Real Academia de Ingeniería

Reconocimiento como Ingeniero Laureado

César Sagaseta Millán

Dr. Ingeniero de Caminos, Canales y Puertos

Profesor Emérito de Ingeniería del Terreno
Universidad de Cantabria. Santander

Madrid, 26 de septiembre de 2019

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Algunas soluciones analíticas para problemas geotécnicos

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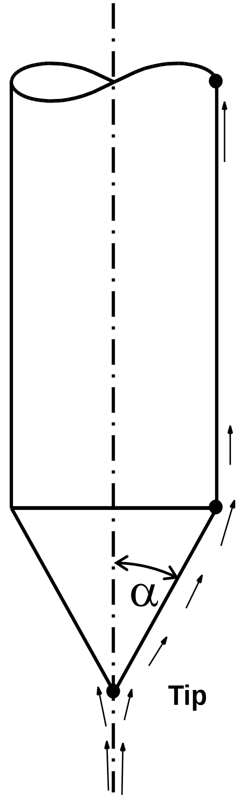
1. Análisis del ensayo de penetración estática en arcillas

1984: Integración en Grupo Univ. Oxford (Dep. of Eng. Science):

- C.P. Wroth, Prof. (Head of Department)
- G.T. Houlsby, H.J. Burd (Geotechnical Group)
- J. Norbury, A. Wheeler (Mathematical Group)
- C.I. Teh (Grad. Student)



- Análisis general: Teh and Houlsby (1991)
- Fuste: Sagaseta, Houlsby and Burd (2003)
- Hombro: Sagaseta and Houlsby (1992)

$10° \le \alpha \le 45°$ (standard: α=30°)

- Punta: Sagaseta and Houlsby (1988)

PLAXIS Version 7 Manuals.
Part 5: Validation and Verification (1998)

3.4 CYLINDRICAL CAVITY EXPANSION

For expansion of a cylindrical cavity in an elastic perfectly-cohesive soil, theoretical solutions exist for both large and small displacement analysis Sagaseta (1984). A cylindrical cavity of initial radius a_o is expanded to radius a by the application of an internal pressure p. The radius of the elastic-plastic boundary is represented by r. The soil is incompressible with an angle of friction of zero and cohesion c.

Small displacement solution: $r^2 = 2\left(\frac{G}{c}\right) a_o(a-a_o)$

$$p = \frac{2G(a-a_o)}{a_o} \quad for\ r < a_o \qquad p = c - 2c\ln\left(\frac{a_o}{r}\right) \quad for\ r > a_o$$

Large displacement solution: $r^2 = \frac{1}{\eta_r^2}(a^2-a_o^2)$

$$p = GF(\eta) \quad for\ r < a \qquad p = GF(\eta_r) + 2c\ln\left(\frac{\eta}{\eta_r}\right) \quad for\ r > a$$

where:

$$\eta^2 = \frac{a^2-a_o^2}{a^2} \qquad \eta_r^2 = 1 - \exp\left(\frac{-c}{G}\right) \qquad F(\eta) = \eta^2 + \frac{\eta^4}{4} + \frac{\eta^6}{9} + \dots$$

Input: The axisymmetric mesh used in the calculations is shown in Fig. 3.12.

