

# BACKWARD SEISMIC ANALYSIS OF STEEL TANKS

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# **GENERAL TOPICS**

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**Non-Building Structures**

**Seismic Performance of Steel Tanks**

**Seismic Activity**

**Backward Analysis**

**Performance During Chile Subduction Earthquakes**

**Seismic Horizontal Sliding of Self-Anchored Steel Tanks**

**Conclusions**

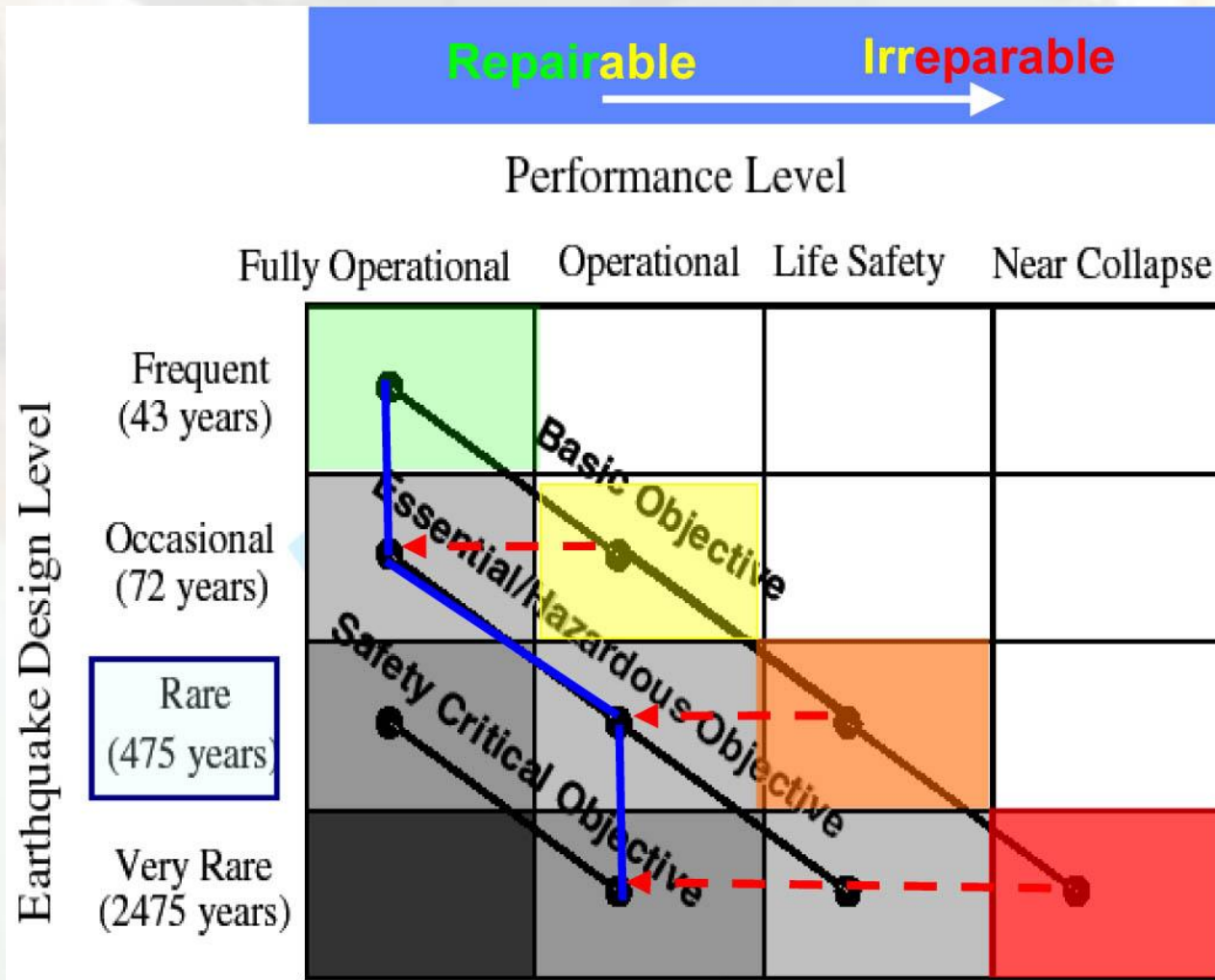
A large, circular, white structure is under construction. The interior of the structure is visible, showing a complex network of metal beams and supports. A worker in a yellow shirt and dark pants is standing on a platform or scaffolding inside the structure, working on the interior. The structure is surrounded by a concrete base and other construction elements. The overall scene is a construction site for a large, non-building structure.

## **NON-BUILDING STRUCTURES**

# Distinctive Aspects

“Buildings: Life Safety for People”

“Non-Buildings: Continuity of Operation in Industry”





# Continuity of Operation in Industry

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- Non-interruption of essential processes and services**
- Prevent or minimize the standstill of operations**
- Enable the inspection and repair of damaged elements**

# Relevant Aspects

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**In the last earthquakes is not satisfied the continuity of operation**

**Frequent shutdowns in oil plants**

**Most structures are designed with codes**

**Is no time for repairs after earthquake**

**Design codes do not serve their purpose**

# Tanks Category

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**Mainly used in petrochemical plants and other industrial facilities**

**Irregular distribution of mass in height**

**Different values of damping according to seismic mass type (impulsive and convective)**

**Self-supporting structure (not anchored)**

**Gravity loads be required to resist effects of earthquake**

A large, cylindrical steel tank is shown under construction. The tank is supported by a complex network of steel beams and scaffolding. A worker in a yellow shirt is visible on a platform inside the tank, working on the interior structure. The scene is dimly lit, with a bright light source visible inside the tank. The overall image has a faded, semi-transparent appearance.

