Contribution to the Mechanical Calculus of the Reinforced Concrete Pressure Pipes, Steel Cylinder Type

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ABSTRACT

The mechanical calculus of the buried reinforced concrete pressure pipes, steel cylinder type, is treated by several country regulations and some classic books [1][2]. Most of these documents assume that the pipe is a buried long structure, solely subject to transversal efforts.

However, there are at least two situations where this hypothesis should not be considered: for the stress evaluation against earthquakes and for the case of the pipe finishes with an extreme stub connected to a metallic pipe (e.g. by means of a flange). In both cases the pipe is subjected to some longitudinal efforts which will be much more restrictive than the transversal one. Furthermore, the supported on piers pipe sections were subjected to longitudinal efforts.

The guide M9 of the American Water Works Association [3], devotes a full chapter to the calculus of pipes on supports. The formulation used in the guide is based on the linear analysis of the section. This formulation is incompatible with the actual tendencies, notably with the strength design methods. In the literature can also be found some references on the earthquake effects on buried pipes, but this action is considered as an isolated one.

Given this situation, this paper proposes a whole formulation of the main loads which can act on buried concrete pipes, including both the longitudinal and transversal loads and their combination. In this way, it can be widened the field of action of the existing documents and regulations which only considered the efforts from an isolated approach.

KEY WORDS: buried structures, concrete pipe, seismic analysis

INTRODUCTION

Two different load conditions are usually considered when the buried pipe analysis is normally studied. First and most common, the calculus of the loads over the buried pipe due to pressure effect of the earth over the pipe and the traffic that might occur over the surface that affects the structure. These two effects are compensated, since the deeper the pipe is located, the loads due to the traffic over the surface are more rapidly dumped while the loads due to the earth weight increase, making it necessary to take the "arching" effect into account when a certain deepness is exceeded. The result of these actions, when the pipe is considered rigid, are stresses at the critical points of the cross section of the pipe and, therefore, they can be combined in a natural way.

The other load conditions that are usually considered are those due to an earthquake. In the case of earthquake loads, a simplified approach of non soil-structure interaction may be used when the problem conditions allow it. This simplified approach is not always possible making it necessary to use a more general methodology including the analysis of the soil-structure interaction. In both cases, the analysis is focused in the deformations occurred in the structure during the propagation of the seismic waves.

In the everyday job of designing or checking buried pipes where both actions must be simultaneously considered, the problem of the combination of charges arises. This situation is often encountered when designing structures in seismic regions or structures with safety requirements above the ordinary levels (as it is the case of a nuclear power plant).

This paper presents a methodology for considering simultaneously the ordinary (earth weight and surface traffic) and seismic loads in a buried pipe.

ANALYSIS PROCEDURE

Identification of charges applied to a pipe

The main loads in the case of a buried pipe can be decomposed in 4 types as follows:

1. General loads (always apply):

- Own Weight of the pipe

$$q_1 = \gamma_{pipe} \cdot \pi \cdot D_m \cdot t_{pipe} \quad (1)$$

- Weight of the fluid within the pipe

$$q_2 = \gamma_w \cdot \pi \cdot D_i^2 / 4 \quad (2)$$

- Pressure: Operating Pressure and transitory regime surcharge

$$N = p \cdot D_i / 2 \quad (3)$$

- Temperature effect

In the case of pressurized cold water pipe the temperature effect can be considered as negligible.

2. Transversal loads (which induce a deformation of the cross section from a circular to an oval shape)
   - Due to the earth weight. (Both vertical and lateral effect)
     The charges due to the earth weight are evaluated according to the classic Marston theory of loads over pipes. This methodology takes into account the construction procedure (trench or embankment). Marston methodology considers the arch effect (Fig. 1) which had already been studied by Jensen. The arch effect can significantly reduce the pressure on the pipe (trench case) or increase it (embankment case).

