SEISMIC ANALYSIS AND DESIGN OF INDUSTRIAL CHIMNEYS

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SUMMARY

This paper describes a simplified method that allow obtaining the fundamental period of vibration, lateral displacement, shear force and bending moment through a set of equations, obtaining for all cases studied an error below 10%.

The results obtained in this study were applied to a total of 9 real chimneys (4 of steel and 5 of reinforced concrete) built in Chile, with the objective of calibrating founded expressions.

During the stage of the analysis, it was verified that the criterion of consistent masses provide better results than the criterion of lumped masses, and as a very important conclusion a discrete analysis of the model in twenty segments of the beam is satisfactory.

The most representative variables that define the model with which it is possible to carry out a parametric analysis of the chimney. As important parameters we could refer to: slenderness ratio H/D_{inf}, radius ratio R_{sup}/R_{inf}, thickness ratio E_{sup}/E_{inf} and thickness diameter ratio D_{inf}/E_{inf}. Later, by varying each one of the chosen parameters several analysis of representative chimneys of this great family, could be carried out.

As seismic loads, the spectrums of accelerations recommended by the code of seismic design for structures and industrial installations in Chile, have been considered. Modal responses were combined using the combination rule CQC.

In all the cases studied in this investigation, the influence of the P-Δ effect, the soil structure interaction, and the influence on responses that provoke the inclusion of lining, have been disregarded.

INTRODUCTION

During the past few years industrial chimneys have undergone considerable developments, not only in their structural conception, modelling and method of analysis, but also in the materials employed and the methods of construction. In this sense the outstanding increase in height should be highlighted as a consequence of a better control of environment pollution in populated areas. With the increment in height the seismic action and wind have become important for working out actuating stresses on this particular type of continuous structures, making it necessary, for this reason, to study the vibratory nature by carrying out a dynamic analysis.

If a modelled chimney is analysed as in a projected beam embedded at the la base and free at its upper end, considering the behaviour of the lineal elastic material, capable of deforming only by the effects of flexion and shear, and that it also has geometric properties (area, inertia, etc.) which vary with height, differential equations will be obtained of the movement that apply both to free and forced vibrations that cannot be resolved exactly. Only for certain laws of geometrical properties of variation, it is possible to express the solution of the differential equation of the movement based upon known functions, as it has been extensively demonstrated in literature on the subject. [Carrión y Dünner, 1999].

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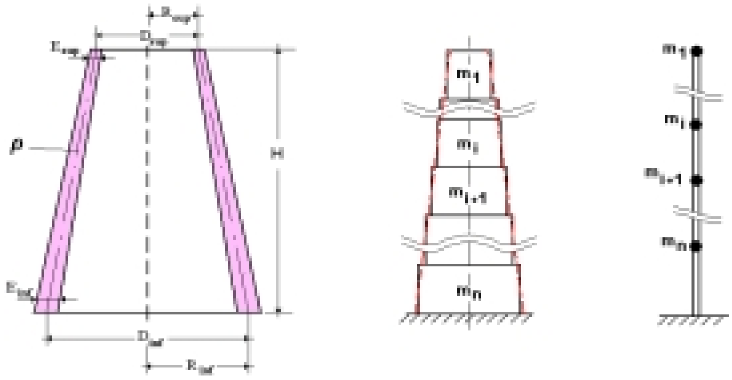
The mathematical type of difficulties that the current study presents has made it necessary to simplify the problem, by discretization the continuous structure for its solution, but not worrying to verify the merit of the assumptions involved in the results obtained.

DISCRETING THE STRUCTURE

Due to the complexity that means trying out one of the four particular solutions that the differential equation presents governing the movement of a continuous element like a chimney type, (see Fig. 1(a)), it was decided to solve the problem by discretization the structure. For this purpose, two discreting criteria were used:
lumped masses criterion and consistent masses criterion.

The most simple method to consider the properties of a dynamic system is to concentrate the mass of the structure on the nodes that define transfer displacements, that is why it is called lumped masses criterion.