# **SEISMIC PERFORMANCE OF STEEL TANKS**



# Characteristics



**Petroleum,  
Liquefied Gas,  
Sulphuric Acid,  
Water Storage**



**Anchored**



**Self-anchored**

# Observed Tanks Failures on Earthquakes

Earthquake	Mag.	Principal Failures						
		RS	BS	WR	CB	RP	AB	HS
Chile 1960	9.5		X		X	X		X
Alaska 1964	9.2		X			X	X	X
Armenia 1972	7.0	X	X		X			
Loma Prieta 1989	6.9	X	X	X				X
Hokkaido 1993	7.6		X					X
Northridge 1994	6.7	X	X		X	X	X	X
Observed Failures (%)		50	100	17	50	50	33	83

Rupture of Shell Wall : RS      Rupture in Roof Plates : RP  
 Buckling of Shell Wall (foot of elephant) : BS      Rupture of Anchorage Bolts : AB  
 Failures in Joints Wall – Roof : WR      Horizontal Sliding : HS  
 Failures in Columns and Beams : CB

(Pineda (2000))

**Main fails are buckling Shell and horizontal sliding**

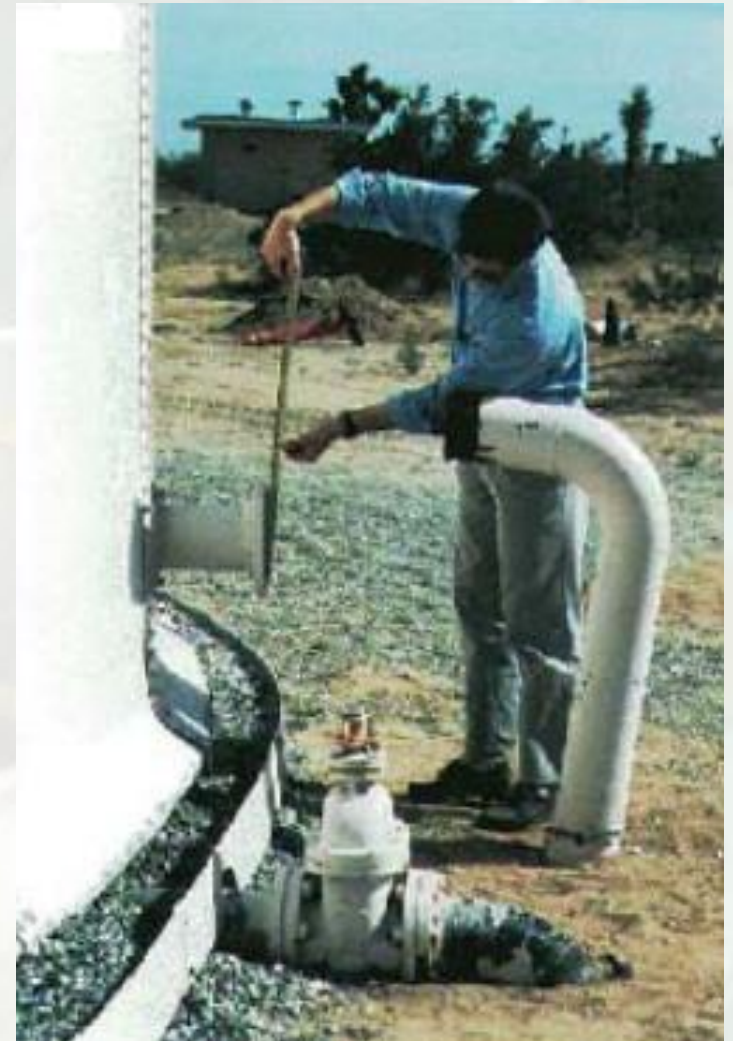


# Observed Tanks Failures on Earthquakes

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**Buckling Shell**



**Horizontal Sliding**

# Other Damages – Japan Earthquake (2011)

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**Collapsed by the Tsunami**



**Burned-out gasoline tank**

# Comments

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**Presented repeated failures in large earthquakes**

