# Outfall performance during Earthquakes and Tsunamis: Lessons learned from the Earthquake and Tsunami Chile 27/02

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**Abstract**
This paper discusses the design criteria of sea outfalls in Tsunami zones and their modes of failure. As current structural design criteria for sea outfalls does not normally consider extreme events this paper uses the failure of two outfalls during the February 2010 Chile Tsunami as case studies to evaluate established best practice, discuss the costs and benefits of increasing the design standards to take into account extreme climatic events, and the role of all the stakeholders in the design construction and operation of sea outfalls.

**Keywords**
Earthquake, tsunami, structural design criteria, design life cycle, pipe material

## INTRODUCTION

The construction of sea outfalls in Chile began in the 1980's and to date more than 50 have been built for the disposal of domestic and industrial waste water, of which 95% are made from polyethylene pipes. Since the introduction of sea outfalls in Chile, the country has suffered three major earthquakes. The most recent one in February 2010 which triggered a large Tsunami.

The earthquake occurred at 03:34:17 local time (GMT -3) on Saturday 27th February 2010 and reached a magnitude 8.8 Mw[12]. The epicenter was located offshore below the Pacific Ocean at longitude similar to that of the city of Concepción and 63km southwest of Cauquenes, at a depth of 47.4km below the earth's crust. The earthquake lasted for two minutes and forty-five seconds[3] and the effects were felt strongly in the regions of Valparaiso, Metropolitana de Santiago, O'Higgins, Maule, Bio Bio, Araucania and Los Rios.

The earthquake caused around 500 fatalities, 500,000 houses were severely damaged and an estimated 2,000,000 people were left homeless. This was the worst natural disaster in Chile since the Valdivia earthquake in 1960[45],and was felt with varying magnitudes throughout much of South America from Ica in Peru to the north, to Buenos Aires and Sao Paulo to the east.

Following the earthquake a strong tsunami struck the Chilean coast destroying several areas already severely damaged. Although the earthquake was not felt in the Juan Fernandez archipelago, the ensuing tsunami devastated a town called San Juan Bautista on Robinson Crusoe Island. The tsunami alert in the Pacific Ocean was extended to 53 countries including Peru, Ecuador, Colombia, Panama, Costa Rica, Antarctica, New Zealand, French Polynesia and the cost of Hawaii[6].

The earthquake is estimated to have been the second strongest in the history of the country, and one of the five highest registered in history. In Chile the earthquake was only second in magnitude to the one in Valdivia in 1960. The 2010 earthquake was 31 times stronger than the earthquake of Haiti that occurred one month before, and the energy released equivalent to 100.000 atomic bombs dropped on Hiroshima in 1945.[7]

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[1] U.S:Geological Survey (27/02/10) Magnitude 8.8-Offshore Maule, Chile
[2] Sistema Sismológico Nacional de la Universidad de Chile(27/02/19) Informe de Sismo
[3] Saber, Patrick (27/02/10) Huge earthquake hits Chile
[4] El Mercurio (28/02/10)
[5] La Tercera (28/02/10) Peor tragedia natural en los últimos 50 años deja huella de destrucción en zona centro sur
[6] Sky News (27/02/10) Tsunami Alter Major eartquake hits Chile
[7] Christensen, Axel y Escobar, Javiera (28/02/10) La Tercera

