

Study of the seismic response of reinforced concrete isolated elevated water tanks

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Abstract

This investigation carries out the seismic response of parametric elastic models of reinforced concrete isolated elevated water tanks. From the study of the physical and geometric variables that characterize elevated water tanks it was possible to define parametric models with the purpose of obtaining a wide representative family of structures. The parameters were grouped in the following form: a) elevated tank: ratio of heights, ratio of slenderness, ratio of diameters, ratio diameter-thickness, and ratio water mass-structure mass, b) isolation system: ratio of slenderness, horizontal and vertical stiffness, c) water: the water-structure interaction effect is modeled using the mechanical analogy proposed by Housner.

This special type of continuous structure, similar to an inverted pendulum, has been discretized according to the lumped mass criterion and the support structure of the tower was partitioned in ten one-dimensional elements. As seismic loads were applied the design spectrum of accelerations were used as recommended by the Chilean code NCh 2745 Of.2003, respectively.

The maximum responses were obtained for the lateral displacements, the shear forces and bending moments. The sensitivity analysis of the structural models of isolated elevated water tanks allowed us to observe that the maximum bending moments and the maximum shear forces are equivalent to the eighth part of the maximum responses obtained in a similar fixed-base elevated water tank, and that the relative lateral displacements are lower than 0.2%, reducing the deformations in the structure significantly.

Keywords: elevated water tanks, dynamic of structures, seismic loads, seismic base isolation, lateral displacements, shear forces, bending moments.



1 Introduction

Chile has suffered devastating seismic effects of great magnitude on many occasions, which resulted in serious consequences such as the loss of human lives and resources. On the basis of past experiences, the repetition of this phenomenon in the future must be thought of as a certain possibility, incurring the same catastrophic effects that have occurred in the past and maybe in higher proportions. Having taken this consideration into account, it is necessary to prepare to face new menaces of this nature, adopting ways to avoid or minimize the effects of earthquakes that could occur in the future [4, 9].

Elevated water tanks are industrial structures built for the purpose of maintaining the water supply. There are researches on this special kind of continuous structure that has its bases fixed and isolated [11]. The application of seismic isolation systems in other parts of the world has concentrated its efforts on the research of conventional structures such as buildings, that results in very attractive research about its application in this special kind of continuous structure generally considered as rigid [9]. Indeed, in the last years, the seismic isolation system has seen an increased application on buildings in countries that have high seismic risks (Japan, United States, Italy, Canada, New Zealand). Its effectiveness was proven during the occurrence of important earthquakes such as Northridge (USA, 1994) and the Kobe (Japan, 1995), due to the fact that these areas presented an important number of structures designed with frictional and elastomeric isolation systems [10].

The objective of this investigation is to study the seismic responses of this special kind of “compound structure” with the purpose of understanding the structural behaviour due to seismic action.

2 Methodology

2.1 Type of structure

A reinforced concrete elevated tank of drinkable water which had a flexible connection between the superstructure and the foundation, denominated seismic isolator, was analyzed. These mechanisms (table 1) work in an elastic range and consist basically of a collection of thin rubber plates interspersed with steel plates which are stuck to the rubber with an adhesive gum and then are subjected to a vulcanisation process. A resistant element of a low horizontal rigidity and high vertical rigidity was obtained as a result, succeeding to uncouple the structure from the seismic movements of the land. Twelve isolators that are equidistant to each other and located in the perimeter of the structure of support, were used (figs. 1, 2).

The kind of superstructure used is the elevated water tank made of reinforced concrete as the composite. This kind of structure presents a support base or shaft and in its higher area a tank or barrel, both elements are of transversal, circular section.



