Numerical Simulation of Pipe-Soil Interaction

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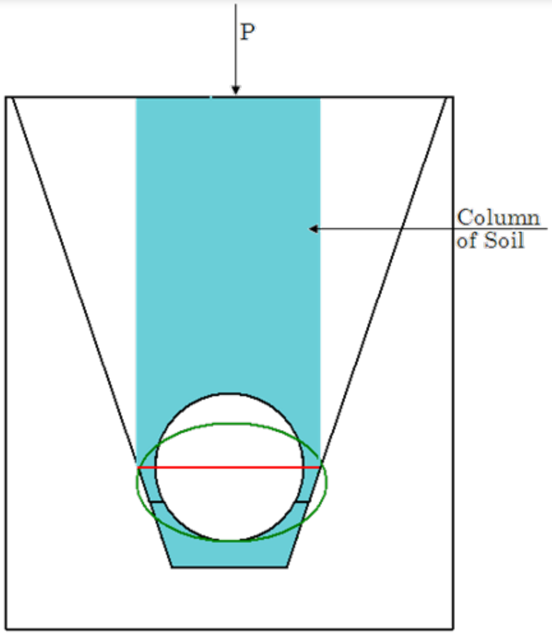
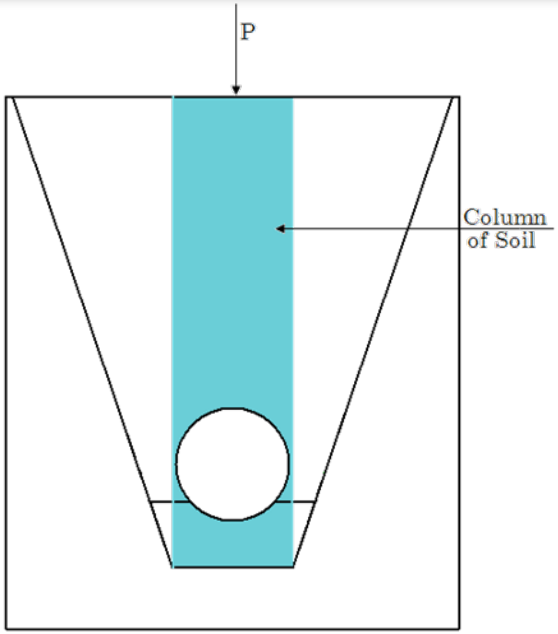


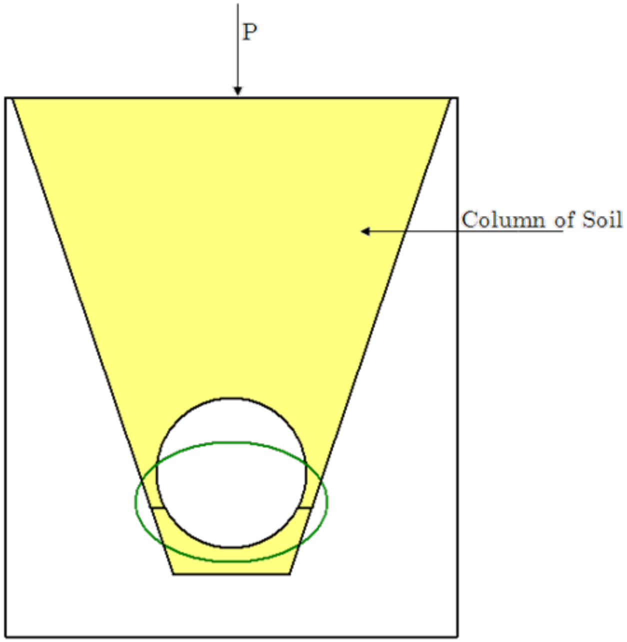
Spangler design



Marston design

- Differs between kinds of Pipes (Flexible / Rigid)
- Soil is considered to have an Elastic behavior
- Fill is considered to have an Elastic Behavior
- Only properties of a vertical column of soil/fill affect results

- Model has an exact geometry, which includes trench angle (b)
- Different constitutive models can be used in natural soil
- Different constitutive models can be used in fill
- It takes into account the different friction coefficients that exist between materials.



FEM Analysis

Outline

1. Traditional Design Methods.
2. Constitutive Methods
3. FEM Analysis
4. Results
5. Numerical Example – Emisario Cartagena
6. Preliminary Design Abaqus

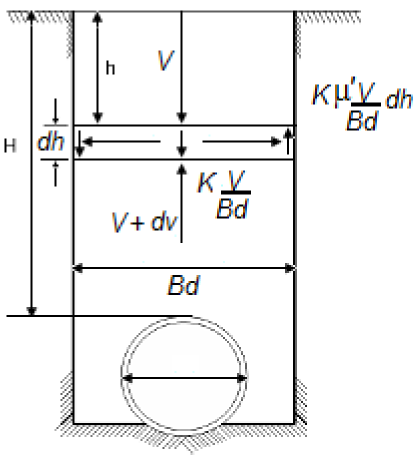
In flexible pipes, pipe material stiffness is negligible in comparison with soil stiffness.

$$\Delta\chi = \frac{D_L K W_c r^3}{EI + 0,061E' r^3} \qquad \frac{\Delta y}{D} = \frac{(D_L W_c + W_l) W_c}{149PS + 61000M_s}$$

Where,

D_L	Deflection Factor
K	Foundation Constant
Wl	Live load at top of pipe (N/m^2)
W_C	Dead load per pipe length
r	Pipe radius
E	Youngs Modulus (Elasticity)
I	Inertia Modulus per pipe length $I = \frac{\pi}{64}(D^4 - d^4)$
E'	Soil Modulus
PS	Pipe stiffness (kPa)
Ms	Constrained soil modulus (MPa)
D	Outer pipe diameter
Δy	Vertical pipe diameter variation
$\Delta\chi$	Horizontal pipe diameter variation