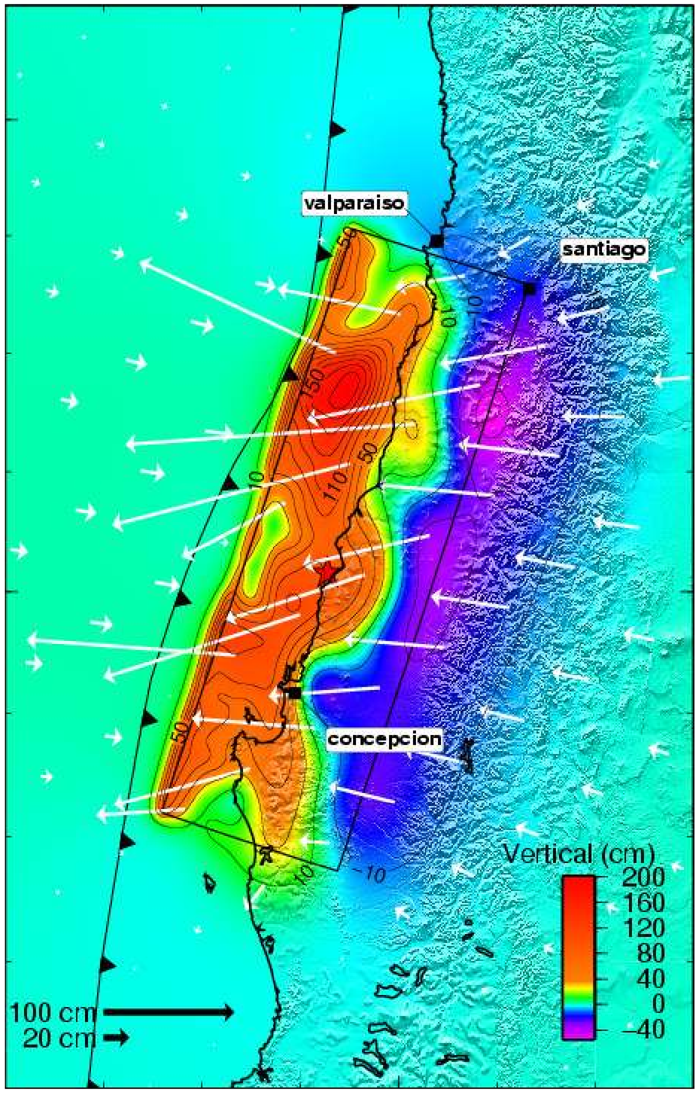



*Figure 1*- Deformation of the surface determined from the slide model. The vertical component is showed by a colored scale and the horizontal through arrows.[8]

The tsunami affected more than 600km of the Chilean coast, where at least 15 sea outfalls were located. The worst effected areas were around Talcahuano and Arauco, as shown in figure 1. In the area of Talcahuano, wave heights of 2.34m (7.7ft) where registered at 6.53a.m.[9] Topographic surveys show that the Continental Plate suffered a displacement of over 2m vertically, and 10m horizontally.

As consequence of the earthquake and tsunami, the Penco and Lebu sea outfalls suffered severe damage.

[8] http://tectonics.caltech.edu/slip_history/2010_chile/index.html
[9] Pacific Tsunami Warning Center Tsunami Bulletin Number 15

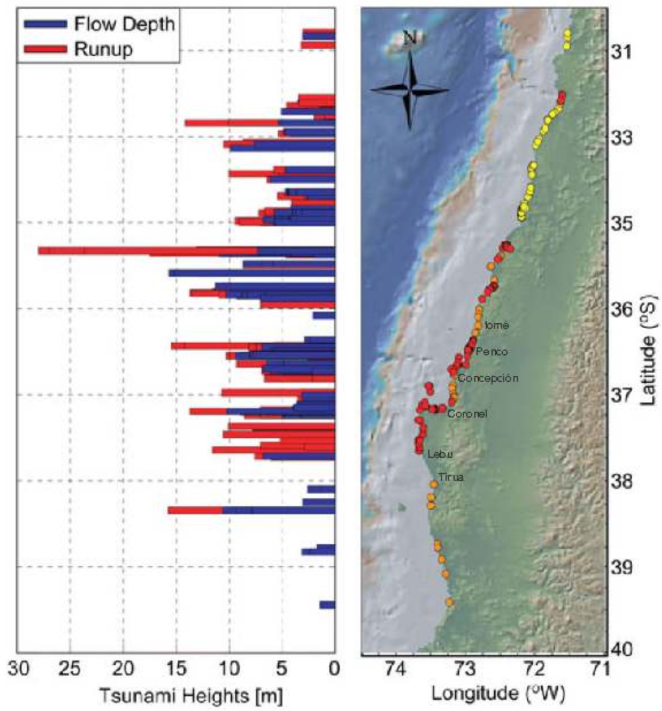



*Figure 2- Depth of the flow and height tsunami run-up along the 900km of the Chilean coast from Quintero to Mehuin.*[10]

**OBJETIVES**

The objective of this paper is to analyze the structural design criteria of sea outfalls and asses the failure mechanisms of the Penco and Lebu outfalls that were badly damaged by the Chilean earthquake and tsunami. Conclusions and recommendations will be drawn in order to support future sea outfall design criteria which will help mitigate the risk of such failures.