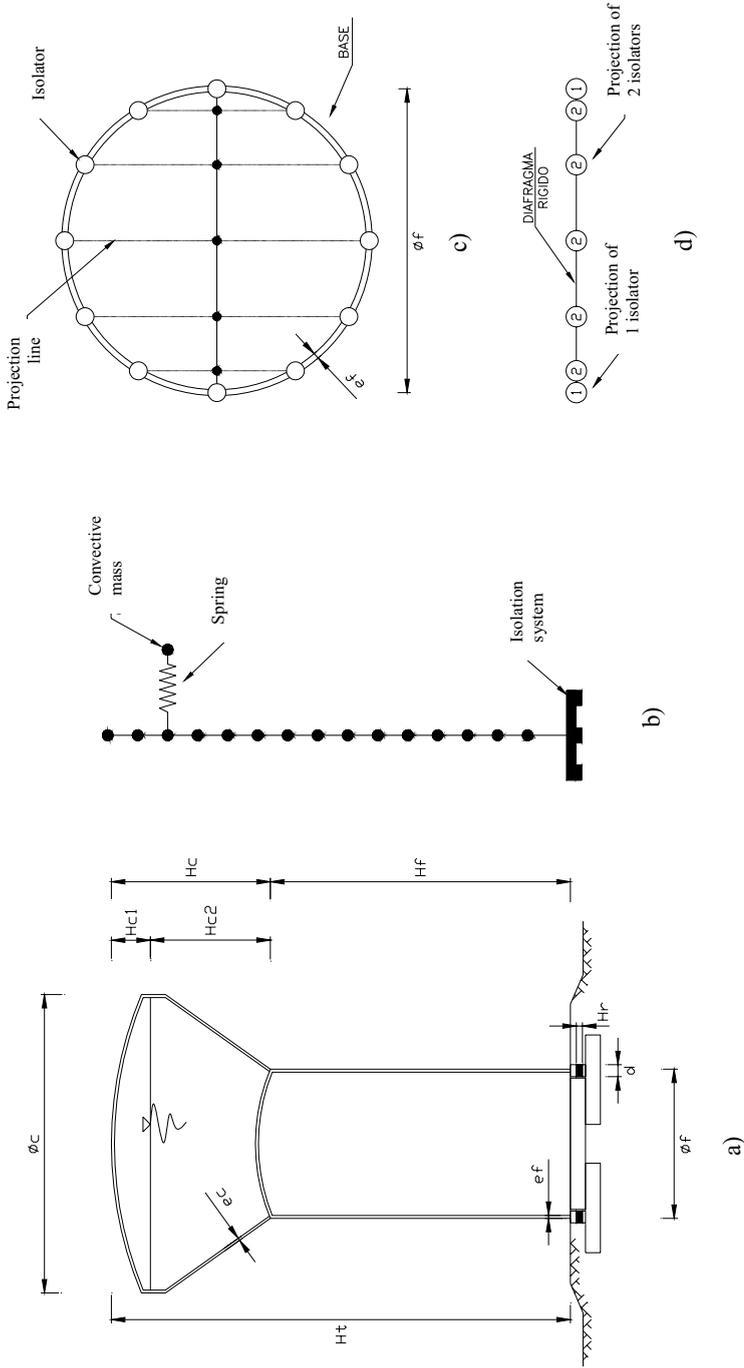


Figure 1: Elevated tank type "composite", and isolation system: a) Transverse section, b) Lumped masses model, c) Location of isolators in the base, d) Projection of isolators in elevation.



This choice was performed from a sensitivity analysis of the tanks of this kind constructed in the central area of Chile and its capacity to support great water masses inside. The kind of isolator considered on the research is the high damping isolator (HDR) [10], owing to the fact of its high capacity to dissipate the energy that comes from the seismic movement of the land, preventing this energy from being totally absorbed by superstructure.

For the sensitivity analysis, eight real tanks that fulfill the required geometry have been found. These tanks constitute the pattern database, identifying the more relevant geometric and physic relevant features (tables 2, 3) from the study of each one of them. Geometric properties were considered such as (fig. 1): H_t , H_c , H_f , which are the total heights of the tank and the structure of support, respectively; in addition, e_f , e_c , are the thicknesses of the structure of support and the tank; ϕ_f , ϕ_c , are the diameter of the structure of support and the tank; and H_{c1} and H_{c2} , are the fixed and variable height of the tank, respectively. The modeling of the tank, such as structures of the reversed pendulum kind, is shown in table 3 and consists of verifying more than 50% of the total weight which is found in the superior level [7].

Table 1: Characteristics of the isolators.

Description	Unit	Reinforced rubber	No reinforced rubber	Steel
IRHD ¹		45	65	100
σ_t	MN/m ²	28	21	420
σ_u	%	680	420	40
E	MN/m ²	1,9	5,9	210.000
G	MN/m ²	0,54	1,37	81.000
k	MN/m ²	1.000	1.200	176.000
v		0,4997	0,4997	0,29
Resilience	%	80	60	100
V_s	m/s	37	37	5.000

¹International Rubber Hardness.