In Rigid Pipes, pipe stiffness is much higher than soil stiffness. It is necessary to determinate if pipe resistance is enough to support applied load. Pipe takes the major portion of the loads.



$$(V + dV) + \left(\frac{2K\mu' V}{B_d}\right) dh = V + \gamma B_d\, dh$$

$$(V + dV) + \left(\frac{2K\mu' V}{B_d}\right) dh - V + \gamma B_d\, dh = 0$$

$$\frac{dV}{dh} = \left(\lambda B_d - \frac{2K\mu' V}{B_d}\right)$$

The general expression of Hooke's Law

$$\sigma_{ik} = C_{iklm}\varepsilon_{lm} = \lambda\delta_{ik}\delta_{lm\varepsilon_{lm}} + 2\mu\left[\frac{1}{2}\delta_{il}\delta_{km}\varepsilon_{lm} + \frac{1}{2}\delta_{im}\delta_{kl}\varepsilon_{lm}\right]$$

$$\underline{\sigma} = \lambda tr\left[\underline{\varepsilon}\right]\underline{1} + 2\mu\underline{\varepsilon}$$

$$\underline{\sigma} = \lambda e 1 + 2\mu\varepsilon$$

Hypoplasticity is a constitutive model developed for granular soils. It is constitutive equation should be written in an incremental way. Wollfersdorff equation (1996) improves mathematic formulation introducing four material constants that depend on stress and void relation and four other calibration constants that do not vary with material.

$$\overset{\circ}{\mathbf{T}} = f_b f_e \left(\mathcal{L}\mathbf{D} + f_d \mathbf{N} \left\| \mathbf{D} \right\| \right)$$

Where,

D	Strain rate
f_b	Barotropic's factor
f_e	Pyknotropy factor
f_d	Density factor

1. Barotropic Factor is modified
2. Pyknotropy and Density factor are removed.
3. Void dependecy is introduced by OCR parameter

$$\overset{\circ}{\mathbf{T}} = f_b f_e \left(\mathcal{L}\mathbf{D} + f_d \mathbf{N} \left\|\mathbf{D}\right\|\right) \qquad \overset{\circ}{\mathbf{T}} = f_b \left(\mathcal{L}\mathbf{D} + \mathbf{N} \left\|\mathbf{D}\right\|\right)$$

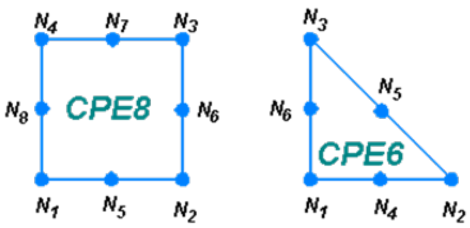
$$\overset{\circ}{\mathbf{T}} = f_b \mathcal{L} \left(\mathbf{D} + \left(\mathcal{L}^{-1}\mathbf{N}\right) \left\|\mathbf{D}\right\|\right) \qquad \overset{\circ}{\mathbf{T}} = f_b \hat{\mathcal{L}} \left(\mathbf{D} - \underbrace{\left[\left(-\hat{\mathcal{L}}^{-1}\mathbf{N}\right) \left\|\mathbf{D}\right\|\right]}_{\mathbf{D}^{v}}\right)$$

$$\overset{\circ}{\mathbf{T}} = f_b \hat{\mathcal{L}} \left(\mathbf{D} - \mathbf{D}^{v}\right) \text{ ConstitutiveEquation,Niemunis(1995)}$$