**DESIGN CRITERIA**

The effects of tsunamis are not considered in the design of waste water sea outfalls. When considered for other marine structures only the solitary wave theory is applied[11].

The Coastal Engineering Manual (CEM, 2008) recommends the use of the "Stream-Function" theory, whereas according to the American Society of Civil Engineering (ASCE) the use of a method based on Fentons Theory[12] that fulfills the following conditions is used: differential equations, boundary conditions in the bottom, and free cinematic boundary conditions on the surface but without free dynamic boundary conditions in the surface.

The following criteria are normally used for the design of the stability a marine outfall.

1.1 Wave Propagation Model: A detailed analysis of the deformation of the wave along the propagation of the wave in deep to superficial water is undertaken, using a recognised

[10] AGU Chapman Conference on giant Earthquakes and their Tsunamis, 16-24 May 2010, Viña del Mar, Chile: poster # 18P-10
[11] CEM 2008
[12] Fenton, J.D., 1985. A fith-order Stokes theory for steady waves. Journal of Waterway, ASCE

methodology (RCPWAVE, STWAVE, MIKE 21 SW). This analysis is carried out along the length of the sea outfall with a definition of the breaking depth.

1.2 Resistant Loads: Determination of the loads that are common for outfalls, such as dead weight of the pipeline, the transported effluent, anchor ballasts, hydrostatic pressure and buoyancy.

1.3 Outfall direction: The optimal direction of the outfall should be assessed in order to achieve the lowest possible angle towards the existing forces, especially the wave effect.

1.4 Determination of the forces generated by the waves and marine currents:

- The maximum individual wave with it associated duration should be used.
- The magnitude of the current forces depends mainly on:
  - Current velocity,
  - Pipe diameter,
  - Density of water,
  - Distance to seabed.
- Lifting forces will decline as the distance between the seabed and pipe increase. This is a fundamental consideration when designing concrete ballast weights.
- Calculation of seismic loads for which the seismic effect on ballast weights is considered.
- Calculation of seismic loads and the hydrodynamic effect of water generating a tsunami, for which the theory of the Stream-function, the Stokes of $5^{th}$ order or the Solitary Wave are used, and it is assumed that only the dragging effect is considered.

1.5 Sliding and rotation: The compliance with the safety factors relating to sliding and rotation of the ballast weights must be verified, although it is unlikely that rotation will govern the design. The safety factors for sliding, and rotation depend of the considered standard.

1.6 Air entrapment in the pipeline: Air in the pipeline is not desirable as it can contribute to pipe flotation. To reduce the risk of air entrapment the surge chamber at the start of the outfall should be constructed based on the MLLW (Mean Low Low Water) level and the fluctuations in head caused by sudden changes in flow rate. Surge chambers that are built against soil are likely to be circular in shape and the crown of the outfall pipe should be installed at least 50cm below MLLW to avoid air entrapment in the pipe. The incoming pipe to the surge tank should be designed to minimise turbulence in order to avoid air entrainment in the effluent. Despite the incorporation of measures to avoid air entrapment in the outfall during operation, such as the installation of a surge tank and the laying of the pipe below the MLLW level, for safety reasons the structural design usually considers a certain amount of air entrapment for buoyancy calculations. The amount considered usually varies between 30% and 100% of the pipe cross section.