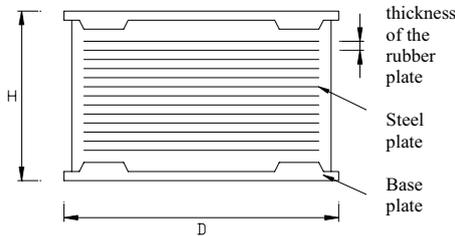


Figure 2: Elastomeric seismic isolator.

Table 2: Characteristics of the real tanks and seismic data.

Nº	Tank	Capacity (m ³)	H _t (m)	H _c (m)	H _f (m)	φ _c (m)	φ _f (m)	e _c (m)	e _f (m)	H _{c1} (m)	H _{c2} (m)	Seismic data		
												Zone	Soil	ξ (%)
1	Pontigo-Buin	2.000	31,3	10,1	21,2	23,8	12	0,2	0,25	2,1	8,0	2	II	5
2	Linderos	2.000	38,3	10,1	28,2	23,8	12	0,2	0,25	2,1	8,0	2	II	5
3	Paine	1.000	35,8	6,8	29,0	19,0	12	0,2	0,20	1,7	5,2	2	II	5
4	Los Tilos	1.500	29,8	8,8	21,0	19,0	12	0,2	0,20	3,6	5,2	2	II	5
5	Estadio-Estación Buin	1.500	32,8	8,8	24,0	19,0	12	0,2	0,20	3,6	5,2	2	II	5
6	Melipilla	500	30,3	5,3	25,0	12,9	9	0,2	0,20	1,6	3,7	3	III	5
7	El Monte	500	25,3	5,3	20,0	12,9	9	0,2	0,20	1,6	3,7	3	III	5
8	El Trébol	2000	38,3	10,1	28,2	24,2	12	0,2	0,25	2,3	7,8	2	II	5

Table 3: Weights of the elevated water tanks (kN).

Tank	W _{fuste}	W _{cuba}	W _t	W _f	W _{total}	W _{sup} = W _{cuba} + W _{H2O}	W _{sup} /W _{total} (%)
Pontigo-Buin	5.000	5.390	10.390	20.000	30.390	25.390	83,6
Linderos	6.650	5.390	12.040	20.000	32.040	25.390	79,3
Paine	5.470	3.410	8.880	10.000	18.880	13.410	71,0
Buin	3.960	3.980	7.940	15.000	22.940	18.980	82,7
Estadio Buin	4.520	3.980	8.500	15.000	23.500	18.980	80,8
Melipilla	3.530	1.750	5.280	5.000	10.280	6.750	65,6
El Monte	2.830	1.750	4.580	5.000	9.580	6.750	70,5
El Trébol	6.650	5.520	12.170	20.000	32.170	25.520	79,3

2.2 Fluid-structure interaction

The fluid-structure interaction was determined using the equivalent mechanical model proposed by professor Housner. Effectively, it proposes that the motion of the total mass of water can be represented in the following way: a) a solidary mass to the tank, called fixes or impulsive mass (M₀); and b) a mass that represents the phenomenon of surge of water, named movable or convective mass (M₁) and connected to the walls of the tank by total stiffness K [5]. Eqs. (1) to (6) allow us to evaluate the impulsive and convective masses, the stiffness of the spring, the water vibration period, and the location of these masses measured from the base of the tank.

$$\frac{M_0}{M_F} = \frac{\text{Tanh}\left(\frac{\sqrt{3}}{2} \cdot \frac{D}{H}\right)}{\frac{\sqrt{3}}{2} \cdot \frac{D}{H}}, \quad \frac{M_1}{M_F} = \frac{363}{512} \cdot \frac{\text{Tanh}\left(\sqrt{13.5} \cdot \frac{H}{D}\right)}{\sqrt{13.5} \cdot \frac{H}{D}} \quad (1, 2)$$



$$\frac{H \cdot K}{W_F} = \frac{45}{2} \cdot \left(\frac{M_1}{M_F}\right)^2 \cdot \left(\frac{H}{D}\right)^2, \quad T_a = 2\pi \cdot \sqrt{\frac{M_1}{K}} \tag{3, 4}$$

