Performance of 'New Chimney Design' Structures in the 2010 Chilean Earthquake

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Abstract

This paper describes the performance of four tall reinforced concrete chimneys which were subject to significant ground shaking during the 2010 Mw8.8 Chilean earthquake event. The chimneys were all recently constructed using the 'New Chimney Design' where the reinforced concrete chimney is designed for ductility in accordance with the CICIND code and the internal face is directly lined with the 'Pennguard Block' lining system. Such chimneys are expected to perform well under seismic loading due to their ductile behaviour and light-weight lining.

Overall the 'New Chimney Design' performed very well under extreme earthquake ground shaking. The two northern power station chimneys of height 95m were subject to ground shaking with a PGV in the order of 100mm/sec, whilst the two southern power station chimneys of height 130m and 100m were located directly within the fault rupture zone region, with PGV in the order of 200-250mm/sec. All chimneys performed very well, with either no cracking or minor circumferential cracks with a maximum thickness of around 0.2mm. The paper provides an overview of the expected ground motion in the form of response spectra and compares the predicted and actual response behaviour of the chimney structures.

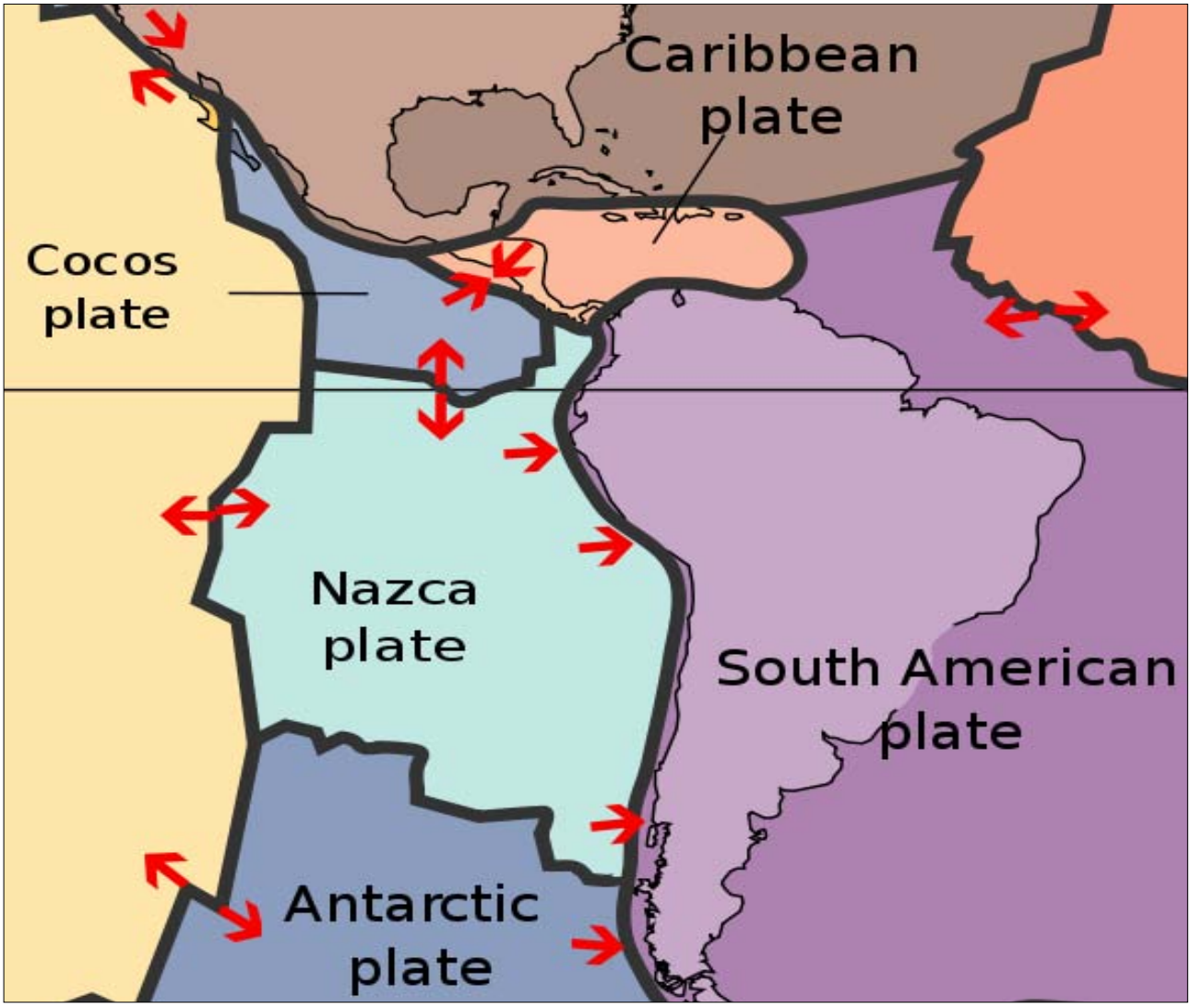
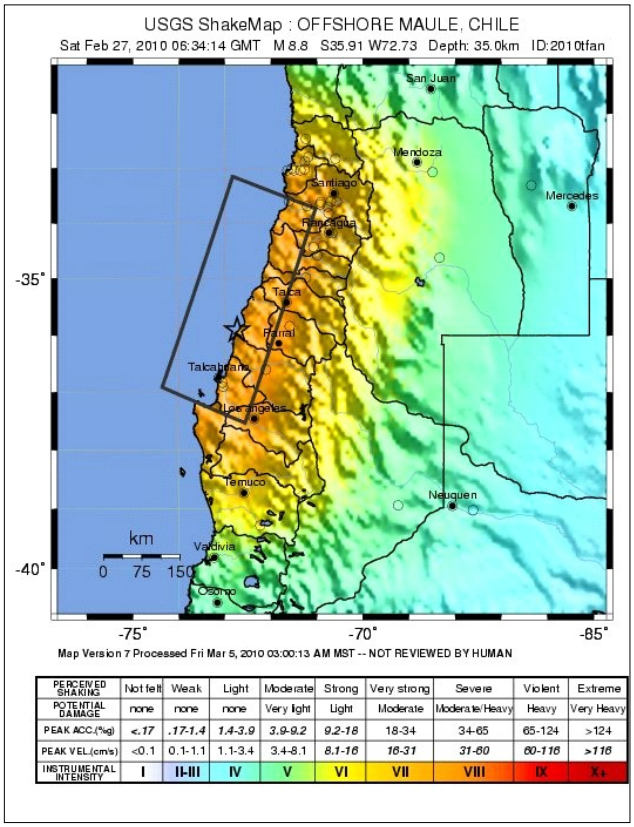