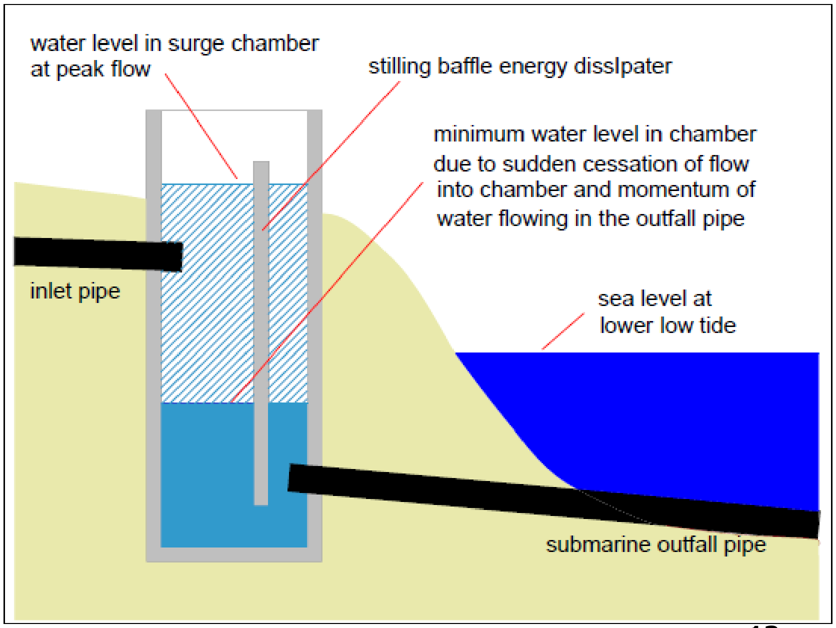



*Figure 3 - Schematic drawing of surge chamber Marine* [13].

Although use of tide flex valves in the diffusers of outfalls offers advantages in terms of improved dilution and reduced risk of foreign object entry, they do not allow water to flow into the pipeline to displace entrapped air. The installation of these systems can therefore represent an operational risk.

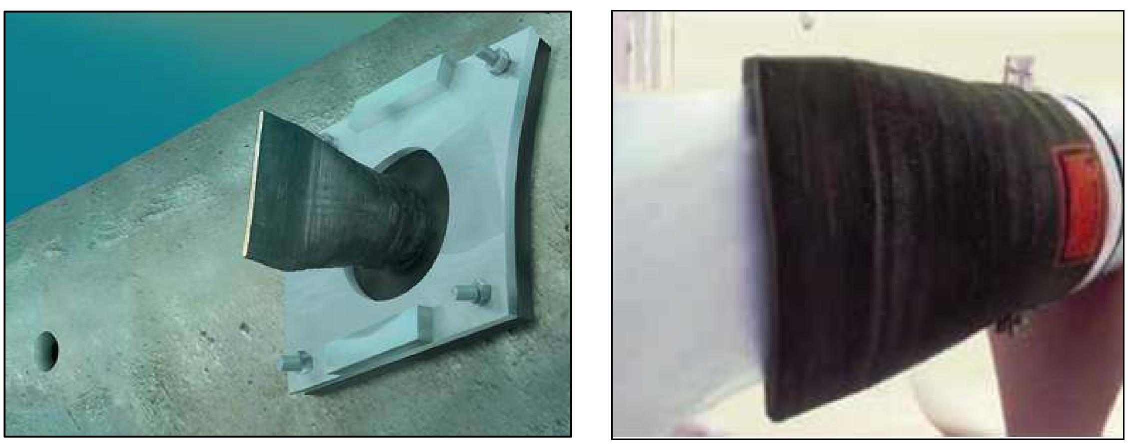


*Figure 4 - "Duckbill" Checks Valves (Courtesy of Tideflex Technologies)*

1.7 Normal loading: Commonly used guidelines[13] suggest that the pipe should not suffer any displacement from wave action on a 5 year return period, can suffer minor displacement from wave action on a 50 year return period and can suffer major displacement for wave action on a 100 year return period, but should never collapse.

[13] Wastewater Outfalls and Treatment Systems, Roberts, et al, 2010
[13] Plastics Pipes for Water Supply and Sewage Disposal, Lars-Eric Janson

1.8 Extreme loading: Design practice dictates that the ballast weights should not suffer displacement for frequent minor earthquakes, and in the case of major earthquakes the displacement should not cause the collapse of the system, as in the case of a tsunami.