**Being design with codes: API650-E, AWWA D100, NZSEE and Chilean Code NCh2369**

**It is necessary a better understanding of seismic response to improve existing code**

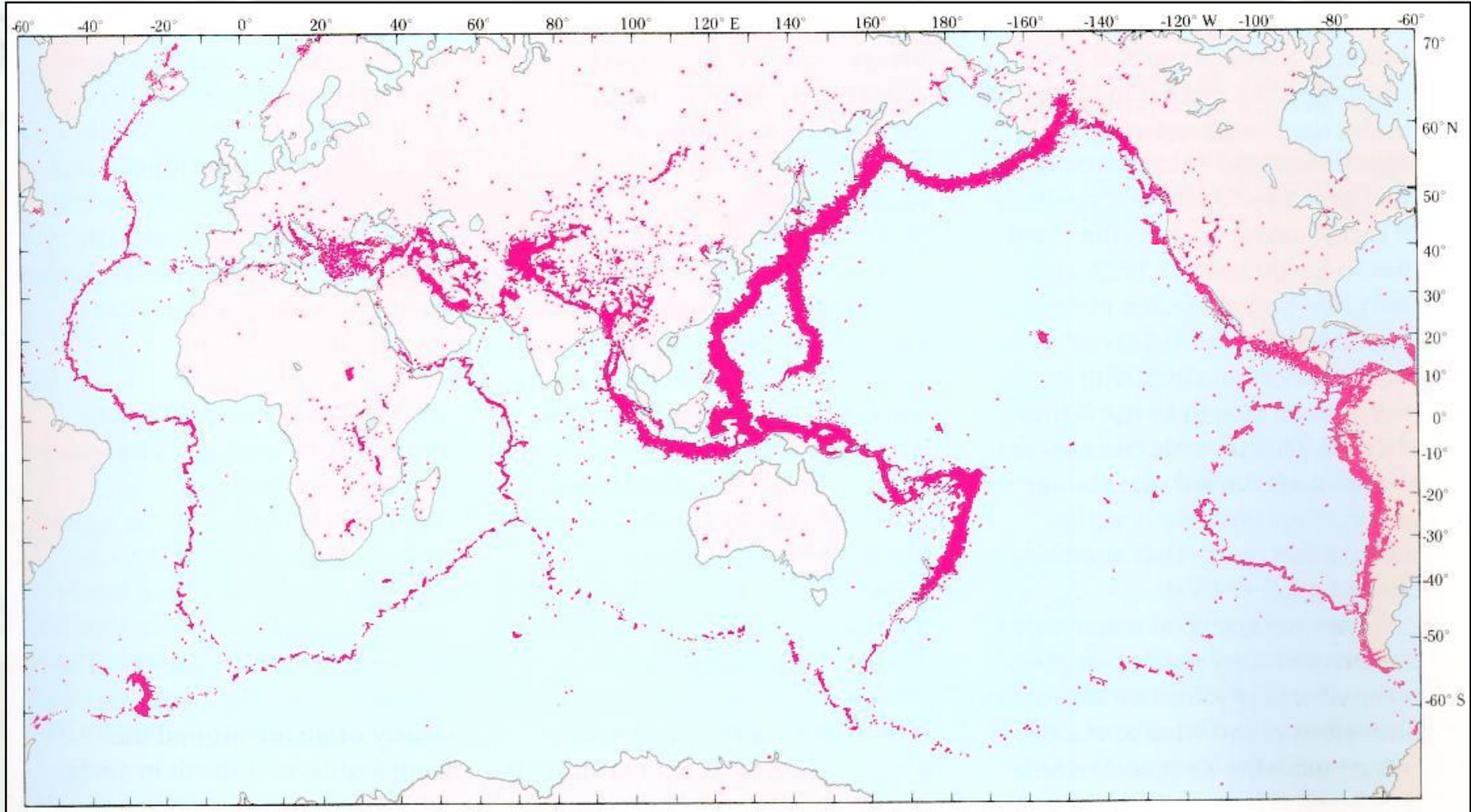




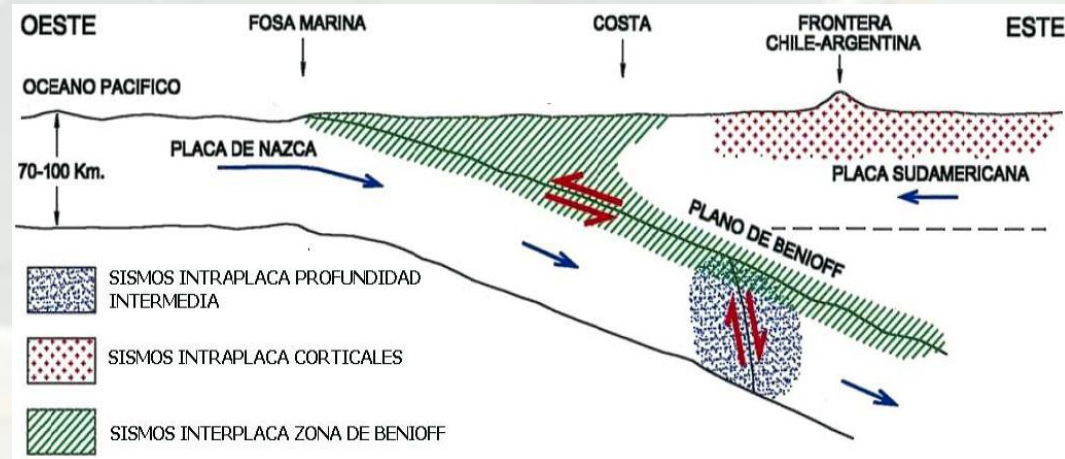
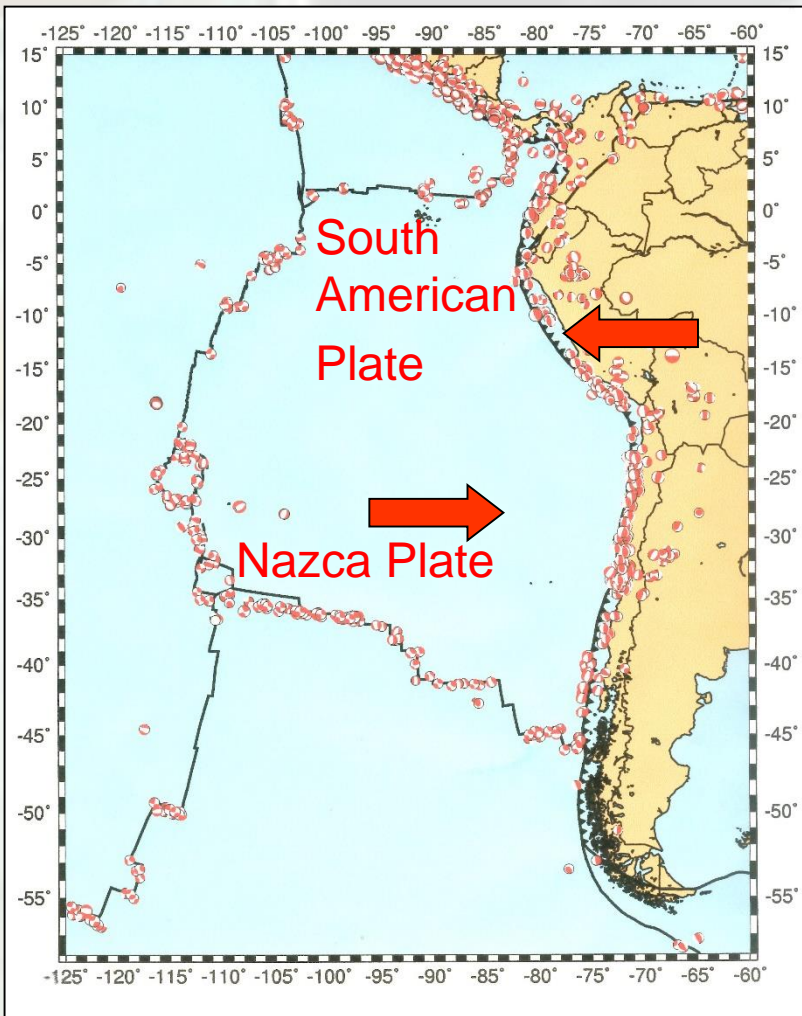
**SEISMIC ACTIVITY**