On the other hand, the consistent masses criterion (Mc), unlike the lumped masses criterion which depends upon the rigidity to bend, cross section of element, form factor, shear module; also, unlike the lumped masses criterion, it considers coupling between rotational and translation degrees of freedom. Therefore, the matrix of consistent masses corresponds to a full matrix that includes the effects of flexion, shear and rotational inertia.



a) Geometry of a variable section   b) Model of a chimney according   c) Model of a chimney according

Figure 1: Geometry of a chimney, according to the consistent masses and lumped masses criteria

Sensitivity Analysis

An analysis was performed for the purpose of responding to the following queries: In how many elements is it necessary to discrete a chimney? What discreting criterion is the most adequate: lumped masses or consistent masses? What effects must be considered in the representative model of a chimney type continuous element? In this manner by means of this study on particular chimneys it is possible to estimate the results of any structure of this type.
The information on Table 1, shows the most important dimensions and pertinent data that will be useful for the subsequent seismic analysis of some industrial chimneys.

Table 1: Geometrical Characteristics and seismic data of some real chimneys built in Chile [Cancino, 1984]

Nº	LOCATION	USE	MATERIAL	HEIGHT (m)	DIAMETER (m)		THICKNESS (mm)		Seismic Data		
					Top	Bottom	Top	Bottom	Zone	Soil	ξ
Ch-1	Paipote Chile	Cu Foundry	Steel	27	1.35	1.35	8	8	3	II	2
Ch-2	Huachipato Chile	Siderurgical Plant	Steel	53	3.50	5.50	8	10	3	II	2
Ch-3	Huachipato Chile	Siderurgical Plant	Steel	47	2.90	5.00	8	10	3	II	2
Ch-4	Con Con Chile	Cu Refinery	Steel	130	4.50	12.00	8	15	3	III	2
Ch-5	Con Con Chile	Chilectra	Reinforced concrete	61	4.60	7.60	152	279	3	II	5
Ch-6	Renca Chile	Chilectra	Reinforced concrete	53	3.40	6.10	152	254	2	II	5
Ch-7	La Calera Chile	Cement Industry	Reinforced concrete	60	2.90	5.40	152	330	3	II	5
Ch-8	Tocopilla Chile	Thermal Plant	Reinforced concrete	75	4.60	7.30	180	450	3	II	5
Ch-9	Con Con Chile	Cu Refinery	Reinforced concrete	155	9.60	17.40	230	420	3	III	5

Each one was analysed under the following considerations:

- Employing lumped masses and consistent masses criteria.
- Varying the number of discreted elements (NE) in 10, 15, 20 and 25 elements.
- Considering the following effects
  - Flexion (lumped masses criterion)
  - Flexion, shear and rotational Inertia (consistent masses criterion)

With these considerations the fundamental periods of vibration were considered employing the computation program CALUC [Vásquez, 1977] and comparing their responses with those obtained through: analytical solution (solution to the differential equation considering a chimney of constant section and flexion effect) and Method of Finite Elements (MEF).

Table 2: Comparison of vibration periods employing the different criteria (MC: lumped masses, Mc: consistent masses and M.E.F) for chimney 9

Criteria	MC		Mc								MEF
Effects	Flexion		Flexion		Flexion + Shear		Flexion + I Rot		Flexion + Shear + I Rot		Flexion + Shear + I Rot
NE	T*	Error	T*	Error	T*	Error	T*	Error	T*	Error	T*
10	2.061	(8.39 %)	1.842	(2.50 %)	1.852	(1.94 %)	1.848	(2.16 %)	1.868	(1.07 %)	1.888
15	1.981	(4.69 %)	1.829	(3.23 %)	1.843	(2.44 %)	1.833	(3.00 %)	1.864	(1.29 %)	1.888
20	1.939	(2.63 %)	1.901	(0.68 %)	1.827	(3.34 %)	1.837	(2.78 %)	1.863	(1.34 %)	1.888
25	1.916	(1.46 %)	1.791	(5.42 %)	1.767	(6.85 %)	1.774	(6.43 %)	1.856	(1.72 %)	1.888

From the analysis carried out, it may be assured that the criterion of consistent masses estimates the fundamental period of vibration, considering the effect of flexion is more accurate than that obtained employing the lumped masses criterion.

When the chimney is analysed considering simultaneously the three effects of flexion, shear and rotational inertia, the number of elements to be discreted is no longer important. This is because the height of the element discreted is controlled by the shear effect $h/D < 2$, and by the effect of flexion if $h/D \geq 2$, in that h is the height of such element. This allows concluding that the analysis if industrial chimneys is controlled by the effect of flexion since according to Table 1, most of these structures possess $H/D > 8$ slenderness, therefore, the shear effect in the analysis may be ignored.

