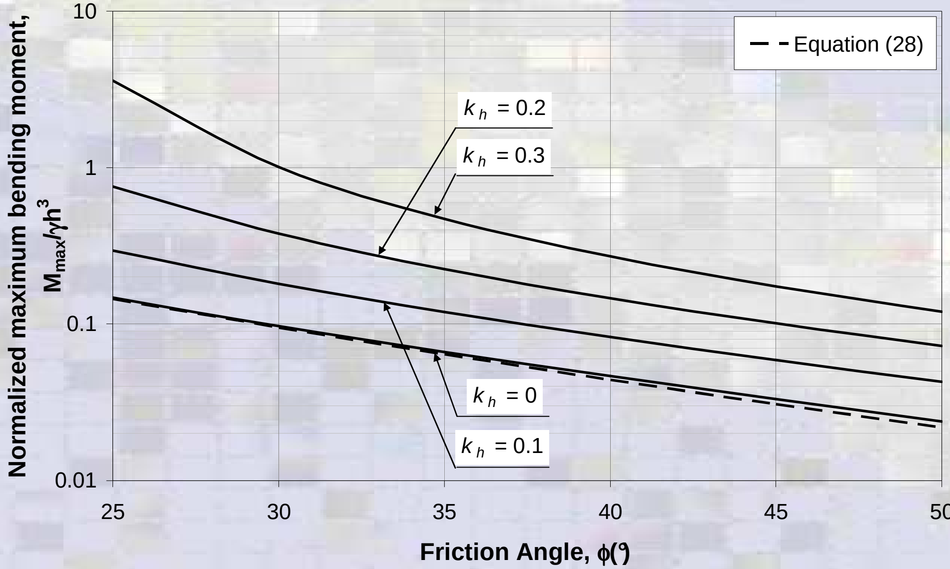
$$M_{\max} = \frac{1}{6}K_A\gamma(h+x)^3 + \frac{1}{4}(K_{AE}-K_A)\gamma(h+d')(h+x)^2 + $$
$$-\frac{1}{6}K_P\gamma x^3 - \frac{1}{4}(K_{PE}-K_P)\gamma d' x^2$$

Zero Shear Force condition

$$[K_A(h+x)+(K_{AE}-K_A)(h+d')](h+x)=$$
$$=[K_P x+(K_{PE}-K_P)d']x$$

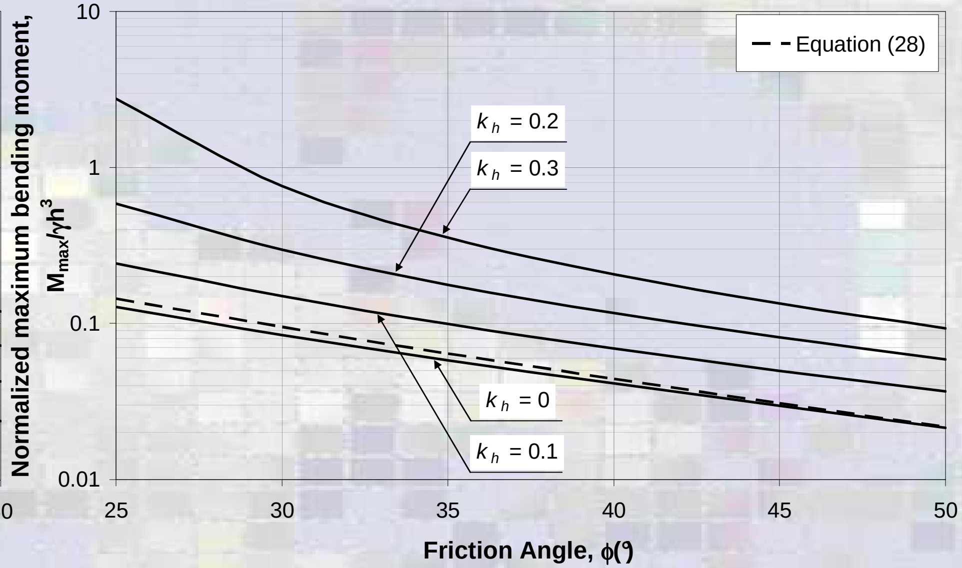
EC8-5

$\delta_A = 2/3\ \varphi;\ \delta_P = 0$



Padfield & Mair, 1984

$\delta_A = 2/3\ \varphi;\ \delta_P = 1/2\ \varphi$



RECENT ITALIAN BUILDING CODE

- In the pseudostatic approach, the seismic action can be represented with an equivalent static force equal to the product of the gravity force and a suitable seismic coefficient. For embedded walls, the vertical component of the seismic motion can be neglected.