# Circumpacific Seismicity

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# Subduction Plate Interaction



**High seismicity**

**Large subduction interplate earthquakes**

**Off shore epicenters with large Tsunamis**

A person wearing a yellow shirt and dark pants is working on a large, cylindrical industrial structure, possibly a water tower or a large storage tank. The structure is surrounded by a complex network of metal scaffolding and pipes. In the foreground, there is a large, white, crumpled bag or tarp. The overall scene is industrial and appears to be a construction or maintenance site.

## **BACKWARD ANALYSIS**

# Chronology of Backward Studies

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**Rinne 1967, after Alaska earthquake**

**Cooper 1997, for Earthquakes from 1933 to 1995**

**Pineda & Saragoni, STESSA 2012**

**Pineda & Saragoni, STESSA 2015**



# Mains Aspects

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**Observed performance of real tanks during large earthquakes**

**Comparing results with theoretical or code recommendations**

**Understand the reason of the poor performance of codes**

**Required Characteristics:**

- **Geometry**
- **Anchorage conditions**
- **Properties of the liquid**
- **Fill Heights**
- **Damages**
- **Soils foundations**
- **Seismic Ground Accelerations**

# Characteristics of Tanks in Major Earthquakes

## Thomas W. Cooper Study (1997)

Earthquake	Mag.	Mech. of Faulting	Distance to Fault <sup>(2)</sup>	Epicentre Distance	Failure	Soil Type <sup>(1)</sup>	Fluid Level (earthquake)
Long Beach 1933	6.4	Cortical	2-5km	3.5-45km	BS/AB/RS	N/I <sup>(1)</sup>	Full
Kern County 1952	7.5	Cortical	N/I <sup>(1)</sup>	3.2-42km	BS	Alluvial	Full
Chile 1960	9.5	Subduction	N/I <sup>(1)</sup>	N/I <sup>(1)</sup>	BS	Sand <sup>(5)</sup>	N/I <sup>(1)</sup>
Alaska 1964	9.2	Subduction	N/I <sup>(1)</sup>	130km	BS/HS	Silt-Clay	Full
San Fernando 1971	6.7	Cortical	N/I <sup>(1)</sup>	21km	AB/BS	N/I <sup>(1)</sup>	(1/2-2/3)H
Armenia 1972	7.0	Cortical	N/I <sup>(1)</sup>	N/I <sup>(1)</sup>	BS	N/I <sup>(1)</sup>	N/I <sup>(1)</sup>
Imperial Valley 1979	6.5	Cortical	4-5km	30km	RS	Rock	Full
Coalinga 1983	6.7	Cortical	N/I <sup>(1)</sup>	6.5km	BS	N/I <sup>(1)</sup>	3/4H
Loma Prieta 1989	6.9	Cortical	N/I <sup>(1)</sup>	40km	RS	Alluvium	Full
Landers 1992	7.3	Cortical	100km	N/I <sup>(1)</sup>	BS/HS <sup>(4)</sup>	N/I <sup>(1)</sup>	N/I <sup>(1)</sup>
Hokkaido 1993	7.6	Subduction	N/I <sup>(1)</sup>	80km	BS	Poor	N/I <sup>(1)</sup>
Northridge 1994	6.7	Cortical	Near	8km	BS	Rock	Full
Kobe 1995	6.9	Cortical	2-4km	10km	Tilting	(3)	N/I <sup>(1)</sup>

(1) N/I: no information available

(2) Tectonic Plates

(3) Liquefaction

(4) Horizontal sliding: 80mm

(5) Compacted sand filling



**PERFORMANCE DURING CHILE SUBDUCTION  
EARTHQUAKES**

# Central Chile Earthquake 1985

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**Epicenter Off Shore in  
front the Algarrobo  
City**