Analysing chimneys with 20 discrete elements is recommended, employing the consistent masses criterion and the effect of flexion since the error committed when evaluating the fundamental period of vibration does not exceed 1.13%.

From Table 2, it may be concluded that the effect of rotational inertia does not influence determining the fundamental period and by not considering it errors not exceeding 3% will be obtained for all cases.

CHARACTERISTICS PARAMETERS

Geometric Parameters

The purpose of establishing parameters is to identify the most important characteristics which define chimneys in order to allow representing a vast universe of such structures. The geometric parameters (see Figure 1) used in this study were as follows:

$RR = R_{sup} / R_{inf}$ = Ratio of Radius

$RE = E_{sup} / E_{inf}$ = Ratio of thickness

$HD = H / D_{inf}$ = Ratio of slenderness

$DE = D_{inf} / E_{inf}$ = Ratio of diameter thickness

R_{sup} : Radius on top section of chimney

R_{inf} : Radius of section at the base of chimney

E_{sup} : Thickness of mantle at the top section of chimney

E_{inf} : Thickness of mantle at the base of chimney

Seismic Parameters

In order to carry out a spectral modal analysis of adimensional form, the spectrum was set in parameters according to Chilean standard NCh 2369.c97 [INN, 1997]. Since the design spectrum is applied to real structures and not to adimensional structures, a parameter called seismic parameter will be introduced:

TT* = *T** / *T' = Ratio of Periods

T* : Fundamental period of structure, expressed in seconds

T' : Parameter depending on the type of soil, expressed in seconds, per Table 6 [INN, 1996].

Parameter *TT* or Ratio of Periods, is reflected in the seismic coefficient of the design spectrum per Chilean Standard NCh 2369.c97 [INN, 1997] as follows:

$$C = \frac{2.75A_0}{gR}\left(\frac{T'}{T^*}\right)^n\left(\frac{5}{\xi}\right)^{0.4} \qquad \Rightarrow \qquad C = \frac{2.75A_0}{gR}(TT)^{-n}\left(\frac{5}{\xi}\right)^{0.4} \qquad (1)$$

Since it is rather laborious finding a factor to transform responses of adimensional chimneys to real response values of the structure considering all effects (flexion, shear and rotational inertia), the chimneys were modelled employing the following considerations:

- Criterion of consistent masses.
- Deformation by flexion effect.
- Discreting with 20 elements.

Errors obtained due to such considerations do not exceed 2%.

As a consequence of the parametric analysis carried out, it should be mentioned that responses obtained through such methodology have no physical interpretation. However, it is possible to establish parameters for this type of structures, obtaining a low percentage of errors between estimated values of the real response and the adimensional response amplified by the factors of response modification. On Table 3 geometric and seismic parameters have been considered in the present study, represented in 4 terms each.

Table 3: Summary chart of geometric and seismic parameters

Material	Geometric parameters				Seismic Parameter			Models
	RR	*RE*	*HD*	*DE*	*TT*	Zone	ξ	
Steel	0.25 0.50 0.75 1.00	0.25 0.50 0.75 1.00	8 12 16 20	170 380 590 800	0.10 0.77 1.44 2.11	1 2 3	2	3,072
Reinforced concrete	0.25 0.50 0.75 1.00	0.25 0.50 0.75 1.00	8 12 16 20	16 24 32 40	0.10 0.77 1.44 2.11	1 2 3	5	3,072
Number of Models								6,144

Where Zone and ξ are parameters which depend on the seismic zone and material of chimney that have been tabulated in Chilean seismic code NCh 2369.c97 [INN, 1997].

Transformation Factors

The necessity arising to find factors that may transform adimensional responses of chimneys with established parameters to real responses of the structure including their geometric properties, four factors were obtained which modify the adimensional response to real one in function of three variables: two dependant on the structure material, elasticity module E and the density of the material mass ρ and the last and most important, the height of chimney H, since all parameters are in function of height.

A table follows containing transformation factors of the adimensional response to the real one, for each of the responses (periods, displacements, shear forces and bending moment), the percentage of error obtained when using transformation factors is also shown.