$$k_h = \alpha \cdot \beta \cdot \frac{Sa_g}{g}$$

$$S = \text{Soil Factor} = S_S S_T$$

GROUND TYPE	S_S
A	1.00
B	$1.00 \le 1.40 - 0.40 \cdot F_0 \frac{a_g}{g} \le 1.20$
C	$1.00 \le 1.70 - 0.60 \cdot F_0 \frac{a_g}{g} \le 1.50$
D	$0.90 \le 2.40 - 1.50 \cdot F_0 \frac{a_g}{g} \le 1.80$
E	$1.00 \le 2.00 - 1.10 \cdot F_0 \frac{a_g}{g} \le 1.60$

TOPOGRAPHIC CATEGORY	CHARACTERISITCS OF GROUND SURFACE	S_T
T1	Flat Surface, Slope and isolated relief with i ≤ 15°	1.00
T2	Slope with i > 15°	1.20
T3	Relief with a width on the top lower than on the base and 15° ≤ i ≤ 30°	1.20
T4	Relief with a width on the top lower than on the base and i > 30°	1.40

- For walls that can accept displacements, the seismic increment of the thrust can be applied at the same point of the static earth thrust
- In the evaluation of the earth pressures, the soil-wall friction δ can be taken into account. The adopted values should be justified on the base of the materials that interact and of the effective mobilization degree.
- If δ>1/2φ, the evaluation of the passive resistance should consider the non-planarity of the failure surface

RECENT ITALIAN BUILDING CODE

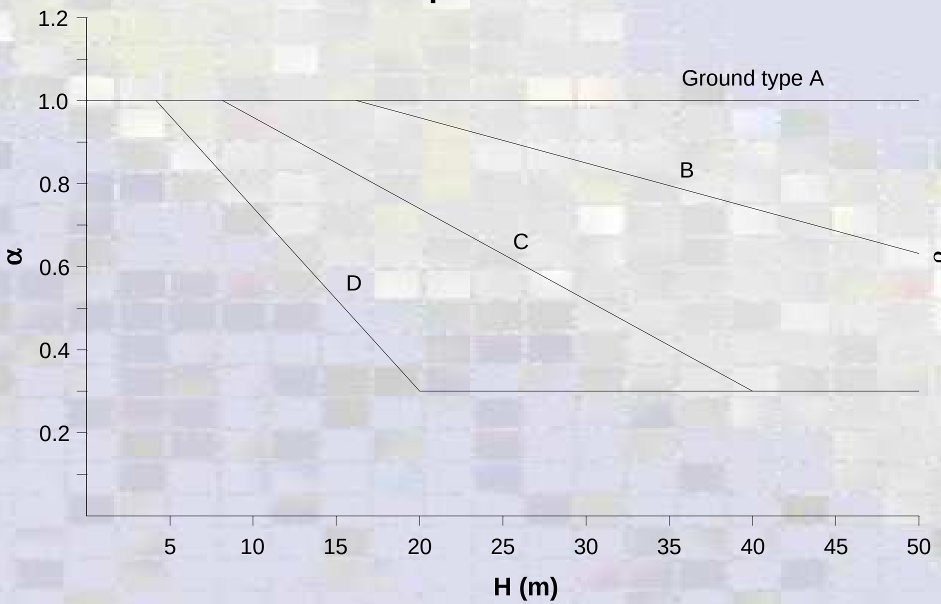
$$k_h = \alpha \cdot \beta \cdot \frac{Sa_g}{g}$$