**Mag. = 7.8**

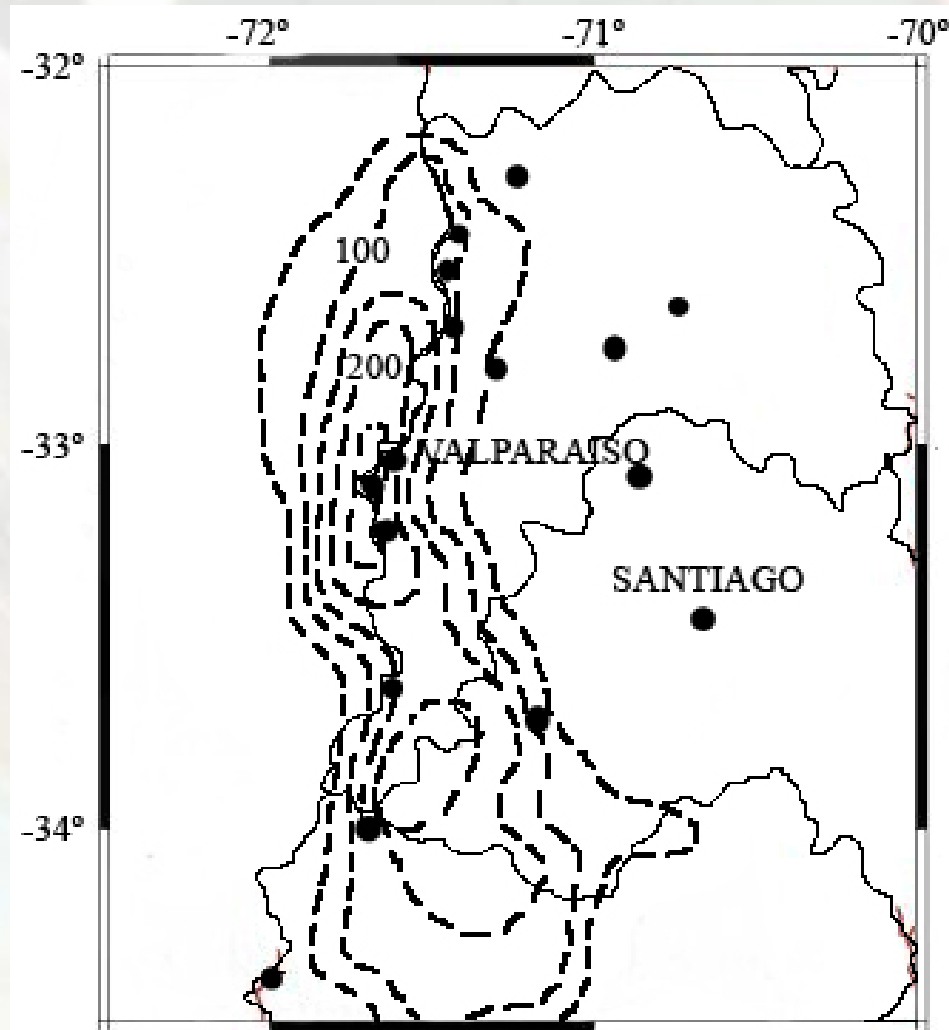
**$PGA_h = 0.67g$**

**$PGA_v = 0.81g$**



# Central Chile Earthquake 1985

At least two large zones of asperities (modified from Barrientos (1988))





# Observed Tanks failures on ENAP Refinery

Tank	R (m)	H (m)	H <sub>1</sub> (m)	H <sub>2</sub> (m)	Product	Fail
T-326A	6.48	12.2	11.30	10.61	Gasoline	BS
T-326B	6.48	12.2	11.30	11.20	Gasoline	BS
T-418A	9.14	12.2	11.30	11.23	Nafta	BS
T-552 <sup>(1)</sup>	5.59	12.2	11.80	11.56	Solvent	BS
T-407A	6.86	12.2	11.60	11.56	Fuel Oil	BS
T-320A	5.59	12.2	11.60	10.42	Fuel Oil	BS
T-4001A	5.59	12.2	11.60	11.15	Slop	BS
T-405A	9.14	12.2	11.60	11.33	Asphalt	BS
T-420A	7.92	11.58	11.60	1.94	Kerosene	(2)
T-301A	7.62	9.75	9.20	3.26	Kerosene	(2)
T-422A	11.17	12.2	11.60	7.88	Kerosene	(2)
T-402	11.20	12.2	11.30	10.80	Gasoline	(3)

H<sub>1</sub>: Maximum height of the liquid (sloshing).

H<sub>2</sub>: Filling height at March 3, 1985.

(1) Tank more damaged only with break in joint bottom shell, with loss of stored liquid.

(2): Slight deformation.

(3): Undamaged.