1.9 Strain: Admissible/maximum strains on outfalls are directly related to the characteristics of the pipe material. Table 1 shows a qualitative comparison of common outfall materials.

| **Pipe Material** | **Resistance against** | | **Axial Flexibility** | |
|---|---|---|---|---|
| | **Internal Pressure** | **External Impact** | **Pipe** | **Joint** |
| Steel | Excellent | Excellent | Good | Excellent |
| Cement coated steel | Excellent | Good | Poor | Poor |
| Ductile Iron | Excellent | Very good | None | Fair |
| Reinforced Concrete | Good | Good | None | None |
| Prestressed Concrete | Very good | Good | None | None |
| Polyethylene (PE) | Fair | Good | Very good | Very good |
| Polypropylene | Fair | Good | Very good | Very good |
| GRP | Good | Fair | Poor | Poor |
| PVC | Fair | Poor | Fair | Poor |

*Table 1 - Pipe material characteristics*[14].

Table 1 demonstrates that PE is highly flexible, a characteristic that gives an advantage in its use for outfalls in seismic areas. This has been confirmed in recent studies.

1.10 Damage caused by wave action and abrasion: Waves approaching the shore are influenced by the seabed conditions. At a certain depth (breaking depth) the waves will break releasing significant amounts of energy that could damage the pipe. To mitigate the risk of damage it is common practice to bury the pipe to a point where the depth of water is equal or deeper than the breaking depth.

To undertake excavations in the breaking zone it is common practice to install sheet pilling. There are however situations that make excavation difficult, or not feasible, such as areas with presence of rock or mud. In these cases the structural design alone must provide an adequate protection to the outfall.

**DESIGN CRITERIA FOR TSUNAMI LOADS**

Tsunami earthquakes are the source of majority of tsunamis (about 90%), but submarine landslides (i.e. sub-seaground movement) and pyroclastic (volcanic) flows also have created high intensity tsunamis. This paper pays direct attention to the former since the latter phenomenon is rare and such localized very high magnitude events are addressed at a policy level (example: Krakatoa).

Tsunami generating earthquakes are identified by the moment magnitude (Mw) scale and the earthquake energy (Es) in generating a tsunami. Tsunami is usually measured as tsunami magnitude (Mt) or tsunami intensity (It). Energy trapped in a tsunami close to the source (Et) is found to be dependent on the earthquake moment magnitude (Mw), amount of crustal settlement (b in cm) at source etc.

[14] Wastewater Outfalls and Treatment Systems, Roberts, Salas, Reiff, Libhaber, Labbe & Thomson, 2010

A tsunami is considered as a wave with a long period where the acceleration with the following general characteristics amplitude = 0.5m to 1m, period = 10min to 30min & wave length = 200km to 600km.

Various models predicting imposed hydraulic forces due to tsunami are available. Muir Wood presented static & dynamic components of the loads offshore and onshore from the shore-line of a beach due to the impact of breaking wave, although not directly applicable to tsunamis.( Muir Wood A.M.,Coastal Hydraulics, 2nd edition, Macmillan Publishers, London, 1981, 280 pp.)

CIRIA(Hallam M.G., Heaf N.J. & Wootton L.R., Dynamics of Marine Structures: Methods of Calculating the Dynamic Response of Fixed Structures subject to Wave and Current Action, CIRIA Underwater Engineering Group Report UR8, London, UK, 176 pp.) gives coastal hydraulic pressures (uniform distribution- Morrison's Formula), which is intended for storm surges (Cd = 2 for square/straight objects; Cm = 2.5 for square,1.6 for straight & 2 for circular objects).

Federal Emergency and Management Agency or FEMA(Federal Emergency Management Agency (FEMA), Chapter11: Determining Site-Specific Loads, FEMA Coastal Construction Manual, 2000, USA. Web site: http://www.fema.gov) developed guidance on the design and construction of buildings in the coasts of USA that is potentially exposed to tsunamis and floods. The document provides good information on the types of loads, bore velocity, load combinations etc.