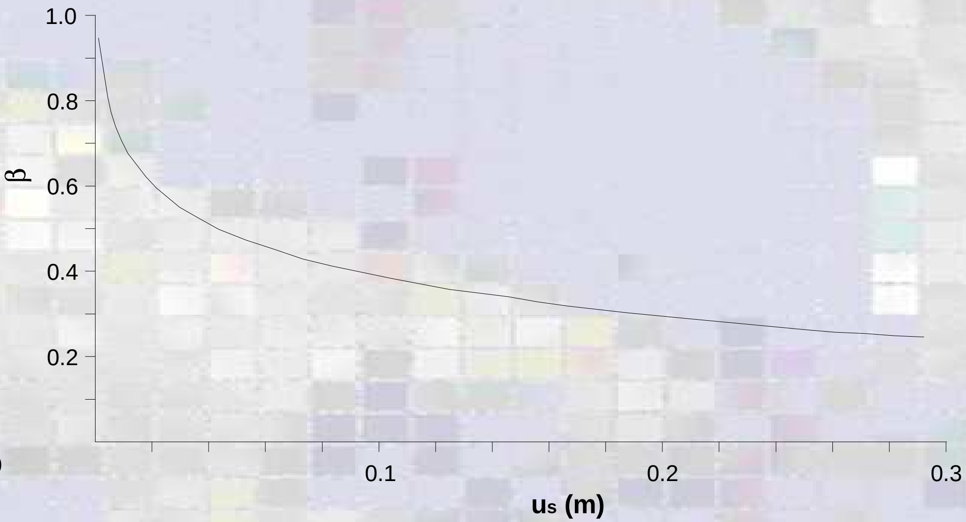
α ≤ 1 and β ≤ 1 are factors for the deformability of the soil that interacts with the wall and for the capability of the structure to accept displacements without losses of strength, respectively.

$$\alpha \beta \geq 0.2$$

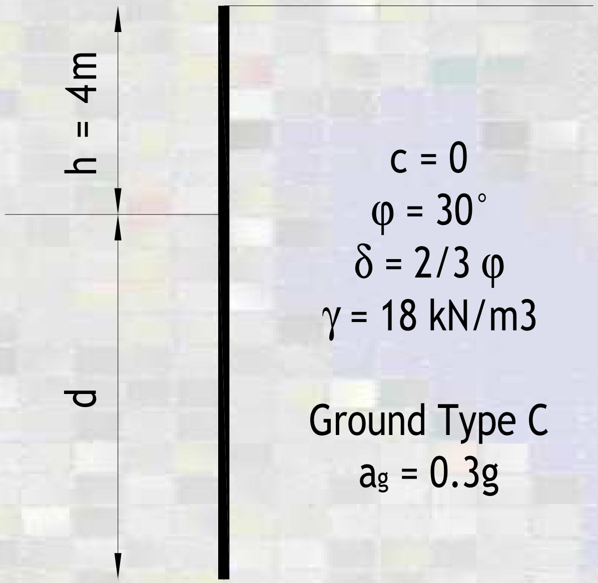
α = 1 for passive conditions

$u_s \leq 0.005\ H$





AN APPLICATION



c = 0
φ = 30°
δ = 2/3 φ
γ = 18 kN/m3

Ground Type C
$a_g = 0.3g$

EC8-5	NTC 2008
$S = 1.5$	$S = S_S\, S_T = 1.3$
$k_h = Sa_g/gr = 0.45$	$k_h = \alpha\ \beta\ Sa_g/g = 0.312$
$\delta_A = 2/3\ \varphi;\ \delta_P = 0$	$\delta_A = 2/3\ \varphi;\ \delta_P = 1/2\ \varphi$

EC8-5

$$d = \frac{1.2h}{\sqrt[3]{\dfrac{3K_{PE} - K_P}{3K_{AE} - K_A}} - 1} = 36.26\ \mathrm{m}$$

$M_{max} = 36311$ kNm/m

NTC 2008

$$d = \frac{1.2h}{\sqrt[3]{K_{PE}/K_{AE}} - 1} = 6.05\mathrm{m}$$

$M_{max} = 1011$ kNm/m

Note that the partial factors of safety for actions and strenght parameters are not considered in both of analyses