   - Due to the surface traffic loads.
     These loads can be evaluated according to several methodologies. The elastic approach proposed by Boussinesq is among the most common ones. Another commonly used methodology is the diffusion of the charge with depth according to a diffusion angle. The M9 American Water Works Association AWWA handbook [3], uses this second methodology as it does the IIET (Spain) [4]. This paper assumes the AWWA/IIET approach.
     Depending on the vehicles speed, a dynamic impact coefficient might be considered if the designer considers it necessary. There are different formulations depending on the methodology that it is applied. For the Spanish case the UNE 641 reference guide is used.

The stresses due to these loads are obtained using the methodologies developed by Paris or Olander. The author has developed the formulas corresponding to the half of a pipe considered as an elastic arch restrained in the base and sliding in top with vertical charges applied on it (Fig. 2).

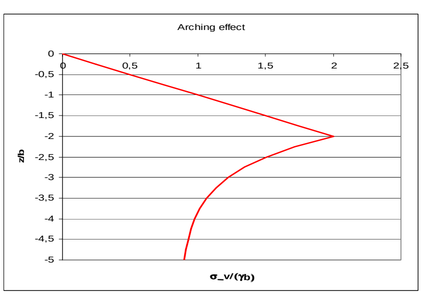

Fig. 1: Arch effect, theoretical description.

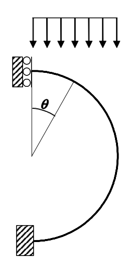

Fig. 2: Theoretical model for truss analysis.

3. Seismic loads.
   - Loads are due to the compression and shear waves (and also the Rayleigh waves)

The main deformations due to earthquake for buried pipe are: compression-tension, longitudinal bending and ovaling/racking.

As it has been highlighted before, there are two alternative approaches depending on the consideration or not of the soil-structure interaction. Both approaches allow a simplified expression with explicit equations to evaluate the deformations.
As the buried pipe considered in this paper is flexible compared to the surrounding medium the free field deformation approach can be applied. The formulation used is the one proposed by Hashash [5].

- Loads due to the "Anchored Suport Movement (SAM)"

When a pipe is linked with another pipe attached to a building, relative displacements between the pipe and the building, as a consequence of the seismic movement of the last, occur. In this case, these loads must be also taken into account. The formulation commonly used to evaluate them is an adaptation of the Hetenyi [6] formulation. For the case of longitudinal and transversal displacement (Δx and Δy respectively), the axial load, and the bending moment can be evaluated using the formulas below:

$$N = \sqrt{2 \cdot E \cdot A \cdot (\pi \cdot D_e \cdot \gamma_t \cdot K_0 \cdot h \cdot f) \cdot \Delta x} \tag{4}$$

$$M = \sqrt{E \cdot I \cdot K_s \cdot D_e} \cdot \Delta y \tag{5}$$

4. Interaction with other pipe sections.

- Case of a "self-sustaining" pipe section chests

A simplified model of the longitudinal behaviour of the pipe section inside the chest is adopted. This model consists of both ends restrained beam with its own weight and a one-point charge in the center representing the manhole. The span of the calculus is the chest width increased by the length of pipe necessary for the restrained condition at the supports. (1 meter is considered enough for this increase)

The estimation of the first frequency can be done (Roark's 3rd ed., 16.7,p 765)

$$f = \frac{13.86}{2\pi} \cdot \sqrt{\frac{E \cdot I \cdot g}{W \cdot l^3 + 0.383 \cdot w \cdot l^4}} \tag{6}$$

For concrete pipes it is common that this frequency is inside the ZPA zone, therefore there are not amplifications of the field spectrum where the pipe is situated.

- Case of a pipe–pipe link using a flange.

A flexibility analysis of the pipe (usually a steel pipe) will be required. The most common case is a building steel pipe connecting with an outer buried concrete pipe by means of a flange.

Combination of the charges applied to a pipe

Among the identified loads we found those which are formulated according to stresses like the earth and traffic loads, and those formulated according to strains like the seismic waves ones. The latter can be formulated in terms of stresses when considering that "Steel Cylinder" takes charge of the earthquake loads.