Structural Design Method of Buildings for Tsunami Resistance or SDMBTR (Building Technology Research Institute, Proposed Structural Design Method of Buildings for Tsunami Resistance (SDMBTR), The Building Center, Japan, 2005) developed in Japan presents simple expressions to determine loads. Pressure distribution due to tsunami is based on the model proposed by Asakura for the case of solution without break-up. The proposed distribution consists of various hydraulic components stated in the FEMA document and elsewhere above.

It is likely that during the tsunami draw back the sea outfalls are likely to get empty. When the sea surges forward again a positive vertical load is induced in the outfall due to air in the empty pipeline.

**TSUNAMI 27/02: CHARACTERISTICS**

The tsunami was a direct consequence of the seismic event and reached the Chilean coast between fifteen minutes and one hour after the earthquake.

Video recordings during the tsunami show a surge with an estimated propagation speed between 3 and 6 m/s, the tsunami wave was not higher than 2.5 meters and a period of 30 minutes or longer, an estimated wave length of several kilometers and a recorded flood height between 10m to 20m.

The distance reached onshore is dependant on the slope of the beaches along the coastline. A similar situation occurred during the tsunami in Indonesia in December 2004, where the reflected wave that hit Sri Lanka travelled several kilometers inland due to the topography.

**BEHAVIOUR OF OUTFALLS**

Most of the outfalls located in the South-Central zone of Chile resisted the effects of the tsunami without major damage. The exceptions were the outfalls of Penco and Lebu, both of which belong to ESSBIO, the regional water utility.

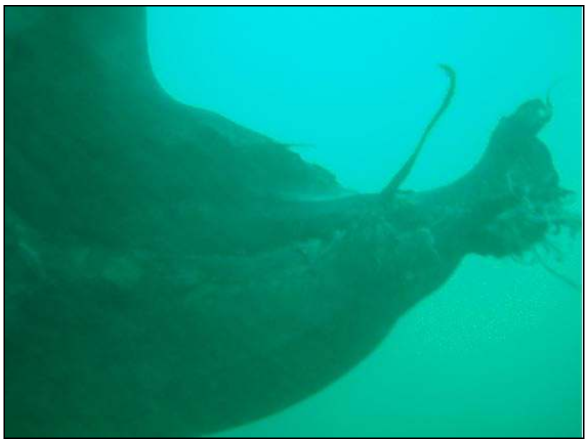

*Figure 5 - Location plan of Penco and Lebu sea outfalls*

*Figure 6 - Penco Outfall after the tsunami (Courtesy of Halcrow)*

The Penco outfall comprised a 1,200m long, 560mm diameter HDPE pipe (equivalent of the current SDR17 pipe) constructed in 1983. According to eye witness accounts, the tide receded hundreds of metres during the tsunami. It is believed that this combined with a lack of water and power supplies, caused by the proceeding earthquake, left the outfall almost completely empty. In addition, the earthquake caused the rising of the continental platform approximately one metre (See Figure 1), leaving the outfall in an elevated position relative to sea level.

These combined effects meant that when the tsunami surged back, there was not sufficient ballast weight to anchor the outfall, and failure was attributed to inter-tidal flotation that led to pipe collapse. As the outfall rose in height it disconnected from the surge chamber and the action of currents parallel to the coast forced the collapse of the pipeline by torsion, as can be seen in the picture above.

The Lebu outfall comprised a 845m long, 450mm diameter HDPE pipe (equivalent of the current SDR17 pipe) constructed in 2006. The repair works (Halcrow, 2010) undertaken for ESSBIO demonstrated that the movement of the continental platform raised the surge tank and outfall in the breaking zone approximately 1.4m. This left the outfall completely unprotected from wave hydrodynamic forces and air entrapment.