**All tanks were self-anchored**

**Mainly designed according to API 650-E**

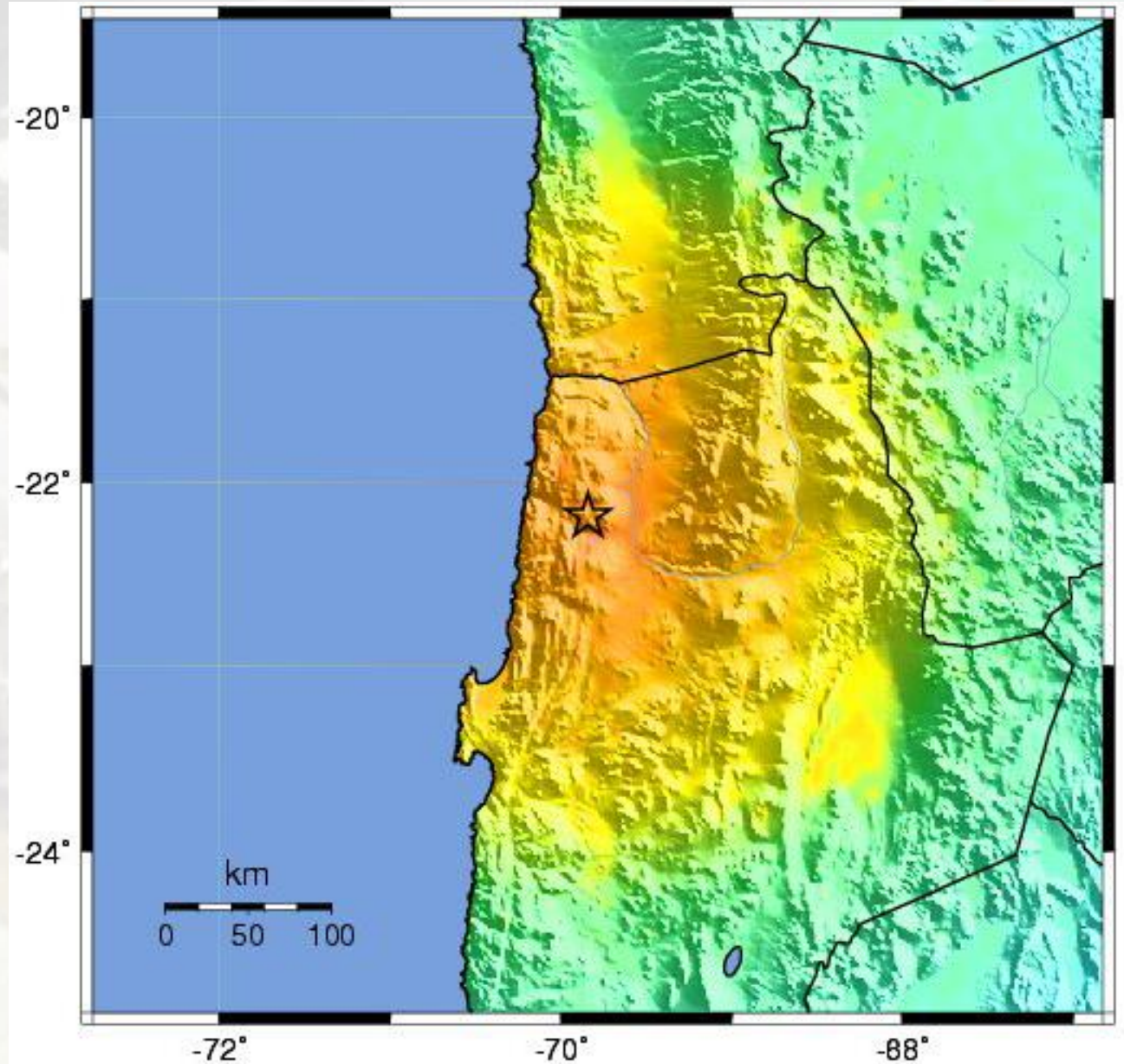
# Tocopilla Earthquake 2007

**Mejillones**

**Mag. = 7.7**

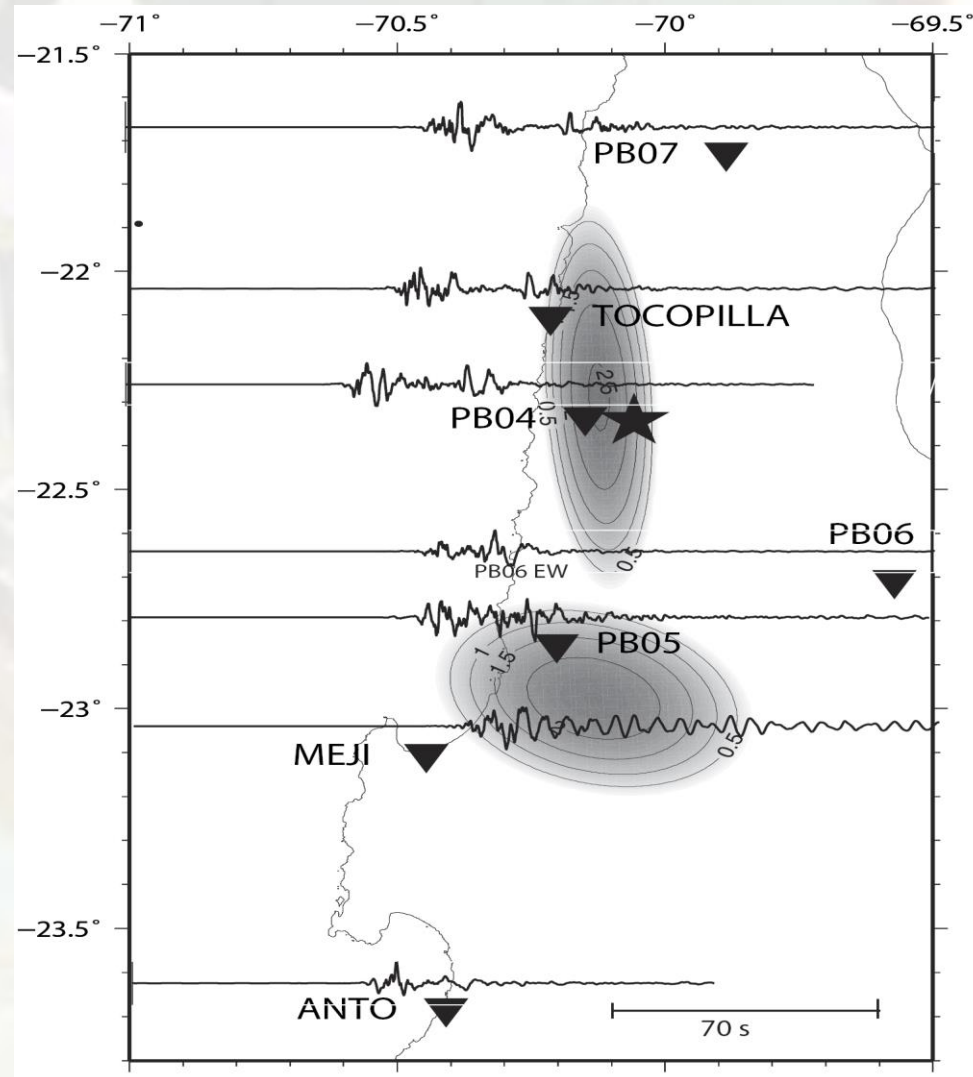
**$PGA_h = 0.42g$**

**$PGA_v = 0.36g$**



# Tocopilla Earthquake 2007

At least two large zones of asperities. South asperity at Mejillones location.