The load combination depends on the guide that is applied, as for instance:

According to AWWA M9:	Condition 1 (Operation pressure):	1.8D+1.8L
	Condition 2 (Without pressure):	1.8D+1.8L
	Condition 3 (With transient pressure):	1.35D+1.35L
According to Standard Review Plan 3.8.4:	OBE:	1.4D+1.7L+1.9E
	SSE:	D+L+E'

For the example application, we applied the nuclear codes, and perform the following combination of actions (table 1):

Comb.	Dead	Earth	Water	Traffic	OBE	SSE	Oper.	Trans.	Test
1	1,4	1,4	1.7	1.7				1.7	
2	1,4	1,4	1.7		1.9		1.7		
3	1	1	1			1	1		

Table 1: Selected combination of actions typical in Nuclear Power Plants with seismic action.

EXAMPLE APLICATION

We consider a pipe segment like the one presented in annex I. This segment consists of a buried pipe with a “T” in the chest for the pipe inspection (manhole) connecting to a building steel pipe using a flange. The question proposed is to verify the design of the cross-section of the pipe at the points “A” and “B”. It is assumed that the pipe is laid on the ground and the embankment is built after.

For the different loads the axial stress and bending moment are obtained. Figures 3, 4 and 5 show the bending moment for the loads corresponding to own weight and earth load.

The axial load and bending moment are combined according to the project criterion. In this example the criterion shown in table 1 is applied.

The most unfavourable stresses for each cross section (longitudinal and transversal) are compared to the ultimate load capacity of the corresponding cross section. For the transversal cross section, as it is rectangular, it is of immediate application the ultimate load analysis (for example following the AWWA methodology).

On the other side, traditional methodologies do not allow a longitudinal cross section ultimate load analysis. However, computer assisted calculation allows nowadays the calculation of the ultimate load for non rectangular cross sections (as the circular cross section of the example). The same ultimate load capacity methodology for the calculation of both longitudinal and transversal section can be used.

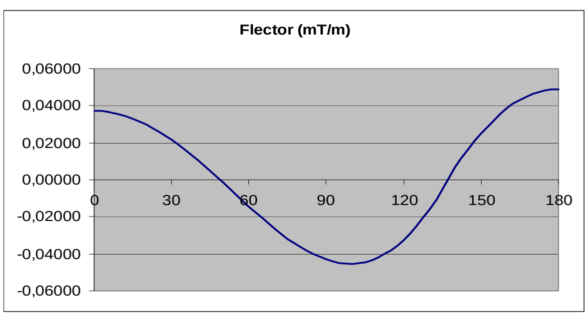

Fig.3: Bending moment due to pipe and water weight.

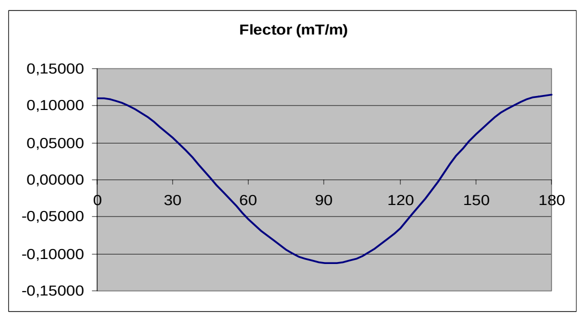

Fig. 4: Bending moment due to earth weight [5].

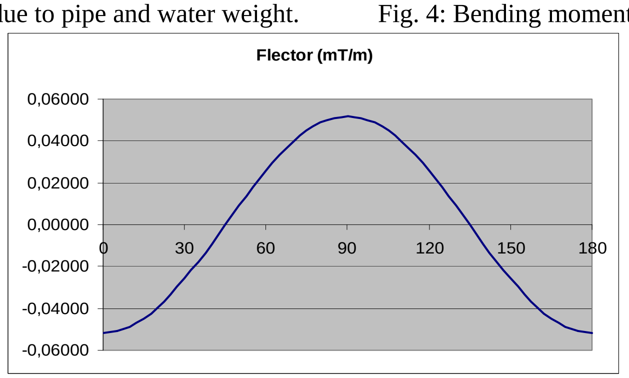

Fig.5: Bending moment due favourable effect of lateral earth pressure.