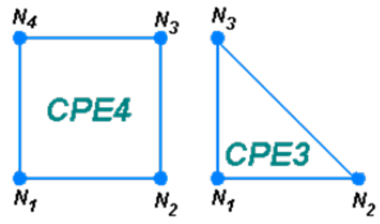
FEM Analysis

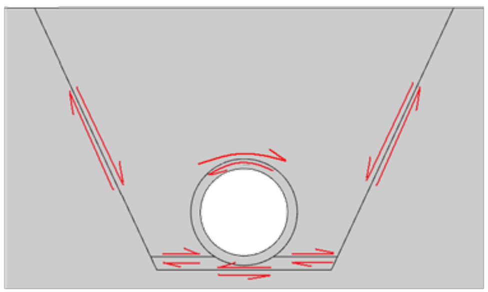
Geometry & Boundary Condition

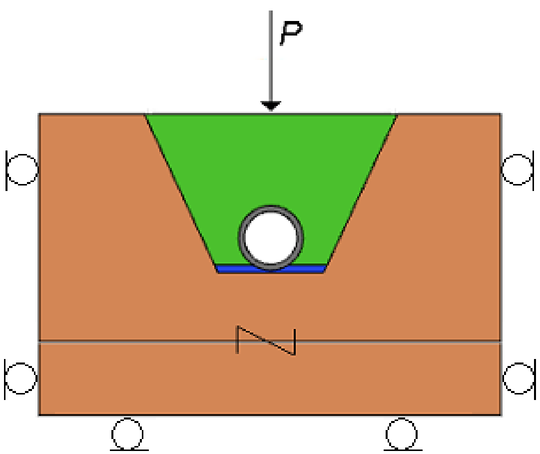
Natural soil structure's elements

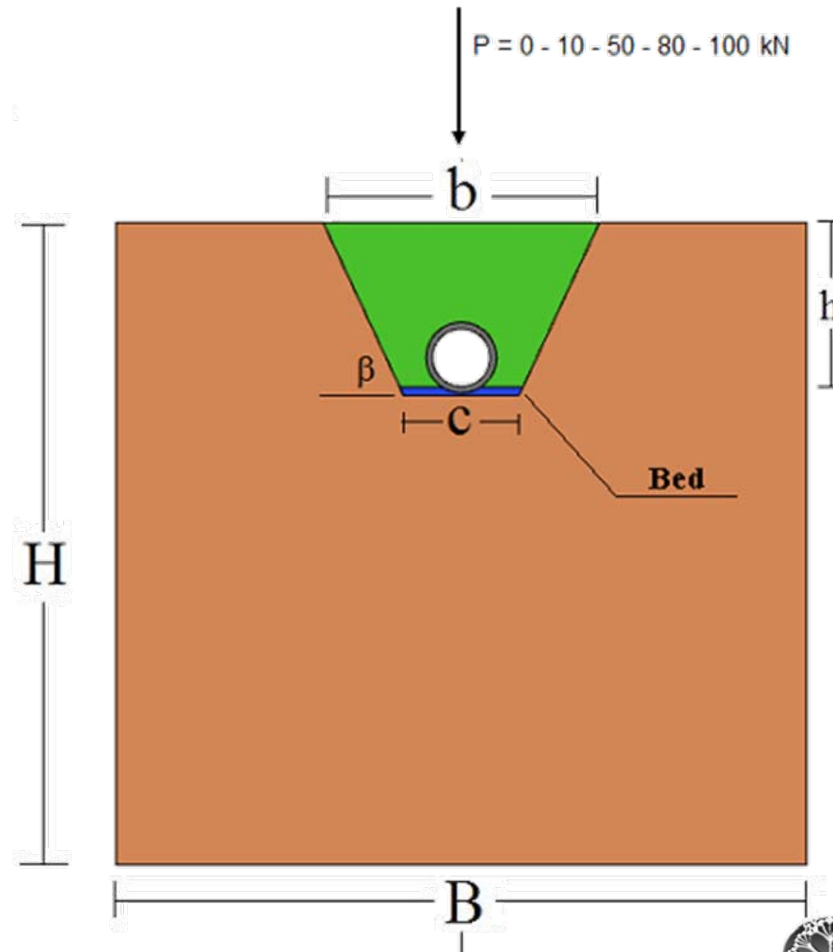


Other structure's elements





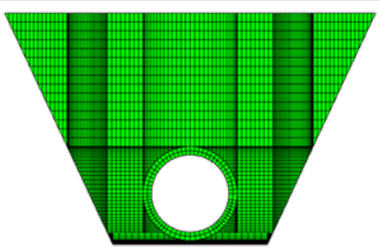


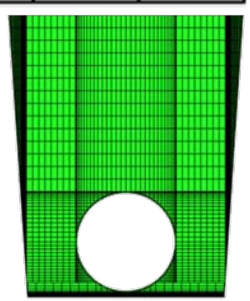


Results

Traditional design procedure

γ [kN/m³]	18.20	18.20	18.20	18.20	18.20
B_d [m]	2.53	2.53	2.53	2.53	2.53
H [m]	1.93	1.93	1.93	1.93	1.93
W_d [kN/m²]	20.13	20.13	20.13	20.13	20.13
D [m]	1.024	1.024	1.024	1.024	1.024
Mp [ ]	1.20	1.20	1.20	1.20	1.20
I_f [ ]	1.54	1.54	1.54	1.54	1.54
LLDF [ ]	1.15	1.15	1.15	1.15	1.15
L_1[m]	3.21	3.21	3.21	3.21	3.21
Hint [m]	1.59	1.59	1.59	1.59	1.59
L_2[m]	2.21	2.21	2.21	2.21	2.21
P [kN]	**0**	**10**	**50**	**80**	**100**
Wv [kN/m]	0.00	2.60	13.02	20.83	26.03
W_t [kN/m]	20.13	22.73	33.14	40.95	46.16
Msn [MPa]	4.00	4.00	4.00	4.00	4.00
Msb [MPa]	4.80	4.80	4.80	4.80	4.80
Bd/D	2.47	2.47	2.47	2.47	2.47
Msn/Msb	0.83	0.83	0.83	0.83	0.83
Sc	0.85	0.85	0.85	0.85	0.85
Ms [MPa]	4.08	4.08	4.08	4.08	4.08
DI	1.05	1.05	1.05	1.05	1.05
149*PS [kPa]	40000	40000	40000	40000	40000
I [m⁴/m]	0.0049	0.0049	0.0049	0.0049	0.0049
E [kPa]	24000000	24000000	24000000	24000000	24000000
Kx [ ]	0.097	0.097	0.097	0.097	0.097
Δy/D	0.71%	0.80%	1.15%	1.41%	1.58%
Δy [mm] Spangler	7.27	8.16	11.74	14.43	16.22





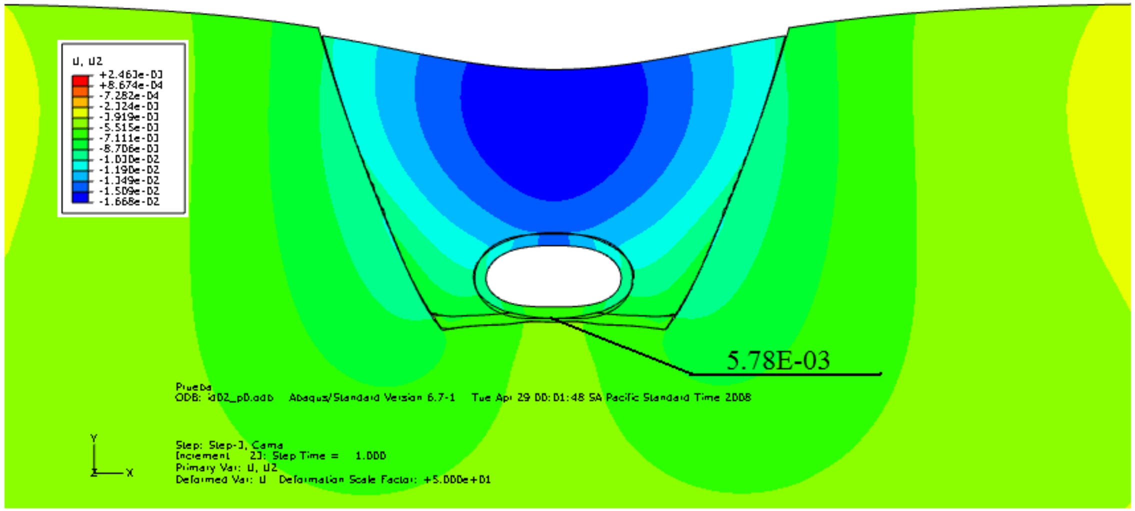
$$W_c = \gamma_s H \quad W_l = \frac{M_p P I_f}{L_1 L_2}$$