# Tocopilla Earthquake 2007

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**Buckling “elephant foot”, lifting of base of 80mm**



**Horizontal sliding (100mm) in perpendicular direction to the coast, in convergence direction of subducted Nazca plate**

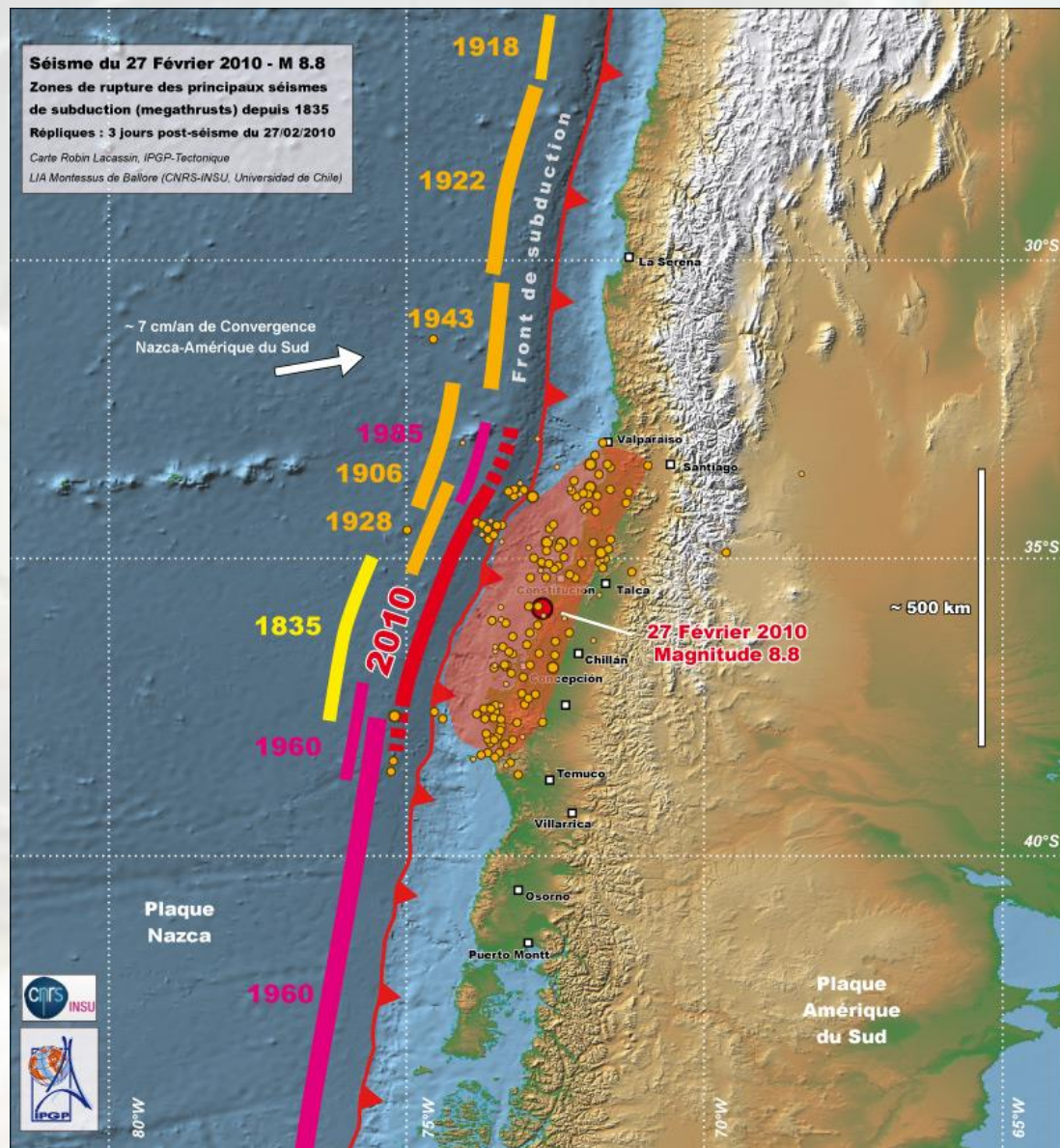
# El Maule 2010 Earthquake

Off Shore in front of  
the coast of Maule  
And Bio

Mag. = 8.8

$PGA_h = 0.93g$

$PGA_v = 0.69g$





# El Maule 2010 Earthquake

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**Observed Tanks on ENAP Bio refinery**