Cross section "A"

The combination of actions that are defined in table 1 was applied. The transversal and longitudinal forces and moments are shown in table 2.

	Transversal		Longitudinal	
	N (T)	M (mT)	N (T)	M (mT)
Comb. 1	40.6	0.768	-	3.053
Comb. 2	26.9	0.366	74.93	3.609
Comb. 3	15.6	0.236	78.87	2.584
Max.	40.7	0.768	78.87	3.309

Table 2: Results of combination of actions for cross section "A".

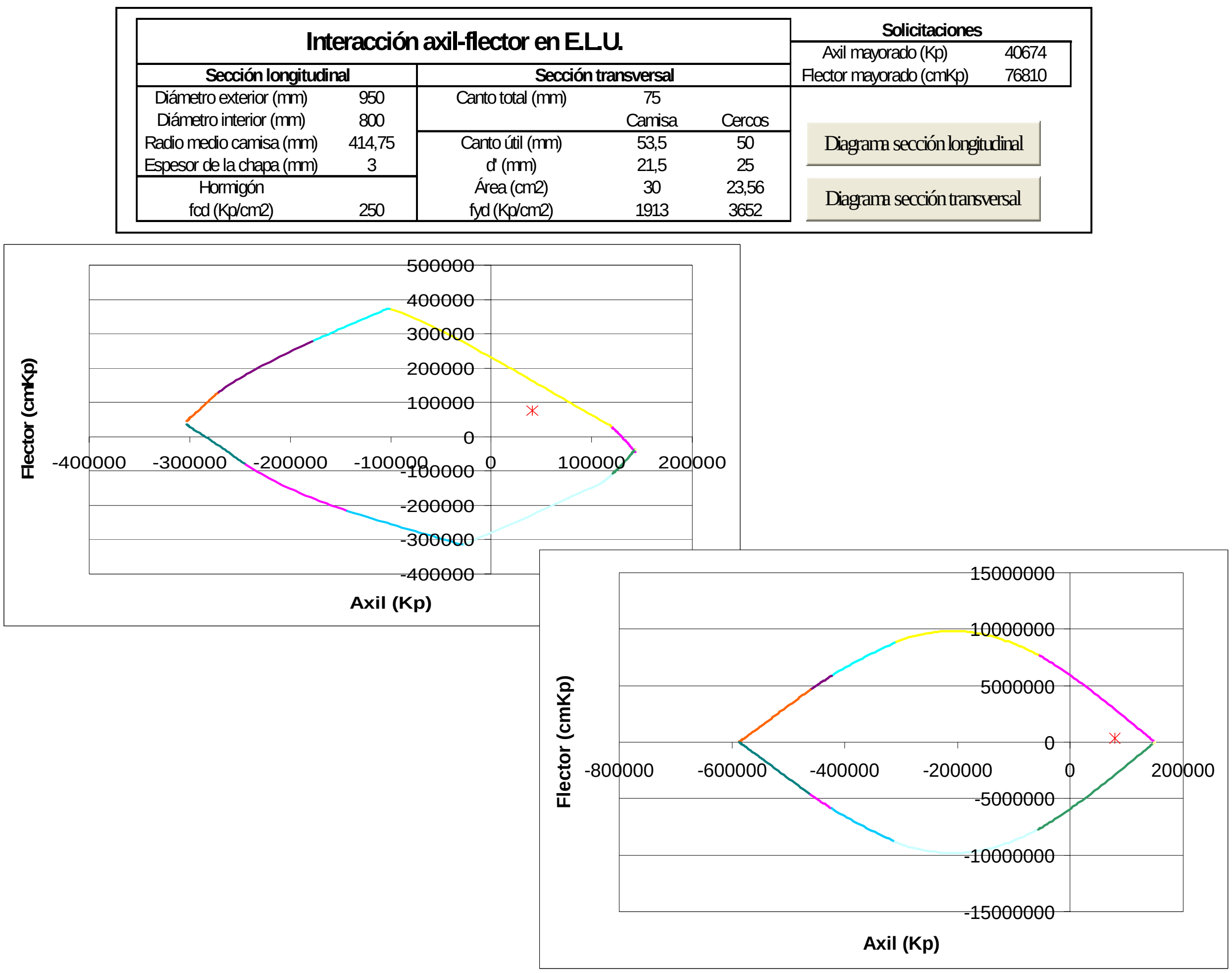

Fig. 6: Cross section "A": response of transversal and longitudinal sections in ultimate state.

In this case, the seismic forces and moments are evaluated with the free field deformation approach and the principal parameters are: velocity of p-waves, C_p=600 m/s; velocity s-waves, C_s=350 m/s; and OBE and SSE ZPA acceleration of 0.1g and 0.2g. The results of this evaluation are shown below (Fig. 7).

The flexibility coefficient, F=120, is greater than 20, therefor the analyzed pipe is flexible compared with the surrounding medium and then the free field deformation approach can be assumed.

Cp (m/s)	600					R (m)	0,4215
Cs (m/s)	350		OBE	SSE		E (MPa)	210000
γ (T/m3)	2	Vp (cm/s)	8	16		S (cm2)	79,17
ν	0,24	Ap (g's)	0,1	0,2		I (cm4)	4364,20
G (kPa)	249745,16	Vs (cm/s)	8	16			
E (Mpa)	620,42	As (g's)	0,1	0,2		I (cm4/cm)	0,2250
	f (Hz)	T (s)	L (m)	D (cm)			
OBE p	1,95	0,51	307,43	0,65			
OBE s	1,95	0,51	179,34	0,65			
SSE p	1,95	0,51	307,43	1,30			