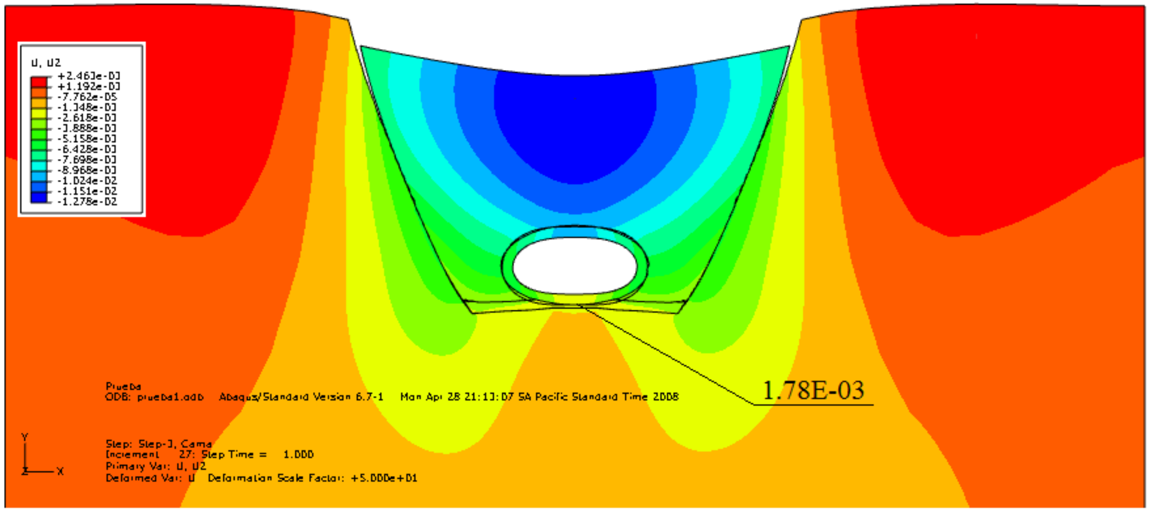
$$W_c = C_d \gamma B_d^2$$

$$W_l = \frac{C_s P F}{L} \text{ Boussinesq}$$

γ [kN/m³]	18.20	18.20	18.20	18.20	18.20
B_d [m]	2.00	2.00	2.00	2.00	2.00
K [ ]	0.33	0.33	0.33	0.33	0.33
u' [ ]	0.50	0.50	0.50	0.50	0.50
Ku' [ ]	0.17	0.17	0.17	0.17	0.17
H [m]	1.73	1.73	1.73	1.73	1.73
Cd [ ]	0.75	0.75	0.75	0.75	0.75
W_d [kN/m]	54.78	54.78	54.78	54.78	54.78
Bc [m]	1.22	1.22	1.22	1.22	1.22
L [m]	1	1	1	1	1
b [ ]	0.35	0.35	0.35	0.35	0.35
a [ ]	0.29	0.29	0.29	0.29	0.29
a2 + b2 + 1	0.21	0.21	0.21	0.21	0.21
a2 + 1	1.08	1.08	1.08	1.08	1.08
b2 + 1	1.12	1.12	1.12	1.12	1.12
Cs [ ]	0.99	0.99	0.99	0.99	0.99
F [ ]	1.00	1.00	1.00	1.00	1.00
P [kN/m]	**0**	**10**	**50**	**80**	**100**
Wv [kN/m]	0.00	9.95	49.75	79.59	99.49
W_t [kN/m]	54.78	64.73	104.53	134.38	154.27
F.S [ ] Marston	0.91	0.77	0.48	0.37	0.32

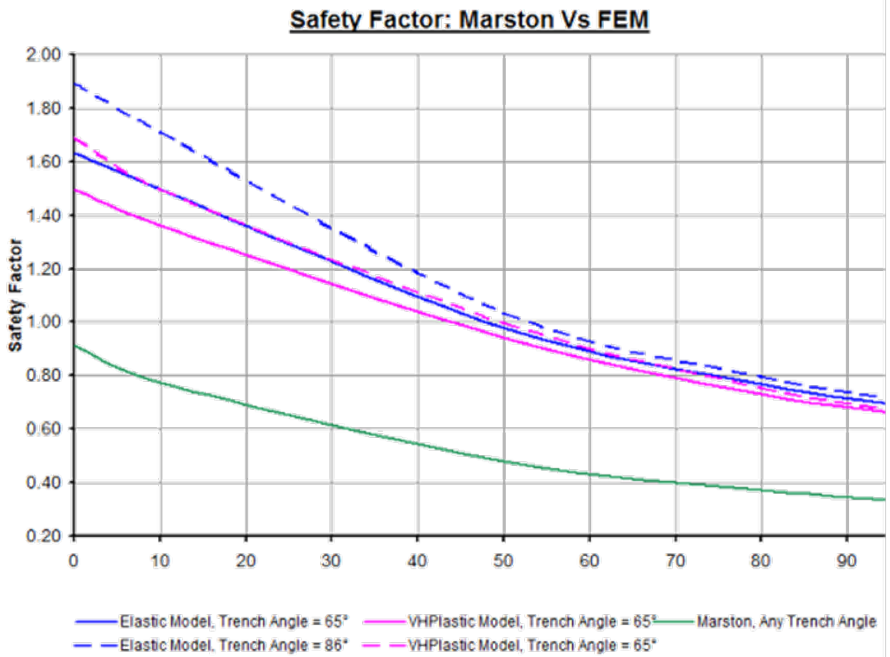
U2 Deformation for elastic natural soil material