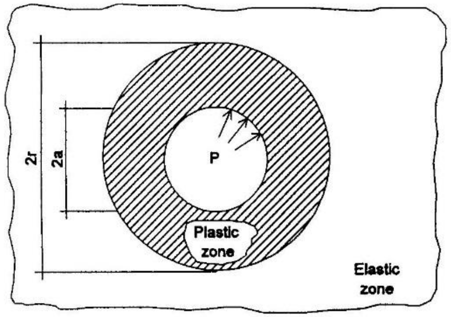


Figure 3.11 Cylindrical cavity expansion

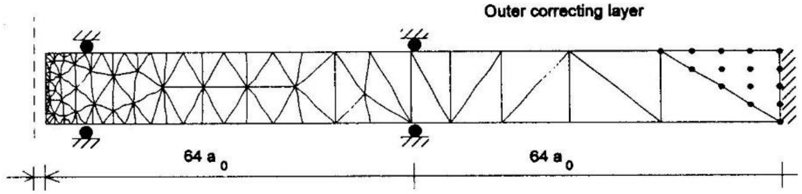


Figure 3.12 Mesh for cavity expansion

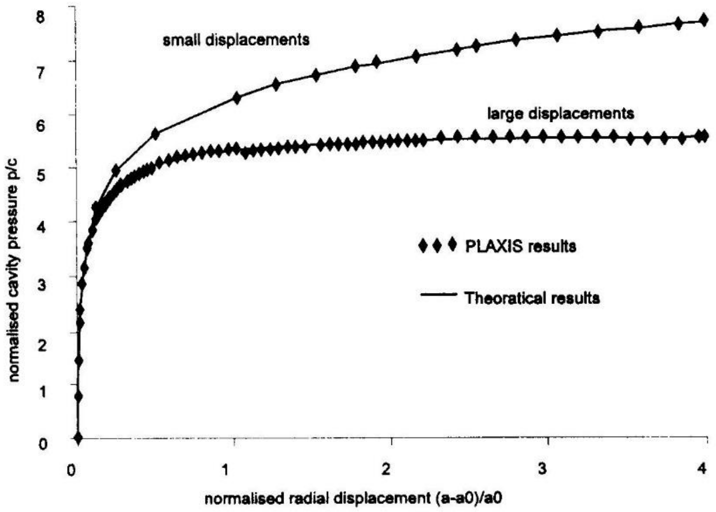
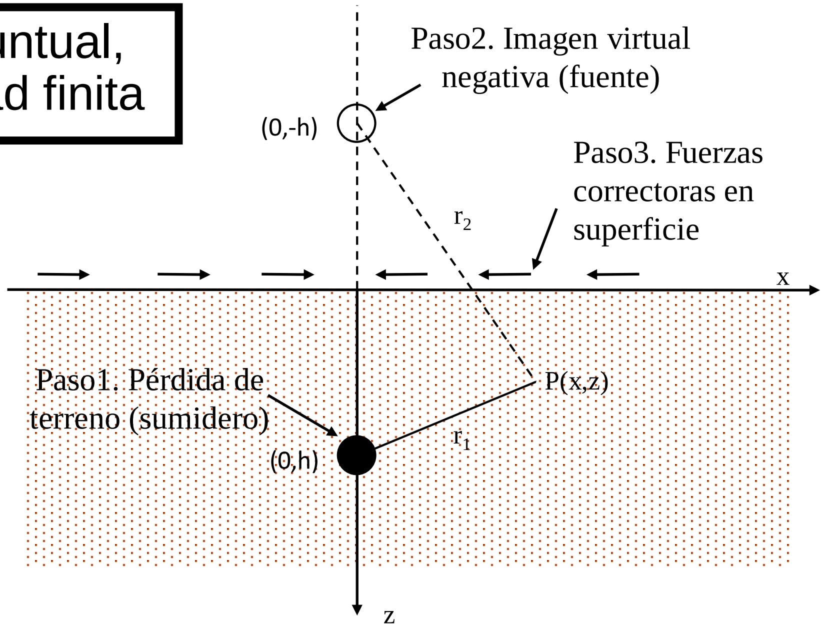


Figure 3.13 Relationships between radial displacement and cavity pressure

2. Pérdida de terreno sin drenaje ($\varepsilon_{vol}=0$) a profundidad finita

Sagaseta (1987)

Sumidero puntual, a profundidad finita



Movimientos en cualquier punto

$$s_x = -\varepsilon_a a^2 \left[x\left(\frac{1}{r_1^2}+\frac{1}{r_2^2}\right) - \frac{4xz(z+h)}{r_2^4} \right]$$

$$s_z = -\varepsilon_a a^2 \left[\left(z-h\right)\left(\frac{1}{r_1^2}+\frac{1}{r_2^2}\right) - \frac{4x^2 z}{r_2^4} \right]$$

Movimientos en la superficie (z=0)