SSE s	1,95	0,51	179,34	1,30			
Free field deformation approach		P - wave		S - wave		Composición - wave	
		OBE	SSE	OBE	SSE	OBE	SSE
Def. longitudinal		1,3333E-04	2,6667E-04	1,1429E-04	2,2857E-04		
Def. transversal		6,6667E-05	1,3333E-04	2,2857E-04	4,5714E-04		
Curvatura (1/m)		1,0491E-06	2,0983E-06	8,0082E-06	1,6016E-05		
Def. long + def. flexion		1,3378E-04	2,6755E-04	1,1766E-04	2,3532E-04		
Axil (kN)		221,67	443,34	190,00	380,01	291,96	583,92
Cortante (kN)		0,0002	0,0004	0,0026	0,0051	0,00	0,01
Flector (kNm)		0,0096	0,0192	0,0734	0,1468	0,07	0,15
Ovaling ratio (%)		0,0033	0,0067	0,0114	0,0229		
Ovaling circular tunnel							
F	120,062709	K1	0,037323564		Tmax (kN)	1,7961	3,5922
Ground-Structure effect will be ingnored!					Mmax(kNm)	0,7571	0,1259
Resultantes 25% margen		**Axil (T)**	**Flector (mT)**				
	OBE	**38,93**	**0,01**				
	SSE	**77,86**	**0,02**				

Fig. 7: Results of free field deformation approach in cross section "A".

Cross Section "B"

In this cross section, the SAM loads and the transferred strength by the metallic pipe in the extreme of buried pipe through the flange connection were applied. The formulation of SAM effects is done by elastic analysis of beam on elastic foundation (Fig.8) and the forces and moments in the anchor are given by the previous flexibility analysis of metallic pipe.

The combination of actions for OBE case is the most restrictive in this section.