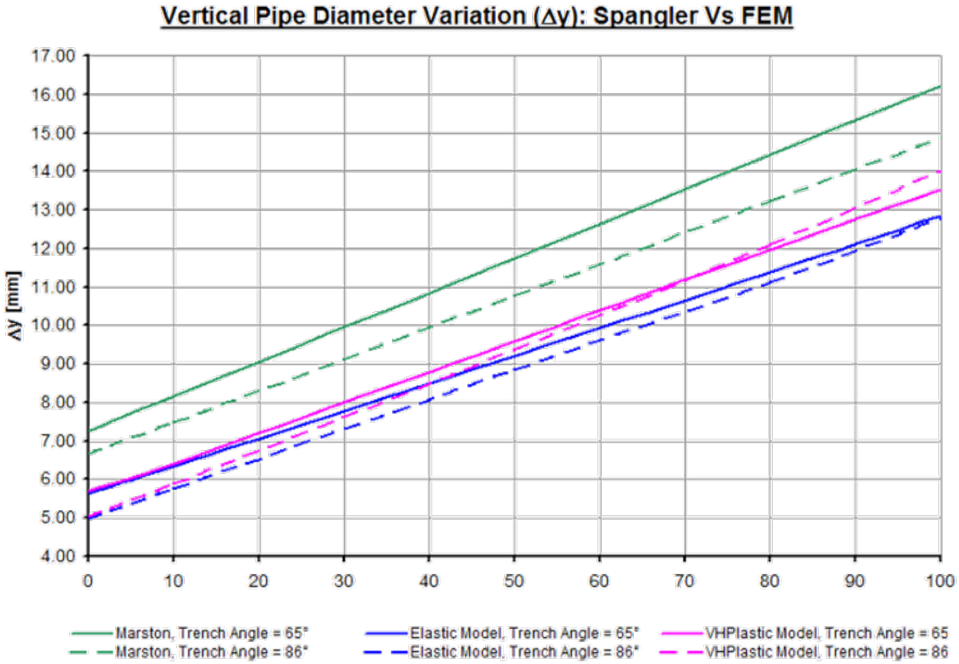




U2 Deformation for viscohypoplastic natural soil material

Results
FEM Vs Actual design





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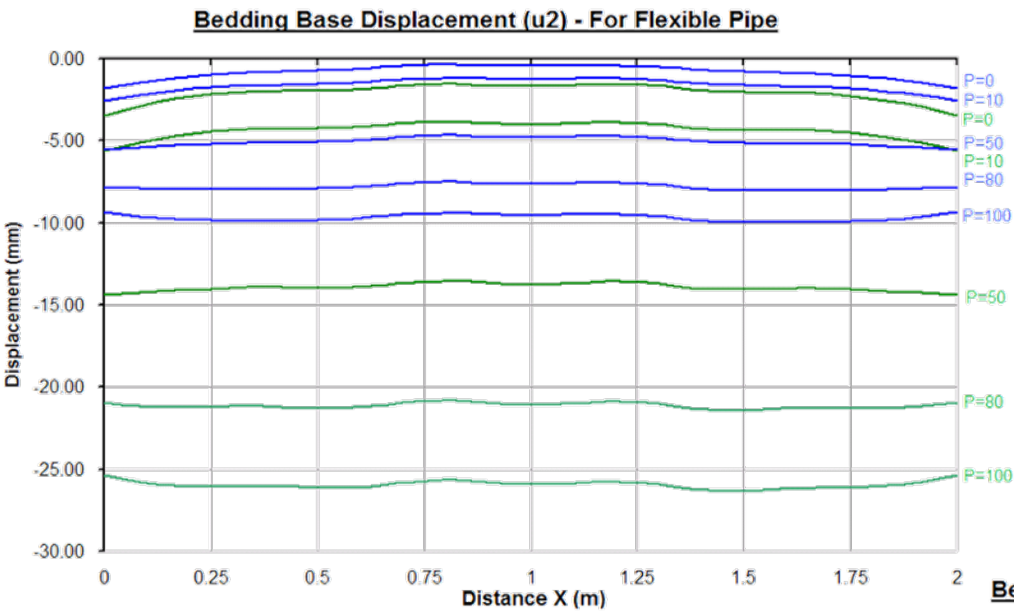