$$s_x = -2\varepsilon_a a^2 \frac{x}{h^2+x^2}$$

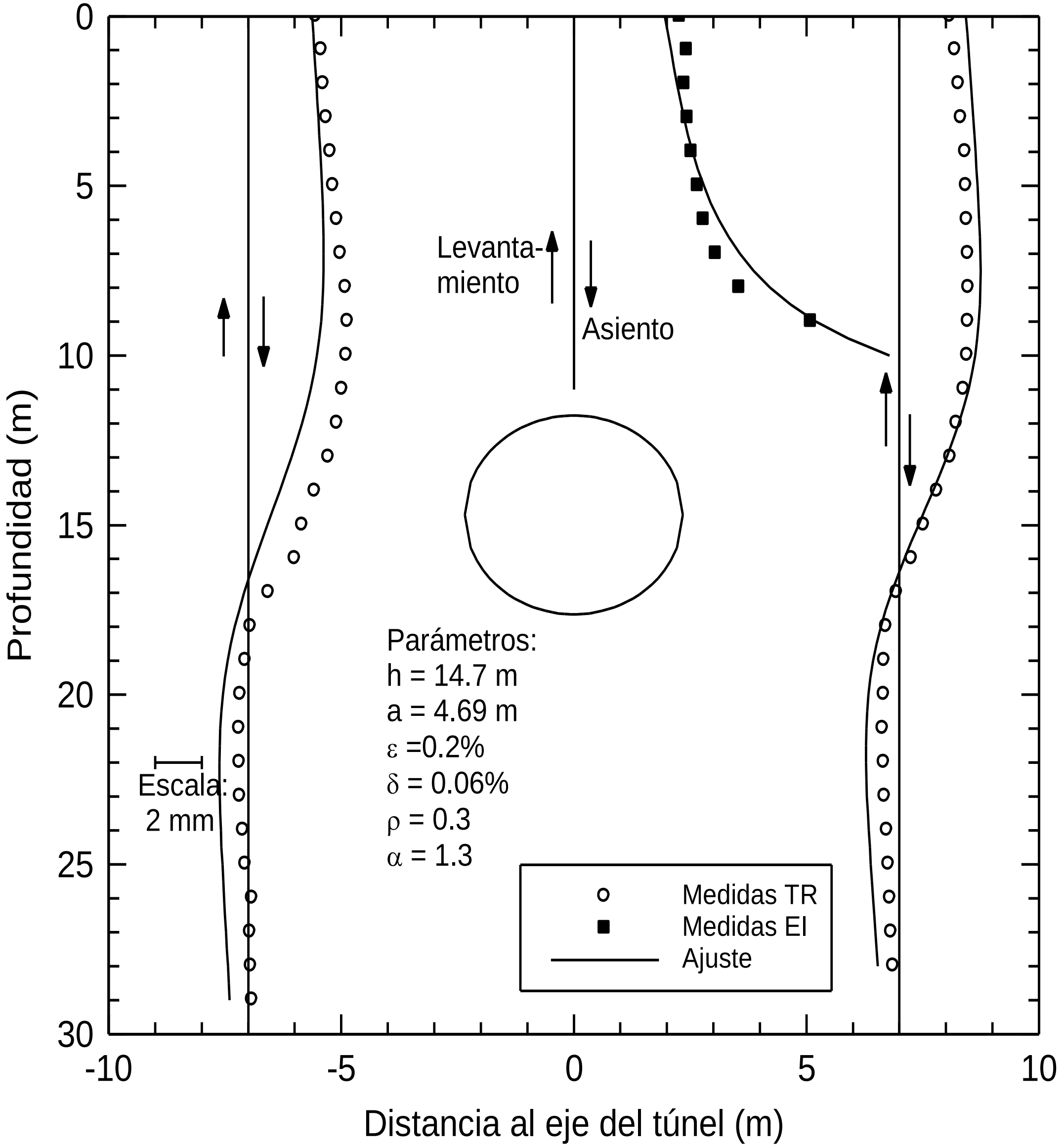
$$s_z = \quad 2\varepsilon_a a^2 \frac{h}{h^2+x^2}$$

Un ejemplo de aplicación a túneles:

Sección en Metrosur

(González, 2000)

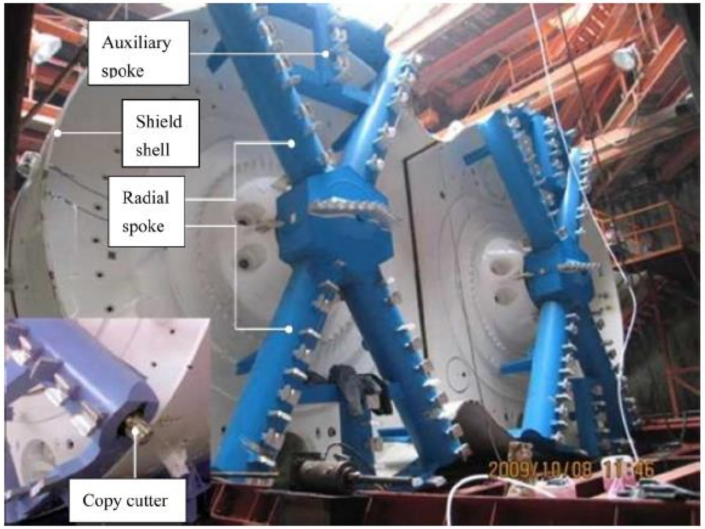
Sección 1+350 Línea 10 tramo 1. Metrosur
Movimientos verticales en el interior del terreno