**Designed according to NCh2369.Of2003**

**Minor damages specifically in three floating roof tanks**



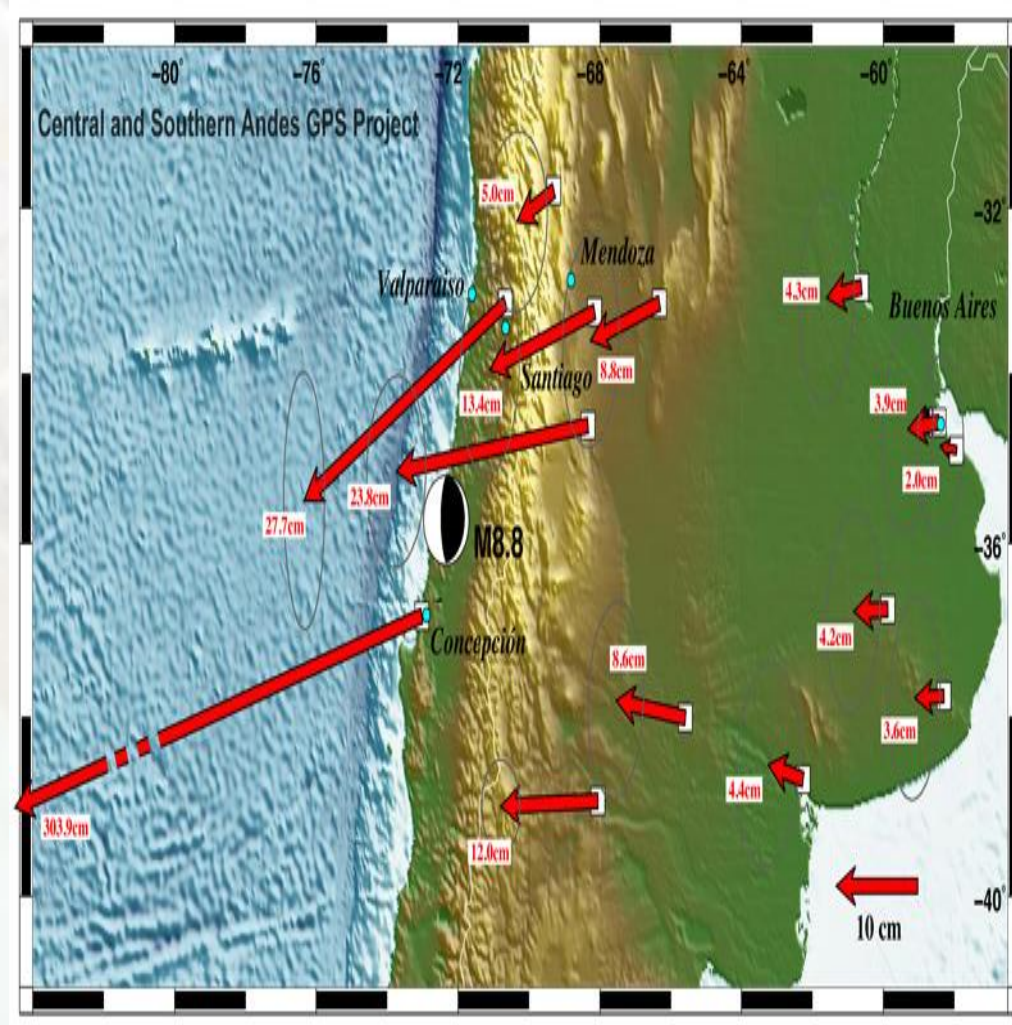
**Spilled oil**



**Lateral spreading and soil  
liquefaction**

# El Maule 2010 Earthquake

GPS coseismic horizontal displacement showing  
303.9 centimetres at the coast (ENAP Refinery)



# Comments

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**Earthquakes of subduction interplate type**

**High levels of seismic energy at few asperities on the subduction plate**

**In Chile there was no failure because the tanks were anchored mostly**

**Proposed formula to estimate displacement Sliding of Tanks**



**SEISMIC HORIZONTAL SLIDING OF  
SELF-ANCHORED STEEL TANKS**



# Principal Observed Horizontal Tanks Sliding

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Earthquake	Magnitude	Plate Fault	Horizontal Sliding (mm)	D(m)	H(m)
Alaska	9.2	Subduction	1524	3.2	9.144
Tocopilla	7.7	Subduction	80	35	14.5
Landers	7.3	Cortical	70-80	16.5	7.3

**These values are very large of the order of meters**

# Preliminary Formula to Estimate Sliding of Tanks

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**On coastal of subduction zones, in terms on magnitude:**

$$S[m] = - 5.47 + 0.76M \quad ; \quad M \geq 7.3$$

**Results in meters**

**In the direction perpendicular to the coast or in the convergence of the subducted plate.**

A large, cylindrical industrial tank, possibly a bioreactor or fermenter, is shown from an elevated perspective. The tank is filled with a dark liquid and has a complex internal structure of metal pipes and supports. A person wearing a light-colored shirt and dark pants is standing on a platform inside the tank, leaning over and working with a white bucket. The scene is dimly lit, with a strong light source from the left creating a bright reflection on the liquid surface. The overall atmosphere is industrial and technical.

## **CONCLUSIONS**

# Conclusions

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**Backward analysis of tanks located in coastal areas**

**Studies of three large Chilean subduction interplate earthquake**

**Large sliding are due to ground coseismic displacement measured by GPS in coastal áreas**

**Proposition of the formula for horizontal sliding of self-anchored tanks**



# Conclusions

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**The sliding in subduction earthquake is almost in the direction perpendicular to the coast or convergence of the subducted plate**

**Requires anchored tanks solutions, despite their geometry**

**Observed tanks functioned satisfactorily according to Chilean code NCh2369.Of2003**

**Using of anchors (uplift) and shear keys (sliding)**

A faded background image of a construction site. In the center, a large circular structure, possibly a tank or silo, is under construction. A worker in a yellow shirt is visible on a platform or scaffolding near the top of the structure. The overall scene is dimly lit and has a soft, hazy appearance.

**THANKS FOR YOUR KIND ATTENTION**

# CONTACT INFORMATION

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