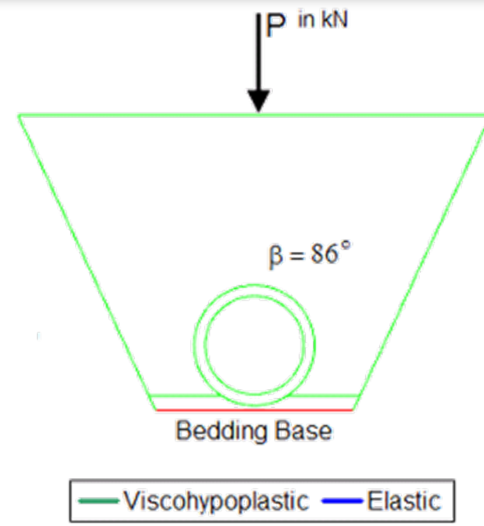

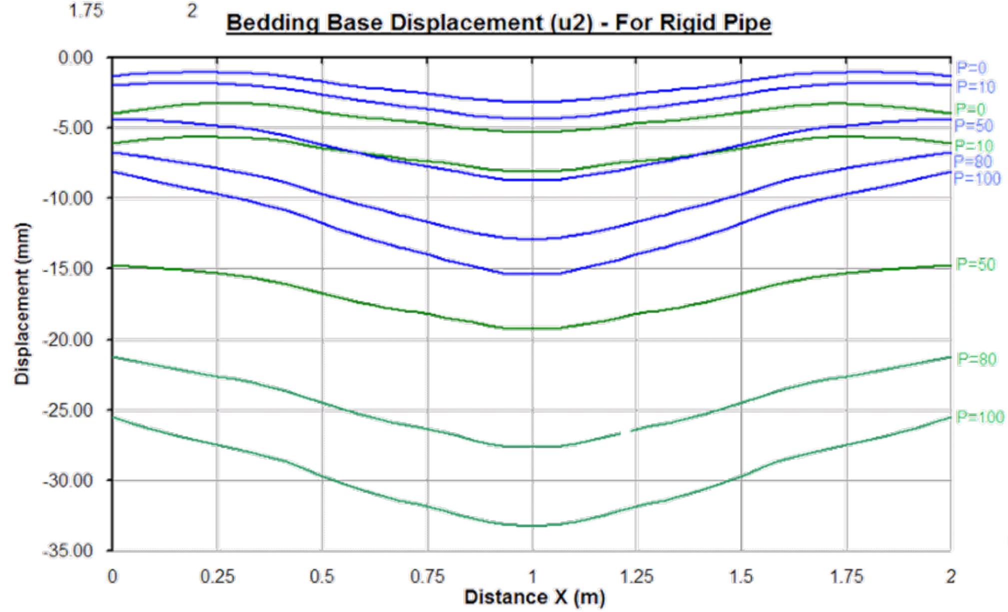

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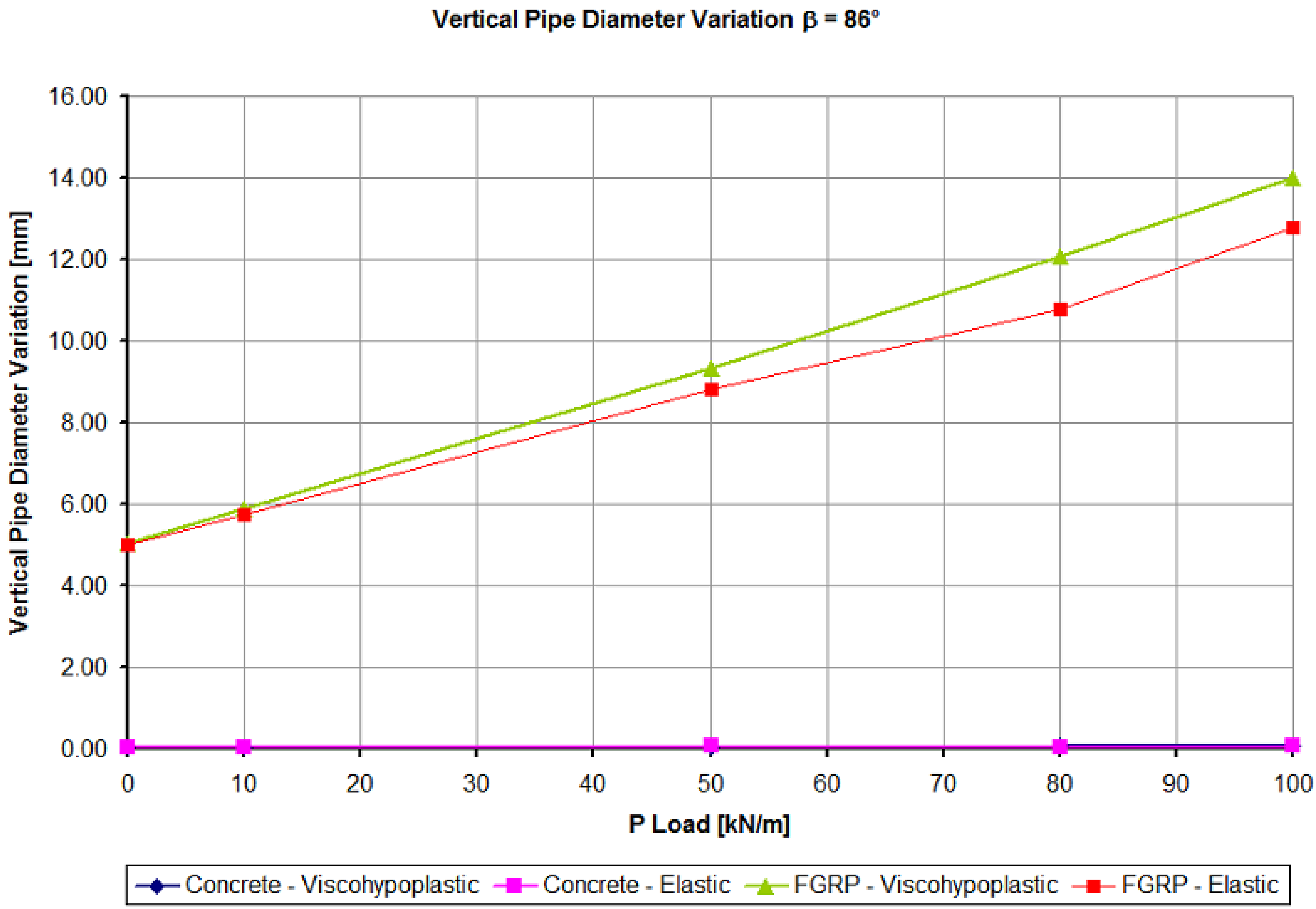
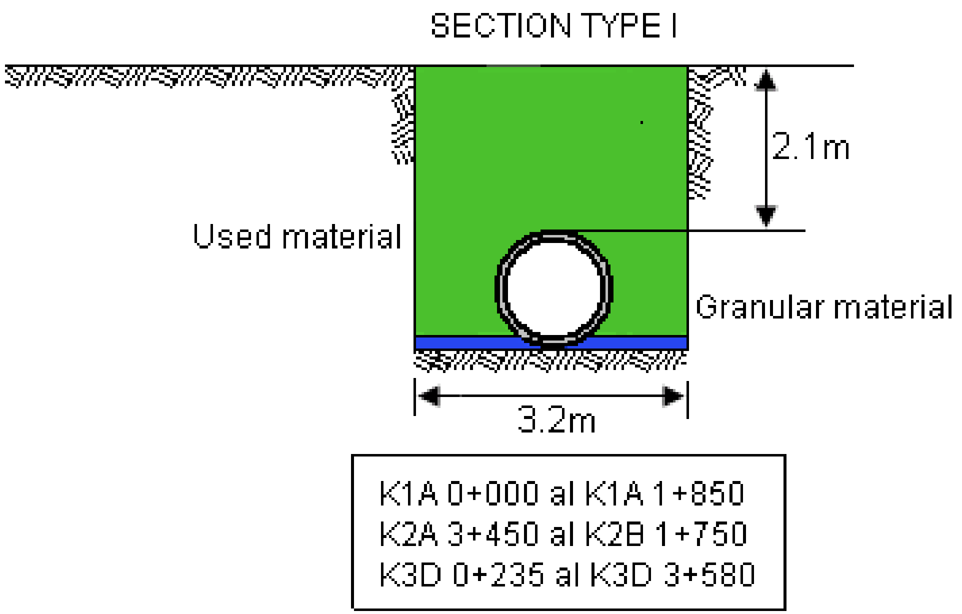
Vertical Pipe Diameter Variation: Flexible pipe Vs Rigid pipe in FEM