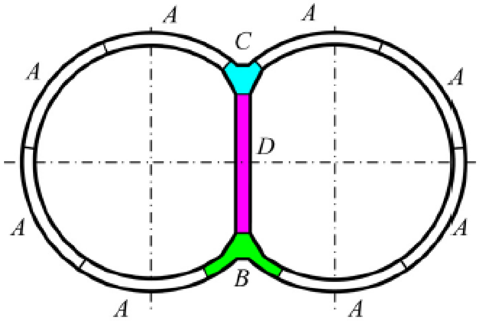


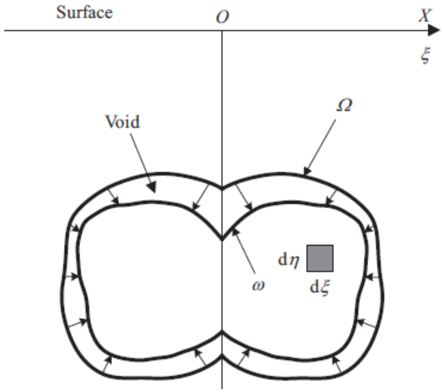
Influence of Double-O-Tube Shield Rolling on Soil Deformation during Tunneling

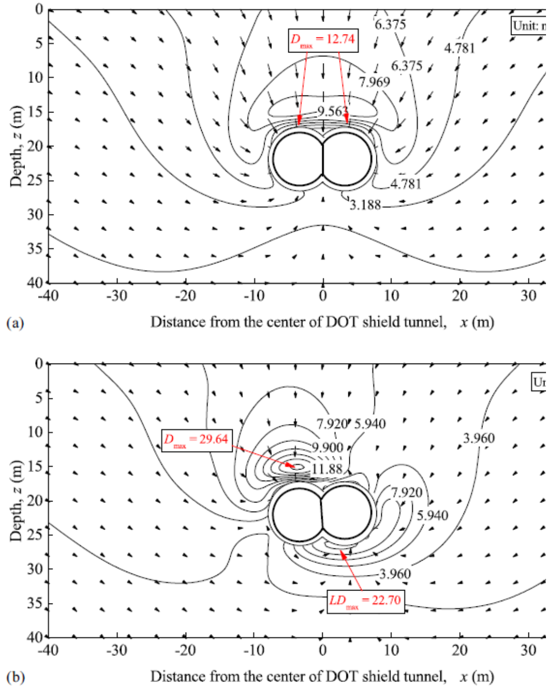
Int. J. Geomech., 2017, 17(11): 04017105

Da Huang[1] and Bin Zeng[2]









reduce the impact of rolling on soil deformation and tunnel lining. A few rolling-correction operations, such as the control of the rolling-correction jacks and the soil conveyor, one-side loading, overexcavation by the copy cutter, real-time grouting, and secondary grouting, can be adopted (Shen et al. 2006).

Analytical Solution of Soil Deformation Considering Rolling

Soil Deformation due to Unit Ground Loss

Any underground excavation certainly leads to the deformation of surrounding soil/rock toward excavated space. In Fig. 5, Ω is the boundary of tunnel excavation (i.e., the outside dimension of the shield machine for shield tunneling); ω is the boundary of the tunnel after the surrounding soil deformation, generally called that of tunnel convergence; O-XZ is the global Cartesian coordinate system; and O-$\xi\eta$ is the local Cartesian coordinate system regarding soil excavated.

Using a virtual image technique, Sagaseta (1987) proposed a closed-form method to evaluate the soil deformation due to a pure point sink in homogeneous isotropic soft soils, which was an extracted finite volume per unit length of subsoil in plane strain. However, the solution assumed that the soil was incompressible (i.e., Poisson's ratio of soil was equal to 0.5). Taking into account the effect of Poisson's ratio of soil, Verruijt and Booker (1996) presented a generalization of Sagaseta's solution in an elastic plane, and in which the ovalization effect of the tunnel lining was considered. The horizontal deformation (U_x) and vertical deformation (U_z) at point (x, z) due to ground loss induced by the excavation of a tunnel with an axis position of (0, z_0) [Fig. 6(a)] can be expressed as Eqs. (1) and (2), respectively

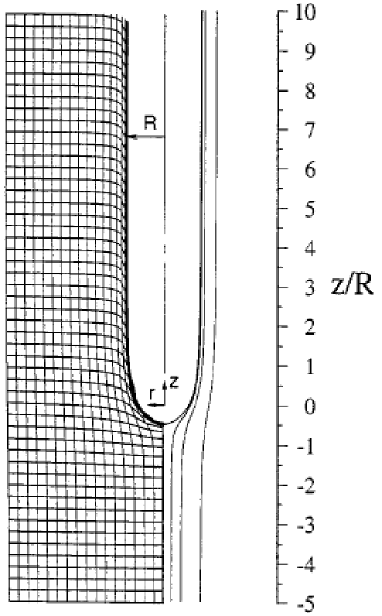
$$U_x = -\varepsilon R^2\left(\frac{x}{d_1^2}+\frac{x}{d_2^2}\right)+\delta R^2\left[\frac{x\left(x^2-kz_1^2\right)}{d_1^4}+\frac{x\left(x^2-kz_2^2\right)}{d_2^4}\right]$$
$$-\frac{2\varepsilon R^2 x}{m}\left(\frac{1}{d_2^2}-\frac{2mzz_2}{d_2^4}\right)-\frac{4\delta R^2 xz_0}{m+1}\left[\frac{z_2}{d_2^4}+\frac{mz\left(x^2-3z_2^2\right)}{d_2^6}\right] \quad (1)$$