Table 4. Transformation factors of responses

RESPONSE	TRANSFORMATION FACTOR	MAXIMUM ERROR
Vibration Periods	$F_T = \sqrt{\frac{\rho}{E}}H$	**1.2%**
Maximum Lateral Displacements Estimated by CQC	$F_D = \frac{\rho}{E}H^2$	**3.0%**
Maximum Shear Stress Estimated by CQC	$F_V = \rho H^3$	**3.4%**
Maximum Bending Moments Estimated by CQC	$F_M = \rho H^4$	**3.2%**

SIMPLIFIED METHOD FOR OBTAINING RESPONSES

For the purpose of providing simple tools for seismic analysis on industrial chimneys in Chile, a study has been carried out on this special type of continuos structures in order to establish a simplified method that may allow to evaluate the follows responses: periods of vibration, lateral displacement, shear force and bending moment.

This has been done by making an analysis of the response of 6,144 chimneys contained in a data base (see Table 3) and which allowed establishing a dynamic behaviour law for any steel or reinforced concrete self-supporting industrial chimney.

The analysis performed is summarised in the following expressions that allow estimating the fundamental period of vibration, lateral displacement, shear force and bending moment shown below:

– Fundamental period of vibration

$$T_1 = \left[4.99 \cdot RR^{0.092} RE^{0.266} \left(HD + 0.12\right)\right] \sqrt{\frac{\rho}{E}} H \tag{2}$$

– Maximum Lateral Displacement

$$D_{máx} = \left[0.59 HD^{1.978} RE^{0.398} \left(TT^3 - 4.74TT^2 + 7.26TT + 0.28\right) \cdot Z\right] \frac{\rho}{E} H^2 \tag{3}$$

– Maximum Shear Force

$$V_{máx} = \left[1.1 \frac{\left(RE + 0.433\right)\left(RR + 0.149\right)}{HD^{2.02} DE^{1.004}} \left(TT^3 - 4.60TT^2 + 6.78TT + 1.55\right) \cdot Z\right] \rho H^3 \tag{4}$$

– Maximum Bending Moment

$$M_{máx} = \left[0.55 \frac{\left(RR + 0.45\right)\left(RE + 0.30\right)}{HD^{2.02} DE^{1.004}} \left(TT^3 - 4.68TT^2 + 7.06TT + 0.48\right) \cdot Z\right] \rho H^4 \tag{5}$$

where:

ρ = density of material mass.
E = elasticity module of material.
H = total height of chimney.
Z = value depending on seismic zone, per Table 7

The simplified method proposed provides errors not exceeding 10% in the estimate of all responses.

Table 5: Equations 2, 3, 4 and 5 Validation

		Chimneys									Units
		Ch-1	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7	Ch-8	Ch-9	
T_1	Real	0.53	0.45	0.39	1.05	0.64	0.62	0.85	1.00	1.95	*Sec*
	Equation 2	0.53	0.46	0.39	1.07	0.67	0.64	0.86	0.97	1.88	
	Error	0.7%	1.4%	0.3%	2.5%	4.9%	3.0%	0.9%	2.7%	3.7%	
$D_{Máx}$	Real	0.05	0.04	0.03	0.25	0.09	0.06	0.16	0.26	0.79	*m*
	Equation 3	0.05	0.04	0.03	0.26	0.09	0.06	0.17	0.28	0.76	
	Error	6.0%	0.4%	3.8%	4.5%	5.7%	2.7%	10.0%	7.2%	4.2%	
$V_{Máx}$	Real	3.6	21.1	16.5	91.7	232.7	112.2	171.6	482.3	2,057.0	*Ton*
	Equation 4	3.7	22.3	16.6	92.8	218.0	102.5	166.4	506.4	1,878.5	
	Error	3.5%	5.3%	0.2%	1.1%	6.7%	9.5%	3.1%	4.8%	9.5%	
$M_{Máx}$	Real	46.0	578	404	6,453	7,008	2,992	5,168	19,430	153,300	*Ton-m*
	Equation 5	47.0	597	403	6,741	6,621	2,780	5,103	19,007	149,134	
	Error	2.6%	3.3%	0.3%	4.5%	5.5%	7.1%	1.3%	2.2%	2.7%	

The behaviour of the vibration period, lateral displacement, shear force and bending moment, normalised at maximum value, are identical to each other (see Figure 2), regardless of the material and geometry of the chimney. Thus, coefficients may be found providing important responses each 0.05 Y/H and the period for the first 20 modes of vibration. (See Table 6).