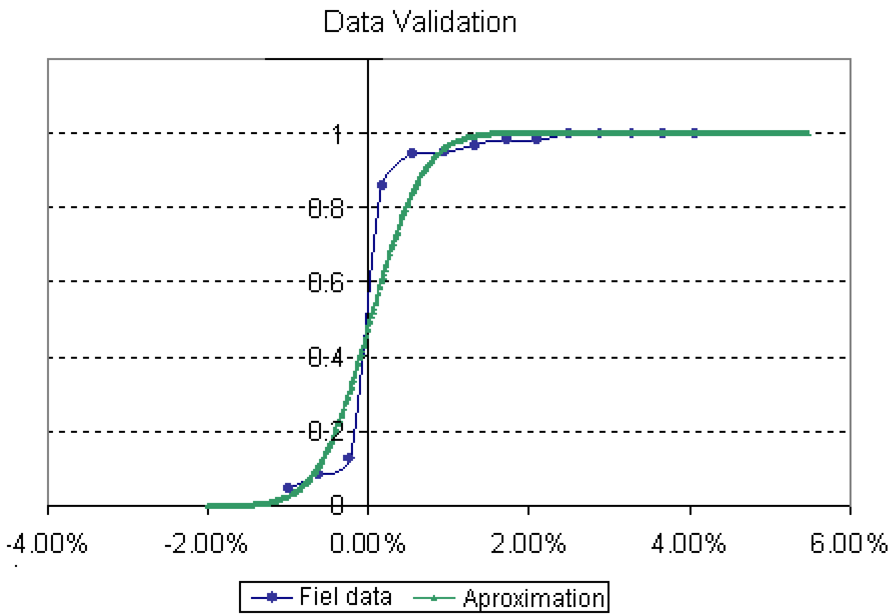
Numerical Example 2 – Emisario Terrestre Cartagena