Movimientos diferenciales					
Desplazamientos relativos			Espesor de chapa (mm)		6
longitudinal (mm)	1		radio exterior chapa (mm)		421,5
transversal (mm)	1			área (cm2)	157,77
vertical (mm)	0,75			E (Kp/cm2)	2,10E+06
Esfuerzo axil debido al desplazamiento longitudinal					
Ángulo de rozamiento (º)	25		Esfuerzo, F (T/m)		3,24735511
Altura de tierras (m)	1,75				
Coeficiente rozamiento, f	0,4		Tensión (Kp/cm2)		**294**
Coeficiente de Marston	1,3460625		Axil (T)		**46**
Flector debido al desplazamiento transversal			Coef. Balasto (Kp/cm3)		2
Momento de inercia (cm4)	138168,75				
Rigidez del suelo (Kp/cm2)	190		Tensión (Kp/cm2)		
Longitud característica, λ	0,00357698		con extremo fijo		**227**
L (cm)	279,57		Flector (mT)		**7**
factor común	4530,11377				

Fig. 8: SAM loads for OBE case

Figure 9 presents the Ultimate Load Capacity for the longitudinal cross section. The longitudinal cross section is in weaker conditions than the transversal one. For this reason, the thickness of the steel-cylinder is 6mm in cross section "B", the double than the thickness of the steel cylinder in cross-section "A".

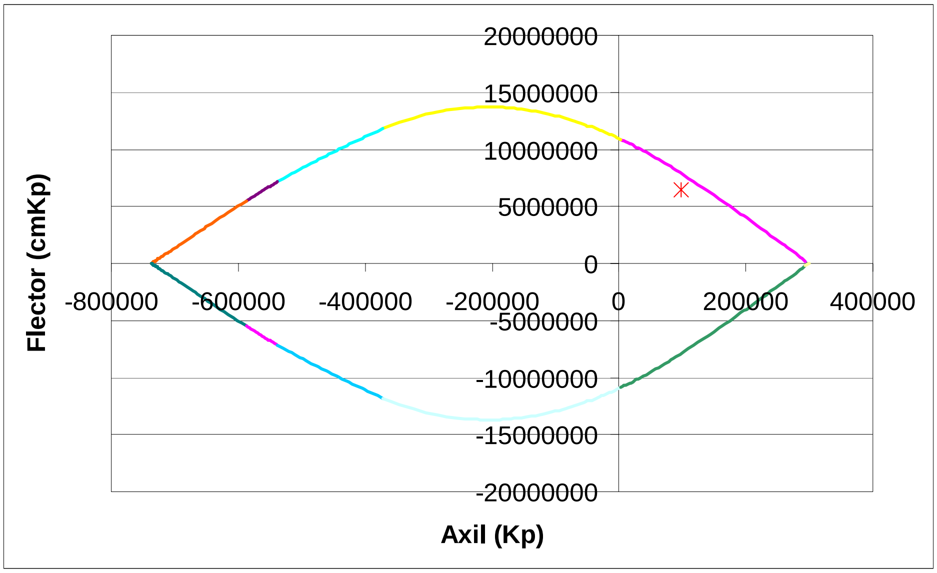

Fig. 9: Ultimate response of cross section "B" to longitudinal actions combined for OBE seismic event.

CONCLUSIONS

The possible loads on a buried pipe have been analyzed both from the transversal and longitudinal cross sections. It has been proposed a methodology to evaluate and combine the stresses in each section due to the different actions, including the seismic ones.

After obtaining the design stresses, the design of the section is verified with the current calculus philosophy of the ultimate load capacity for Reinforced Concrete in Europe. Transversal and longitudinal cross sections reinforcements have been considered in a uniform way. It is thus assured the convenient behaviour in ultimate limit state.

The methodology presented expands the classical approach were only transversal loads are considered independently from the seismic ones. It has been presented a methodology that combines both actions and allows an overall assessment on the behaviour of concrete buried pipes.