$$U_z = -\varepsilon R^2\left(\frac{z_1}{d_1^2}+\frac{z_2}{d_2^2}\right)+\delta R^2\left[\frac{z_1\left(kx^2-z_1^2\right)}{d_1^4}+\frac{z_2\left(kx^2-z_2^2\right)}{d_2^4}\right]$$
$$+\frac{2\varepsilon R^2}{m}\left[\frac{(m+1)z_2}{d_2^2}-\frac{mz\left(x^2-z_2^2\right)}{d_2^4}\right]$$

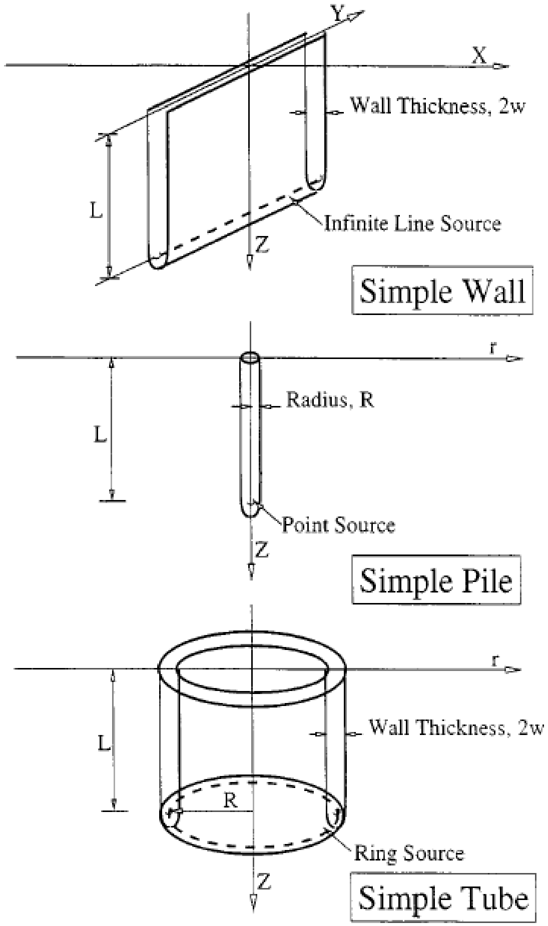
3. Extensión a fuente o sumidero móvil
(extracción o inyección de material)

Integración en Grupo M.I.T. (1993-94):

- A. Whittle, Prof. (Geotechnical Group)
- M. Santagata (Grad. Student)



Hinca estacionaria
(profundidad infinita)
(Baligh, 1985)

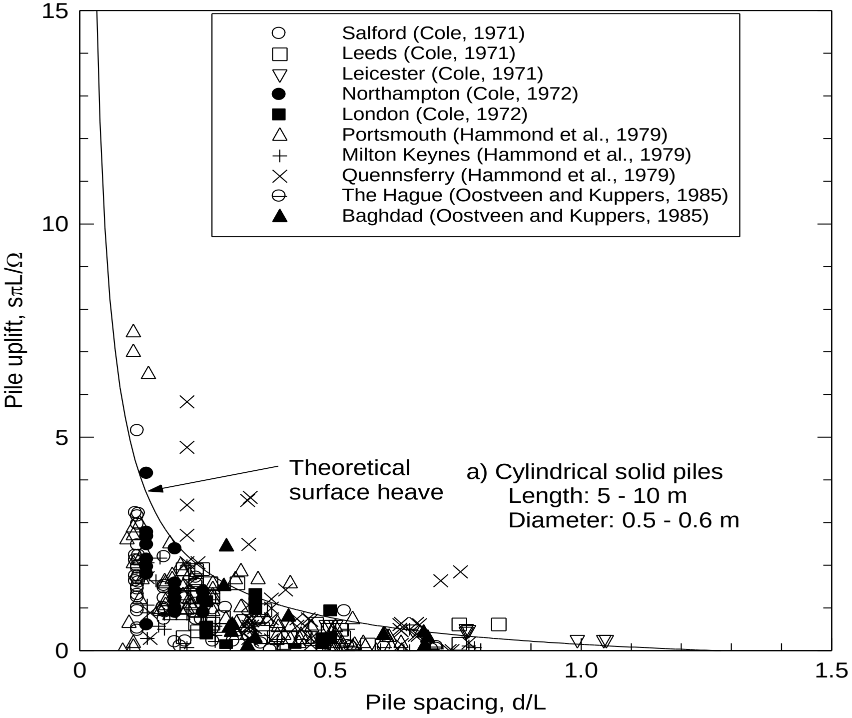


Hinca desde la superficie
(Sagaseta, Whittle y Santagata, 1997)