$$h_0 = \frac{3}{8} \cdot H \cdot \left[1 + \alpha \cdot \left(\frac{M_F}{M_0} - 1\right)\right], \quad h_1 = H \cdot \left[1 - \frac{\text{Cosh}\left(\sqrt{13.5} \cdot \frac{H}{D}\right) - \beta}{\sqrt{13.5} \cdot \frac{H}{D} \cdot \text{Senh}\left(\sqrt{13.5} \cdot \frac{H}{D}\right)}\right] \tag{5, 6}$$

where M_F , and W_F , are the total mass and weight of the water; α and β are dependent variables of the pressures of the walls; h_0 , and h_1 , are the heights of the impulsive and convective masses, both measured with respect to the bottom of the tank; T_a , fundamental period of vibration of the convective mass; H and D , are the height and diameter of the tank, respectively. The values considered for this study were $\alpha=0$, and $\beta=1$ [5], because the pressures of the water stored on the walls of the container are considered. In the present study the height H is equal to the height H_c , and the diameter D is equal to ϕ_c of the analyzed model (fig. 1a). In addition, W_F is equal to W_{H_2O} .

2.3 Parametric analysis of the structure

From the study of the most relevant elastic characteristics that determine the behavior of the eight elevated water tanks defined in the database, it was possible to select ten parameters of interest that, if combined suitably, allow us to represent an ample family of this type of structure [1, 3, 4, 9]. The parameters are as follows:

- (RH) Height ratio (tank – structure of support) = H_c/H_f
- (RD) Diameter ratio (tank – structure of support) = ϕ_c/ϕ_f
- (RR) Height – Diameter ratio = RH/RD
- (HD) Slenderness ratio = H_t/ϕ_f
- (DE_c) Diameter ratio – thickness in the tank = ϕ_c/e_c
- (DE_f) Diameter ratio – thickness in the structure of support = ϕ_f/e_f
- (RD_c) Diameter ratio-thickness = DE_c/DE_f
- Mass ratio = M_{H_2O}/M_t
- (RH_c) Height ratio in the cube = H_c/H_c
- (RH_a) Slenderness ratio of isolator = H_f/d

Table 4: Values adopted for the parameters and number of studied cases.

Id	Tank					Isolator	Seismic			N° of total cases
	RR	HD	RD _c	RH _c	RM	RH _a	Soil	Zona	ξ (%)	
1	0,10	2,4	1,0	0,2	0,9	0,35	2			972
2	0,21	2,9	2,0	0,4	1,5	0,50	3	2	5	
3	0,36	3,2	2,7	---	2,0	1,00	---			

---Value does not exist.



Table 4 shows the geometric and seismic parameters considered in this study, as well as the values assigned to each one of them. These values were obtained from the analysis of sensitivity of the values adopted by each parameter of the eight structures of the database pattern. From this new database, a family of 972 elevated water tank structures could be generated.

2.4 Sensitive analysis

A sensitivity analysis was made in which the responses of a tank modeled by finite elements (MEF) and another one modeled by the criterion of lumped masses were compared (MC), in which the structure of support was discretized in 10 elements and the tank in five elements, both being of frame type [2]. The responses that were compared were the periods of vibration, the lateral displacements, the shear forces, and bending moments. The tank modeled by finite elements took control of elements type shells [2] of size $1 \times 1 \text{ m}^2$.

The maximum errors found were: 2,3% in the periods of vibration, 8,8% in the lateral displacements, 6,6% in the basal shear forces, and 4,3% at the bending moments.

It was observed that the responses determined with criterion MC are greater than the responses obtained by MEF. This comparison was made on an empty and a full water elevated tank, considering, in addition, situations of isolated base and fixed [1, 4].

2.5 Design spectrum

The seismic load that was used corresponded to the design spectrum of the NCh 2745 Of. 2003 code [8]. In this norm is the type of elastic spectrum, which must be reduced by the factor of reduction R that is indicated in the code of industrial structures NCh 2369 Of. 2002 [7]. This design spectrum (fig. 3) depends on as much the seismic zone as the type of ground on which the structure is founded.