Table 6: Coefficients to obtain responses and periods of vibration

Y/H	$D/D_{Máx}$	$V/V_{Máx}$	$M/M_{Máx}$
0.00	0.00	1.00	1.00
0.05	0.00	0.96	0.90
0.10	0.01	0.91	0.80
0.15	0.03	0.84	0.71
0.20	0.06	0.78	0.62
0.25	0.08	0.71	0.54
0.30	0.12	0.65	0.47
0.35	0.16	0.59	0.40
0.40	0.20	0.53	0.34
0.45	0.25	0.47	0.28
0.50	0.31	0.47	0.23
0.55	0.37	0.42	0.18
0.60	0.43	0.36	0.14
0.65	0.49	0.31	0.11
0.70	0.56	0.26	0.08
0.75	0.63	0.21	0.05
0.80	0.70	0.17	0.03
0.85	0.77	0.12	0.02
0.90	0.85	0.08	0.01
0.95	0.92	0.04	0.01
1.00	1.00	0.00	0.00

MODE	T_i/T_1
1	1.0000
2	0.2168
3	0.0854
4	0.0449
5	0.0275
6	0.0185
7	0.0133
8	0.0100
9	0.0078
10	0.0062
11	0.0051
12	0.0043
13	0.0036
14	0.0031
15	0.0027
16	0.0023
17	0.0020
18	0.0018
19	0.0016
20	0.0014

Table 7: Value of Z and T'

Seismic Zone	Z	A_0
1	1.0	0.2 g
2	1.5	0.3 g
3	2.0	0.4 g

Soil Type	T' sec	Description [INN, 1996]
I	0.20	Rock: natural material, with wave travelling velocity (V_S) > 900 m/s.
II	0.35	Soil with V_S > 400 m/s, coarse gravel, coarse sand, hard cohesive soil .
III	0.85	Permanent non-saturated sand, non-saturated gravel or sand, cohesive soil

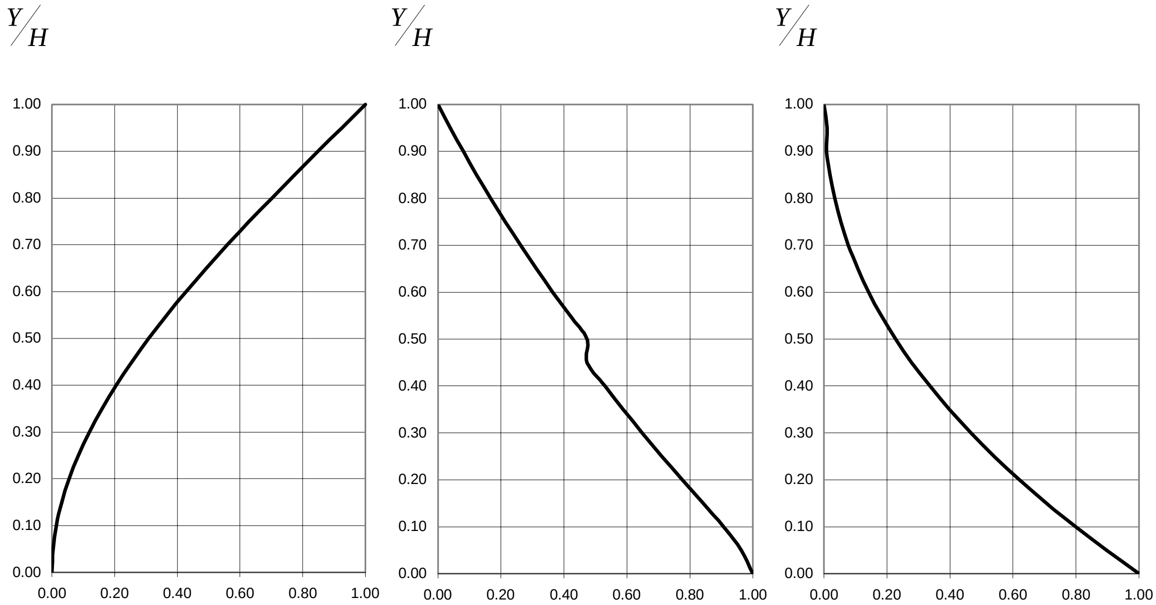


Figure 2: Curves of normalised responses

CONCLUSIONS

1) When the chimney is analysed by the three effects (flexion, shear and rotational inertia), the number of elements to be discreted no longer influences the estimated responses because the height of the element is controlled by the shear if h/D < 2, and by flexion if h/D > 2, h the height of the element.