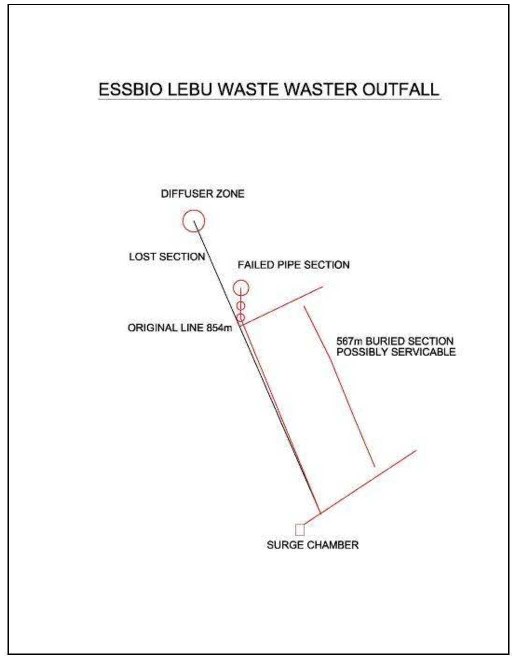



*Figure 7 Lebu Outfall Courtesy: Halcrow Group Limited*

During the first underwater inspection it was observed that a submerged section of the Lebu outfall, located 567m from the shoreline (at a depth of 16m), failed during the tsunami. Initial investigations indicated that the section failed due to torsion, part of the final section of the outfall was never located.

The diagnosis undertaken concluded that:

1. When considering operational wave conditions, the outfall had a lack of sufficient ballast per linear meter from the 470m chainage. This was attributed to the separation between ballast weights being greater than that specified in the design.

2. The reduced ballast weight per linear meter led to rapid fatigue of the pipeline due to cyclic loading from the waves. This would explain the twist in the 97m section after the 470m point.

3. The earthquake caused a raise of the seabed in the area near Lebu of 1.5m, thus changing the relative foundation level of the outfall. Based on the latest bathymetric survey data, undertaken after the earthquake, it is estimated that the sea outfall was empty for approximately 40% of it length.

4. The tsunami in this area generated a surge run-up of approximately 3m, generating dragging and buoyant forces that together with the insufficient ballast weights per linear meter in the unburied section led to the failure and collapse of the outfall from the 470m point.

In summary, the causes that could explain the collapse of the Lebu Outfall can be attributed to two main factors that combined gave conditions making the outfall susceptible to failure:

- A greater separation of the ballast weights than the design specifications for the operational conditions (waves and currents effect) provided the conditions for the initiation of the outfall failure.
- The vertical and horizontal displacement of the continental platform caused the elevation of the surge tank and the outfall to rise 1.5m. This situation allowed air entrapment in the pipe, which had the same effect as reducing ballast weight.

The study concluded that although the outfall was showing signs of failure prior to the earthquake its total collapse was a direct result of the tsunami. However, this can not be definitively stated due to a regrettable lack of systematic inspection and maintenance records. Due to this it has not been possible to review the condition of pipe before the occurrence of the tsunami.

**RECOMENDATIONS**

After the evaluation of the behavior of the sea outfalls during the earthquake and tsunami the following recommendations can be made:

- For the evaluation of the effects of a tsunami it is necessary to implement a numerical model to simulate the generation, propagation and run-up of the tsunami waves. The model would allow the calculation of the heights and velocities reached by the tsunami waves at the coast.
- It is necessary to carefully define the location of the start points of the outfalls as well as their direction in such a way that the propagation of the waves in the basin is parallel to the direction of the outfall.
- In case of ebb, undertow or drawback of the sea between waves the outfall is likely to be un-submerged and filled with air. This could be avoided by installing the surge tank at an elevation lower than the lowest possible sea level during the drawback.
- When selecting the diffusers, it is not only recommendable to consider the effect of the entrance of sediments into the pipeline but also to take into consideration the fact that there use does not permit backflow of water into the outfall, which can have a negative effect in the cases outlined in the paper.

**LESSONS LEARNED**

- In spite of the magnitude of the earthquake, the Chilean outfalls generally behaved well.
- HDPE pipes perform remarkably well in sea outfalls.
- The failure mechanism of the outfalls included a rise of the continental platform, a situation that was impossible to predict.
- No liquefaction was observed along the length of the outfall, as would have been expected.
- These cases demonstrate the importance of an effective, and on-going, inspection and maintenance programme thought out the outfalls serviceable life.

- It is desirable to undertake outfall projects using an EPC contract to ensure that one party takes full responsibility through out the whole studies, design and construction stages.

The relationship of costs and benefits of increased protection of sea outfalls during tsumani events, and their associated investment costs are the subject of other studies.