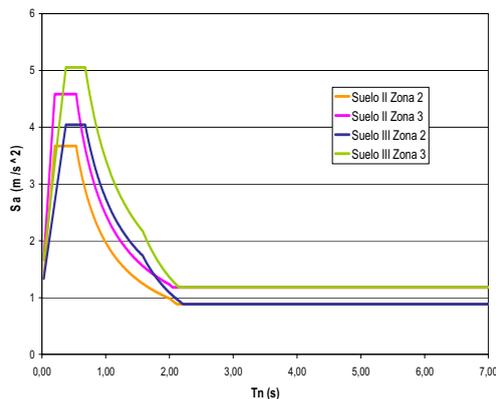


Figure 3: Design spectrum utilized.

3 Analysis of the results

The analysis of the 972 parametric models of the elevated water tanks was made using a computational tool called SAP2000 [2]. In order to obtain the maximum responses, the complete quadratic combination rule (CQC) was used [7]. On the basis of this method the total displacements were obtained, as well as the shear forces and bending moments.

The study considered that half of the models to be founded on soil type II and the rest on soil type III (Fig. 3) [7], with the purpose of comparing the interest seismic responses. The validity of this study is limited to the parameters that are adopted by the following dominions: $RR \in [0.10;0.36]$; $HD \in [2.4;3.2]$; $RDE [1.0;2.7]$; $RH_c \in [0.2;0.4]$; $RM \in [0.9;2.0]$; $RH_a \in [0.35;1.00]$; Soil type [2;3].

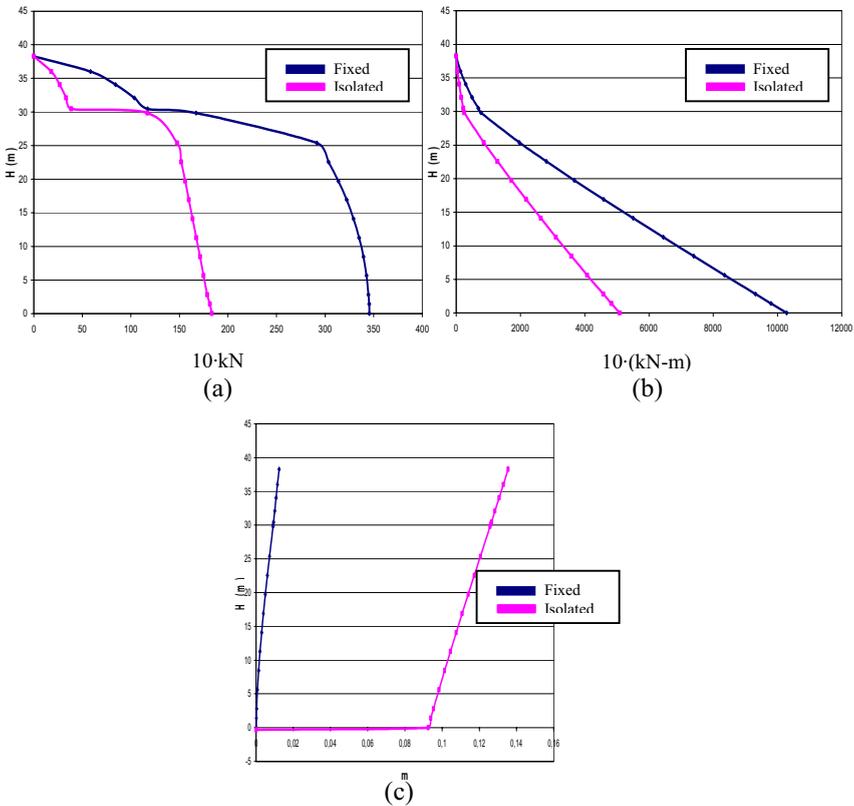


Figure 4: Seismic responses of the Pointigo-Buin tank: (a) shear forces, (b) bending moments and (c) lateral displacements.

The analysis of results shows the following:

- When comparing the tanks of fixed base with their similar of isolated base were verified that with the incorporation of the isolation device to the

shear forces (Fig. 4(a)), and the bending moments are reduced in a 50% (Fig. 4(b)).

- In the cases of fixed and isolated bases, it is demonstrated that the main cause for the abrupt increment of the magnitudes of the shear force is water movement due to seismic excitation.
- The lateral displacement experiments a strong increment of its magnitude in the zone of the isolator that borders 1000%, since the lateral stiffness of this one is considerably smaller for the stiff than it is for the structure of support (Fig. 4(c)).
- For the totality of the parametric models, the safety factors of buckling and rollover of the isolators were verified satisfactorily.