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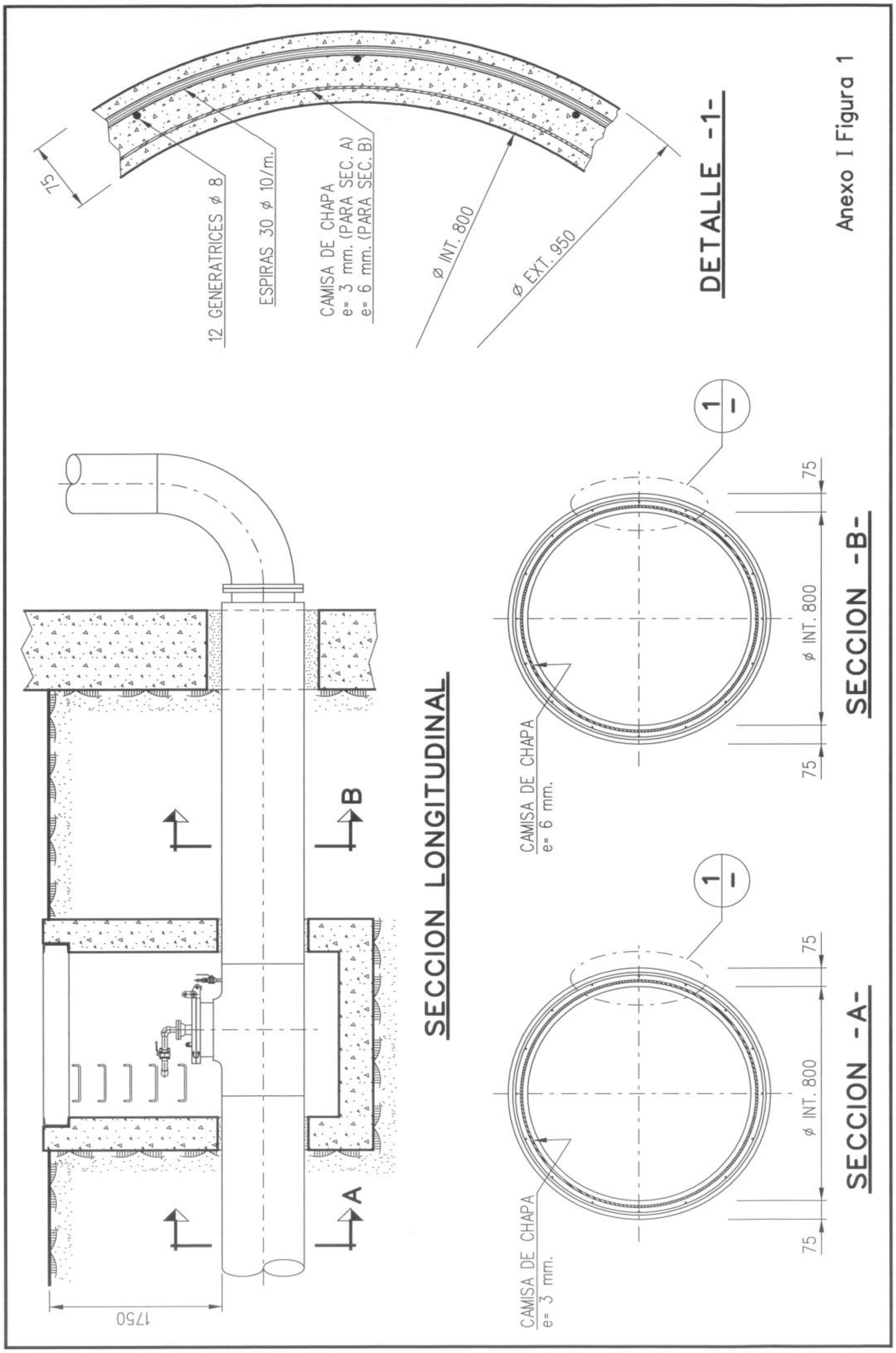
ANNEX I


DETALLE -1-
Anexo I Figura 1
75
12 GENERATRICES ø 8
ESPIRAS 30 ø 10/m.
CAMISA DE CHAPA
e= 3 mm. (PARA SEC. A)
e= 6 mm. (PARA SEC. B)
ø INT. 800
ø EXT. 950
SECCION LONGITUDINAL
A
B
1750
SECCION -B-
SECCION -A-
CAMISA DE CHAPA
e= 6 mm.
CAMISA DE CHAPA
e= 3 mm.
ø INT. 800
75
1
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