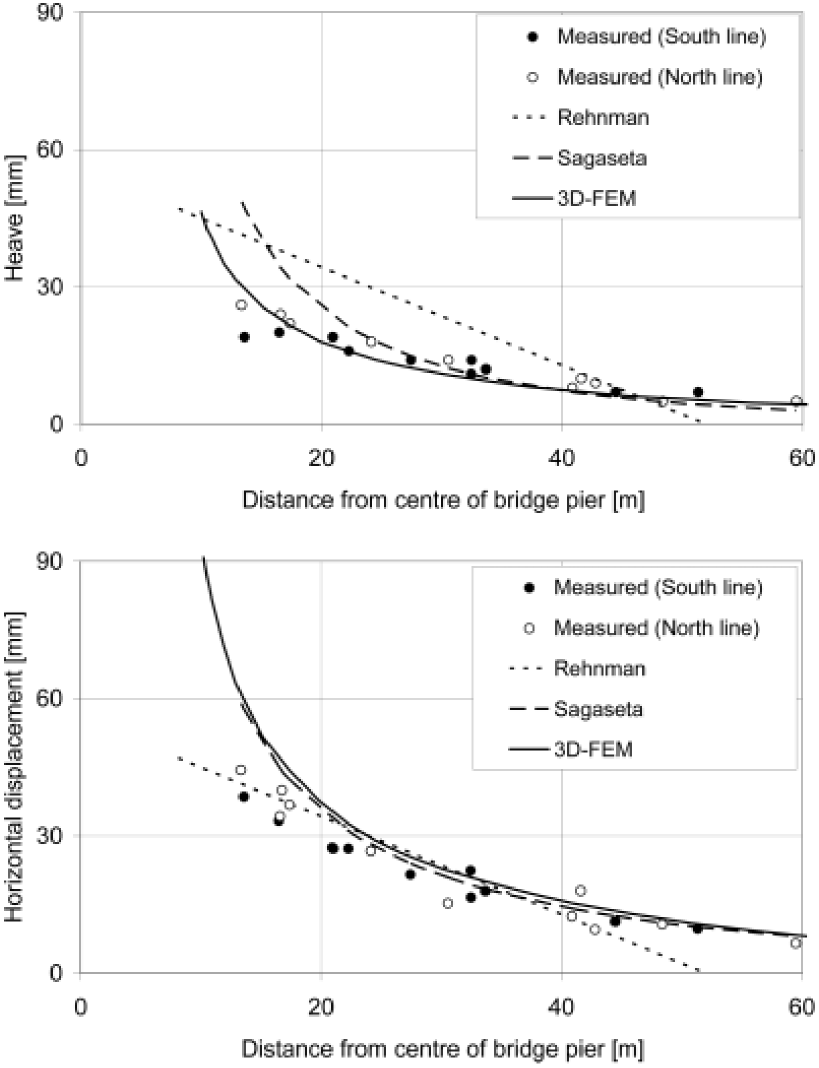
Aplicación a hinca de pilotes

$$s_r = \frac{\Omega}{2\pi}\frac{L}{\sqrt{r^2 + L^2}}$$

$$s_z = \frac{\Omega}{2\pi}\left(\frac{1}{r} - \frac{1}{\sqrt{r^2 + L^2}}\right)$$

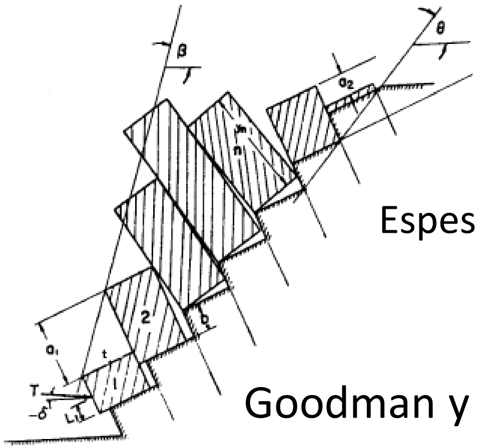


Recopilación de medidas publicadas
(Sagaseta y Whittle, 2001)



Estribo de un puente en Suecia
(Edstam y Kullingsjö, 2010)