4 Conclusions

- When comparing elevated r/c tanks of fixed base with their similar of isolated base, it was verified that the incorporation of the isolation device reduces the shear force and the bending moments in 50%, and although the water stays as the fundamental period of vibration, the isolation system takes the second modal shape of vibration that in the case of the fixed tanks it belongs to the structure (figs. 5, 6).
- The Chilean code [6] indicates that the relative displacement in all the levels of the structure must be smaller than 2‰. For the analysis of the database the tanks fulfill this requirement since the maximum relative displacement was of 1,2‰. This means that the tank has a lateral displacement in the form of a rigid body.
- The incorporation of a system of isolation in the high tanks brings as a consequence that the structure of support presents compressive stress different to the tank that does not consider this flexible fusion that presents tensile effort additionally.

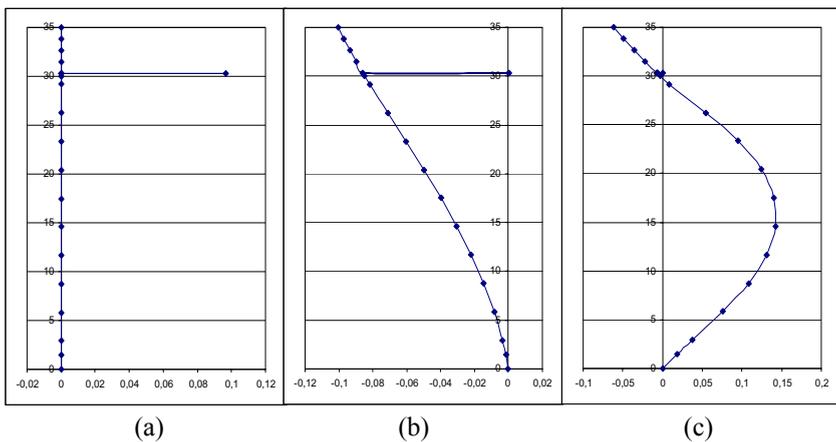


Figure 5: First three modal shapes of the tank N° 1 with fixed base and water full: (a) first mode, (b) second mode, (c) third mode.



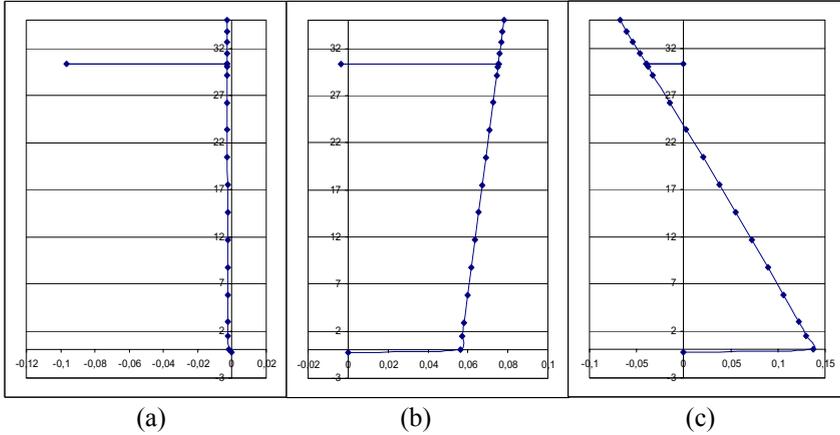


Figure 6: First three modal shapes of the tank N° 1 with isolated base and water full: a) first mode, (b) second mode; (c) third mode.

- d) The differences of the maximum responses found to the finite element analysis with the analysis of lumped masses using the expressions for the fluid-structure interaction [5] were of 2.3% in the periods of vibration, of 8.8% in the lateral displacements, 6.6% in the basal shear force, and 4.3% at the bending moments [1, 4].
- e) The geometric form that acquires the representative outline of the maximum responses of the elevated tanks with isolation is similar to the same structure without isolation. Therefore the seismic behavior of a structure fixed and an isolate is similar, varying only the maximum values.
- f) From this one study it is possible to obtain simplified expressions for the analysis of elevated water tanks with seismic isolation in its base [3].

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