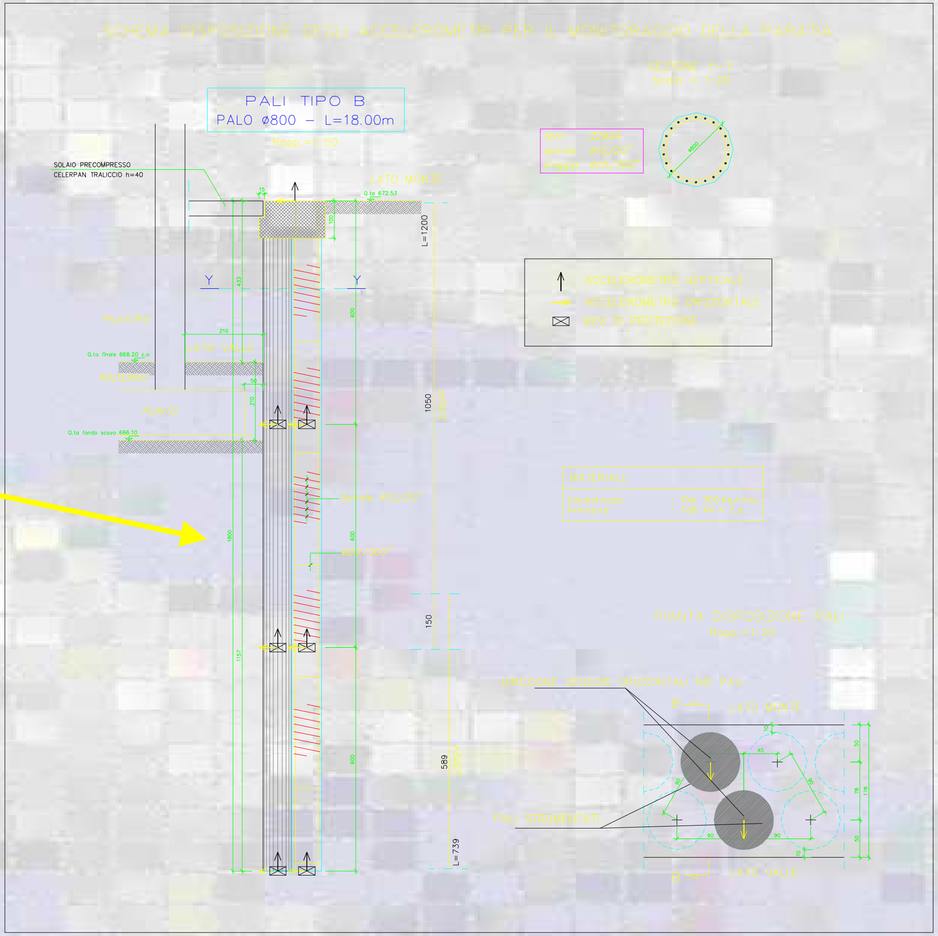
CONCLUSIONS

1. Lancellotta lower bound solution represents a conservative procedure to estimate the static and dynamic soil passive resistances without the necessity to neglect the actual soil-wall friction.
2. The comparisons between the experimental and numerical data published in the literature and the results given by the Limit Equilibrium method in terms of limit depth ratio and maximum bending moment confirm its capabilities into the static design of cantilever embedded walls.
3. The extension of LE method for the pseudostatic analysis of embedded retaining structures requires in-depth investigations. Its validation should be based on in-situ monitoring and physical modeling.

IN-SITU SEISMIC MONITORING

Structural and Geotechnical Dynamic Lab StreGa

Seismic monitoring of a RC sheet pile wall in the city of Campobasso - Italy



A project co-funded by the European Union
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MITIGATION OF THE EARTHQUAKE EFFECTS
IN TOWNS AND IN INDUSTRIAL REGIONAL DISTRICTS

M.E.E.T.I.N.G.

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Mitigation of the Earthquake Effects in Towns
and in
INdustrial reGional districts

- Final Conference -

Earthquake engineering
Presentation of the book
"Strategies for reduction of the seismic risk"
Termoli, July 14th 2008
College of Engineering, via Duca degli Abruzzi

THANK YOU FOR YOUR KIND ATTENTION…

Design of flexible retaining structures under seismic loadings

Ciro Visone & Filippo Santucci de Magistris
Structural and Geotechnical Dynamic Laboratory StreGa
University of Molise