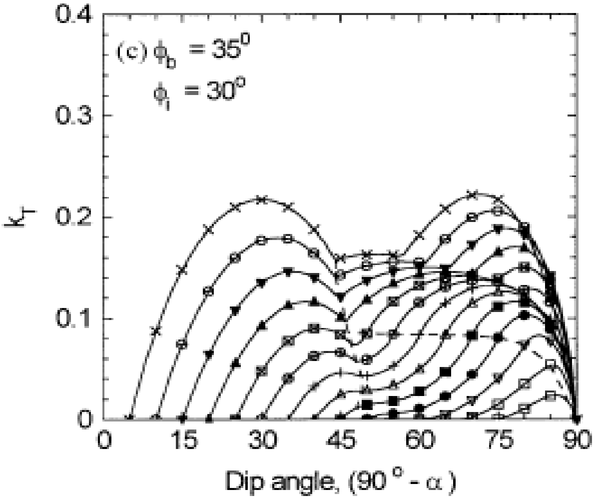
4. Rotura por *toppling* de taludes rocosos. Análisis continuo



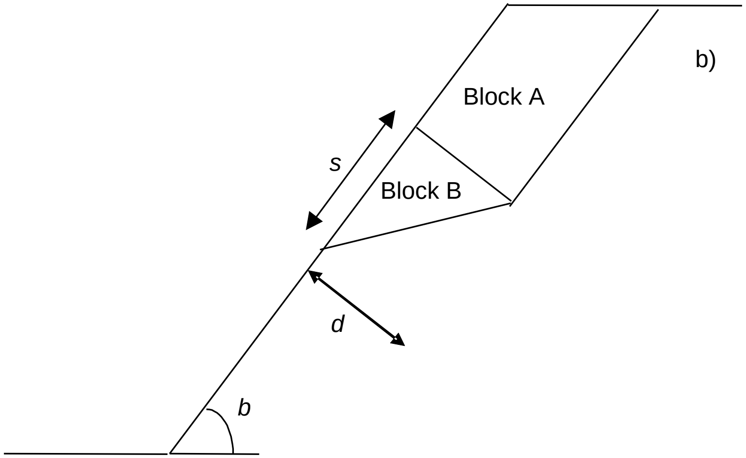
Espesor de bloque: $t \rightarrow dx$

Goodman y Bray (1977)

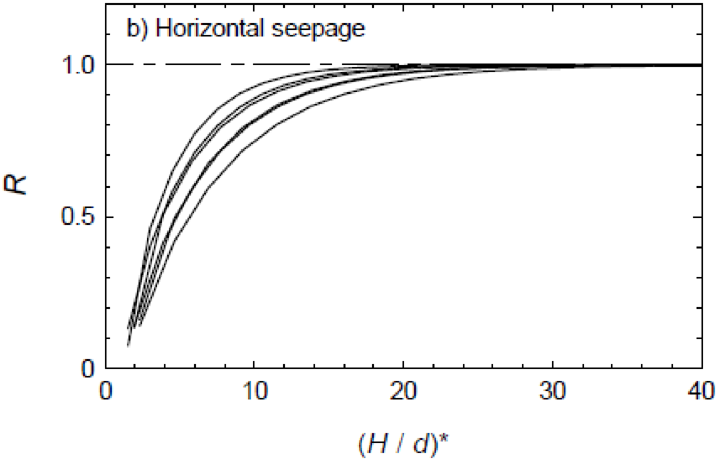
Sagaseta, Cañizal y Sánchez Alciturri (2001)



5. Inestabilidades y refuerzos superficiales en taludes



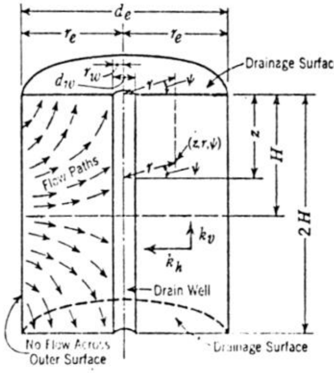
Da Costa (2004)