2) To estimate the fundamental period of vibration, considering only the effect of flexion, the consistent masses criterion is more accurate. The percentage of error obtained, compared to the exact solution given by MEF is 1.13%

3) Since it is very laborious job finding a factor to transform adimensional response values to real response values considering all effects (flexion, shear and rotational inertia), good results can be obtained in the analysis of steel and reinforced concrete industrial chimneys modelling the structure employing the following considerations: Consistent masses criterion, effect of flexion, and discreted in 20 elements. Maximum errors committed as a result of such considerations are under 2%.

4) It is possible to carry out an analysis of a chimney parametrically, finding a factor that will transform these adimensional values into real responses of the structure. The maximum error obtained considering the 4 responses studied (period of vibration, lateral displacement, shear force and bending moment) is 3.5%.

5) The simplified method proposed in this paper provides responses with errors not exceeding 10%. As normalised response curves do not vary, regardless of the material and geometry of the chimney, they allow obtaining coefficients providing important responses every 0.05 Y/H and the period for the first 20 modes of vibration.

REFERENCES

Arya A. S. y Paul, D. K. (1977), "*Earthquake Response of Tall Chimneys*". Proceedings World Conference on Earthquake Engineering. New Delhi.

Astroza I., M y Asfura, A. (1972), *Análisis Dinámico de Chimeneas de Inercia Variable. Comparación entre Modelo Continuo y Discreto*. Memoria de Título (Ingeniería Civil) Sección Ingeniería Sísmica. Departamento de Geofísica Sismología y Geodesia, Facultad de Ciencias Físicas y Matemáticas Universidad de Chile, Santiago, Chile. Pp 208

Cancino, C. H. (1984), *Diseño Sísmico de Chimeneas Industriales*, Memoria de Título (Ingeniería Civil) Departamento de Ingeniería Civil, Facultad de Ciencias Físicas y Matemáticas Universidad de Chile. Pp 150.

Carrión P. L. y Dünner D. R. (1999), *Análisis y Diseño Sísmico de Chimeneas Industriales*, Memoria de Título (Ingeniería Civil) Departamento de Ingeniería Civil, Facultad de Ciencias Físicas y Matemáticas Universidad de Central de Chile. Pp 329.

Fernández-Dávila G., V. I. y Rivera F., J. (1988), "*Planteamiento de Normas para el Análisis Sísmico de Chimeneas"*, Séptimo Congreso Nacional de Ingeniería Civil, Departamento de Ancash., Perú, Pp 383-396.

Fernández-Dávila G., V. I. y Rivera, J. (1990), "*Diseño Sísmico de Estructuras Continuas con Distribución Variable de Masa y Rigidez*", Octavo Congreso Nacional de Ingeniería Civil, Departamento de Piura. Perú Pp 383-396.

Fernández-Dávila G., V. I. (1992), *Análisis Dinámico de Chimeneas Empleando el Criterio de Masas Consistentes*, Proyecto semestral, Asignatura ICE-3722, Dinámica de Estructuras, Pontificia Universidad Católica de Chile. Santiago-Chile.

Husid, R; Asfura, A.; Astroza, M. (1974), "*Vibraciones de Chimeneas de Inercia Variable*", XVI, Jornadas de Ingeniería estructural. Buenos Aires Argentina. Vol. III, Pp. III-28, III-38

Instituto Nacional de Normalización INN (1997), *NCh 2369.c 97-Diseño Sísmico de Estructuras e Instalaciones Industriales*.. Santiago Chile.

Instituto Nacional de Normalización INN (1996), *NCh 433.Of 96-Diseño Sísmico de Edificios*.. Santiago Chile.

Vásquez, J.P. (1997), *CALUC: Lenguaje Computacional para Análisis Estructural*. Manual de Uso. Departamento de Ingeniería Estructural y Geotécnica. Escuela de Ingeniería. Pontificia Universidad Católica de Chile. Santiago-Chile.