Geometry and materials

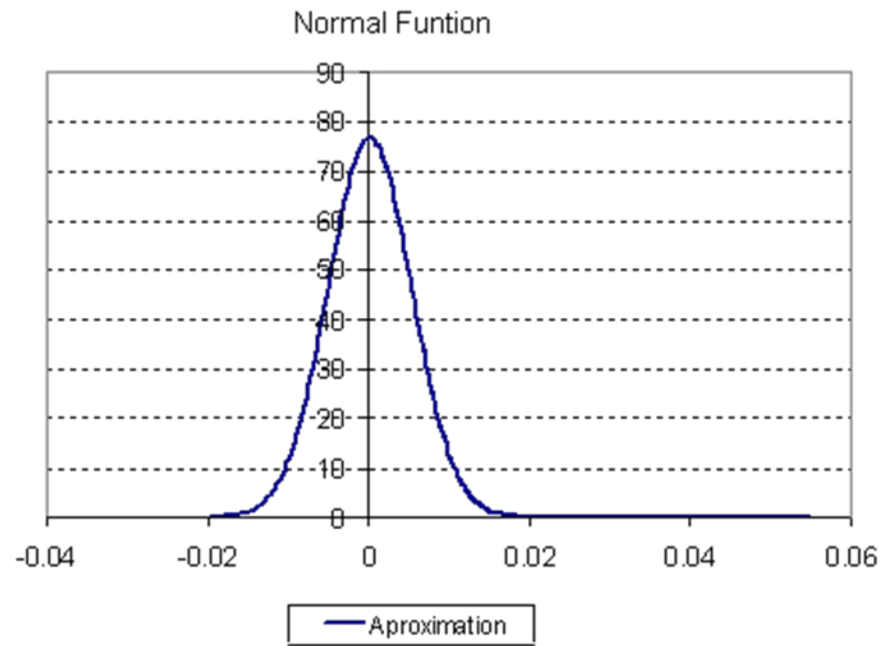


Pipe material	Internal diameter	Thickness	Bed	β
PRFV	1.8m	4.1cm	0.3m	86°

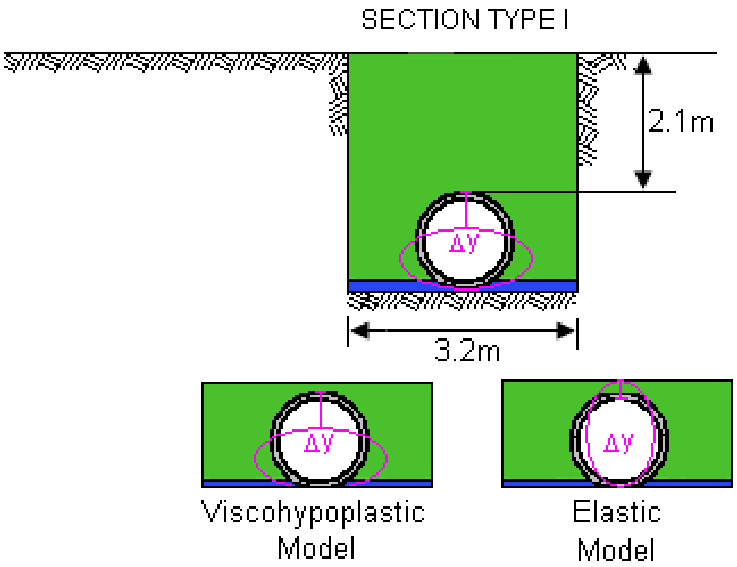
AGUAS DE CARTAGENA S.A. E.S.P.
ALC-06-BM-2006 - PROJECT EMISARIO TERRESTRE
Deflections in installation PRFV Pipes



Date Installation	Start	Final	Section	Average
21-02 / 17-03	K3D 0+708	K3D 0+403	TYPE I	0.028%

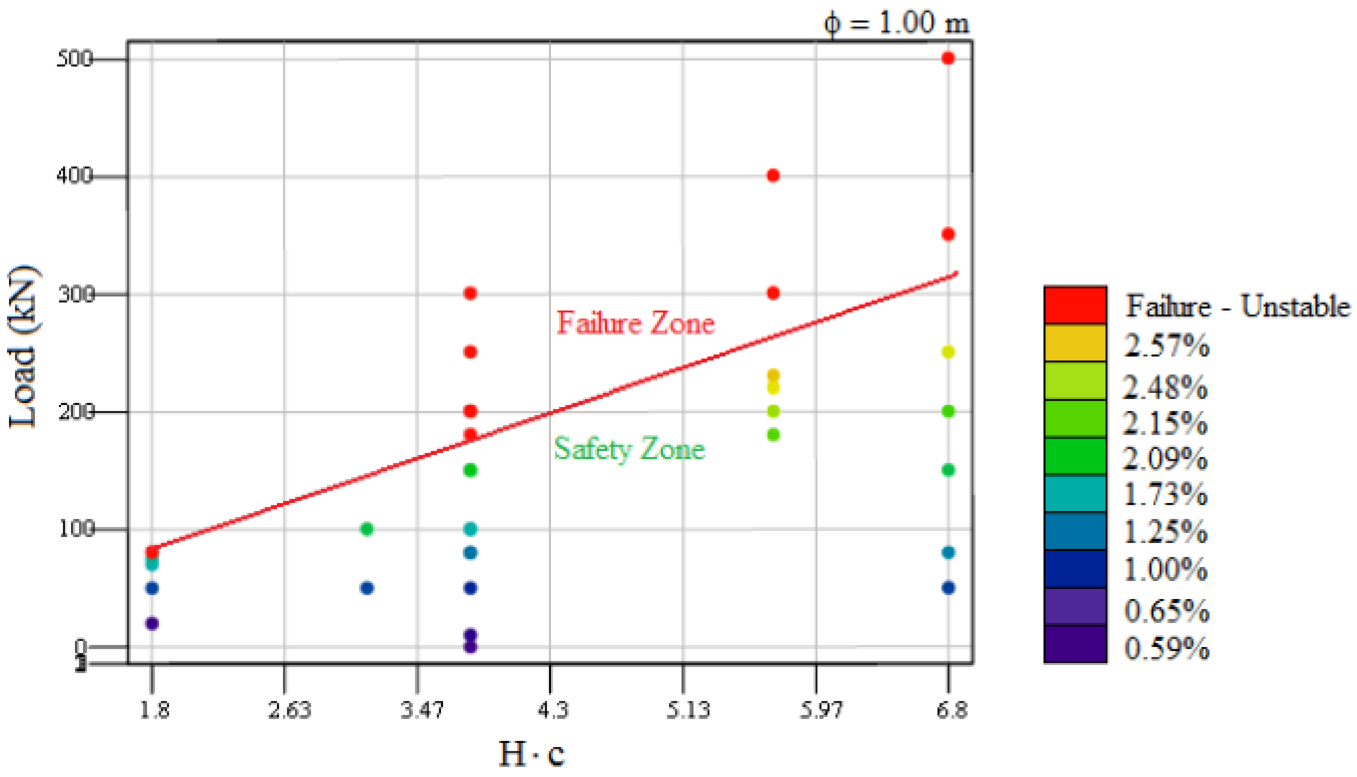


Media	Standard Desviation
0.028%	0.052%



% Deflection		
Elastic	Viscohypoplastic	Installation
-0.021	0.04	0.028

Preliminary Design Abaqus



Acknowledgment

Thanks !