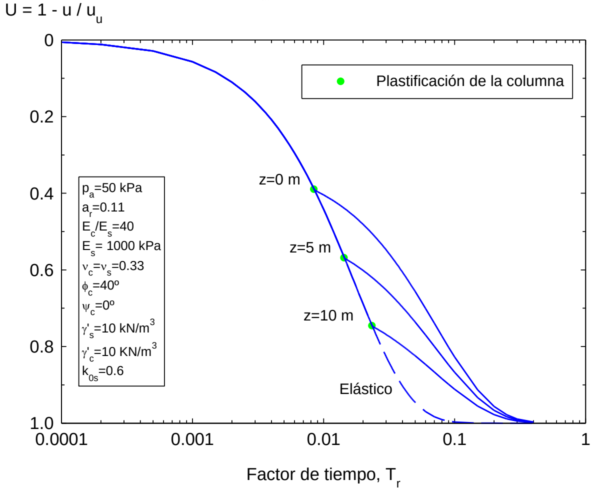


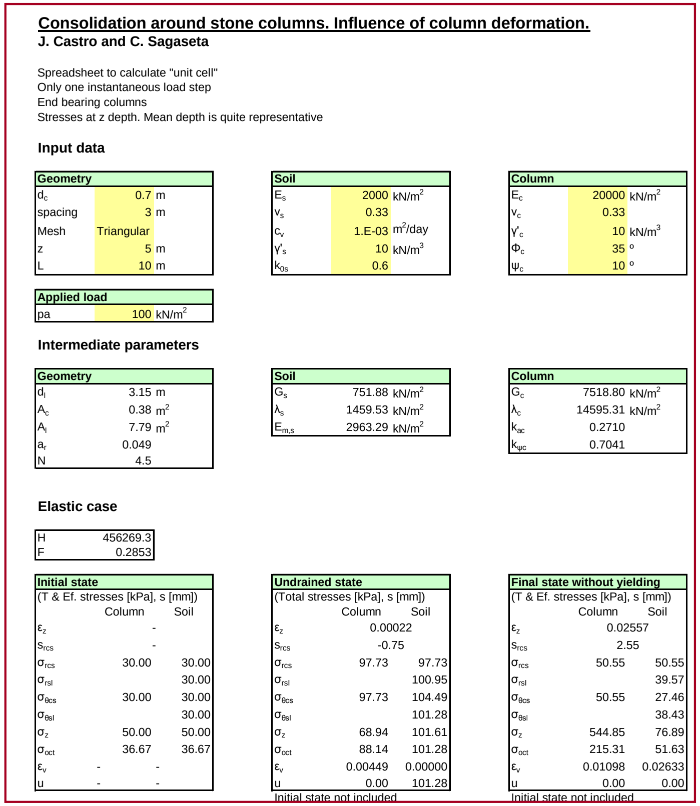
6. Análisis de columnas de grava bajo terraplenes y cimentaciones: Carga sin drenaje y consolidación radial

Tesis Doctorales:

- Solución analítica (columna elastoplástica): Castro (2008)
- Estudios experimentales: Cimentada (2009), Miranda (2014)







Consolidation around stone columns. Influence of column deformation.

J. Castro and C. Sagaseta

Spreadsheet to calculate "unit cell"
Only one instantaneous load step
End bearing columns
Stresses at z depth. Mean depth is quite representative

Input data

Geometry		
d_c	0.7	m
spacing	3	m
Mesh	Triangular	
z	5	m
L	10	m

Soil		
E_s	2000	kN/m^2
ν_s	0.33	
c_v	1.E-03	m^2/day
γ'_s	10	kN/m^3
k_{0s}	0.6	

Column		
E_c	20000	kN/m^2
ν_c	0.33	
γ'_c	10	kN/m^3
Φ_c	35	º
ψ_c	10	º

Applied load		
pa	100	kN/m^2

Intermediate parameters

Geometry		
d_l	3.15	m
A_c	0.38	m^2
A_l	7.79	m^2
a_r	0.049	
N	4.5	

Soil		
G_s	751.88	kN/m^2
λ_s	1459.53	kN/m^2
$E_{m,s}$	2963.29	kN/m^2

Column		
G_c	7518.80	kN/m^2
λ_c	14595.31	kN/m^2
k_{ac}	0.2710	
$k_{\psi c}$	0.7041	

Elastic case

H	456269.3
F	0.2853

Initial state (T & Ef. stresses [kPa], s [mm])	Column	Soil
ε_z	-	
s_{rcs}	-	
σ_{rcs}	30.00	30.00
σ_{rsl}		30.00
$\sigma_{\theta cs}$	30.00	30.00
$\sigma_{\theta sl}$		30.00
σ_z	50.00	50.00
σ_{oct}	36.67	36.67
ε_v	-	-
u	-	-

Undrained state (Total stresses [kPa], s [mm])	Column	Soil
ε_z	0.00022	
s_{rcs}	-0.75	
σ_{rcs}	97.73	97.73
σ_{rsl}		100.95
$\sigma_{\theta cs}$	97.73	104.49
$\sigma_{\theta sl}$		101.28
σ_z	68.94	101.61
σ_{oct}	88.14	101.28
ε_v	0.00449	0.00000
u	0.00	101.28

Initial state not included

Final state without yielding (T & Ef. stresses [kPa], s [mm])	Column	Soil
ε_z	0.02557	
s_{rcs}	2.55	
σ_{rcs}	50.55	50.55
σ_{rsl}		39.57
$\sigma_{\theta cs}$	50.55	27.46
$\sigma_{\theta sl}$		38.43
σ_z	544.85	76.89
σ_{oct}	215.31	51.63
ε_v	0.01098	0.02633
u	0.00	0.00

Initial state not included

… / …