Figure 1: Nazca and South American Plate Tectonics

Figure 2: Location of 27 February 2010 Chilean Earthquake

1. Chilean Earthquake Overview

This paper summarises the findings of a field investigation into the performance of four tall reinforced concrete chimneys which were subject to significant ground shaking during the 2010 M_w8.8 Chilean earthquake event. The chimneys were all recently constructed using the 'New Chimney Design' where the reinforced concrete chimney is designed for ductility in accordance with the CICIND code (Ref 1), and the internal face is directly lined with the 'Pennguard Block' lining system. Such chimneys are expected to perform well under seismic loading due to their ductile behaviour and lightweight lining (Refs 2-4).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 3: Intensity of ground shaking and fault rupture area

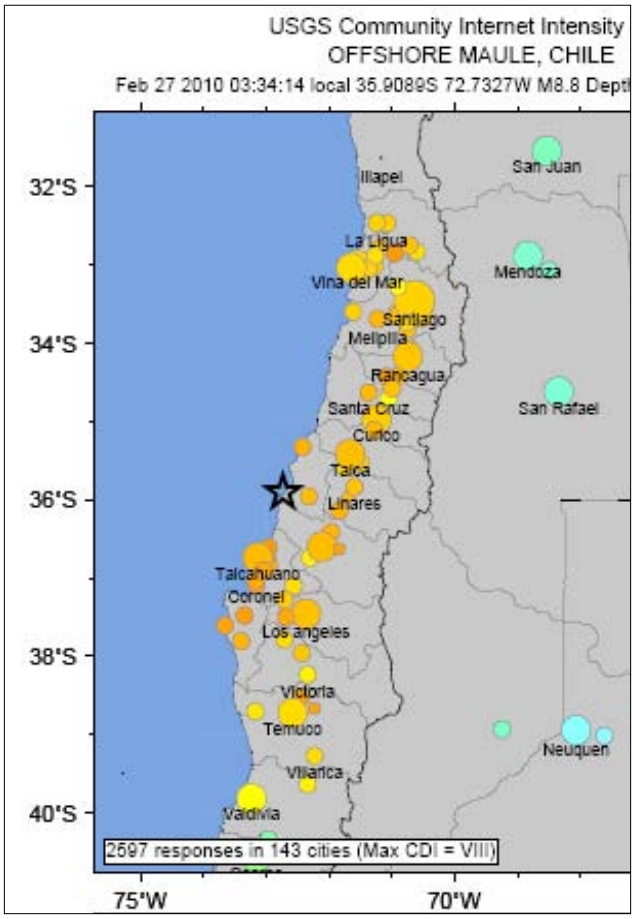


Figure 4: Aftershock Locations of 2010 Chilean Earthquake

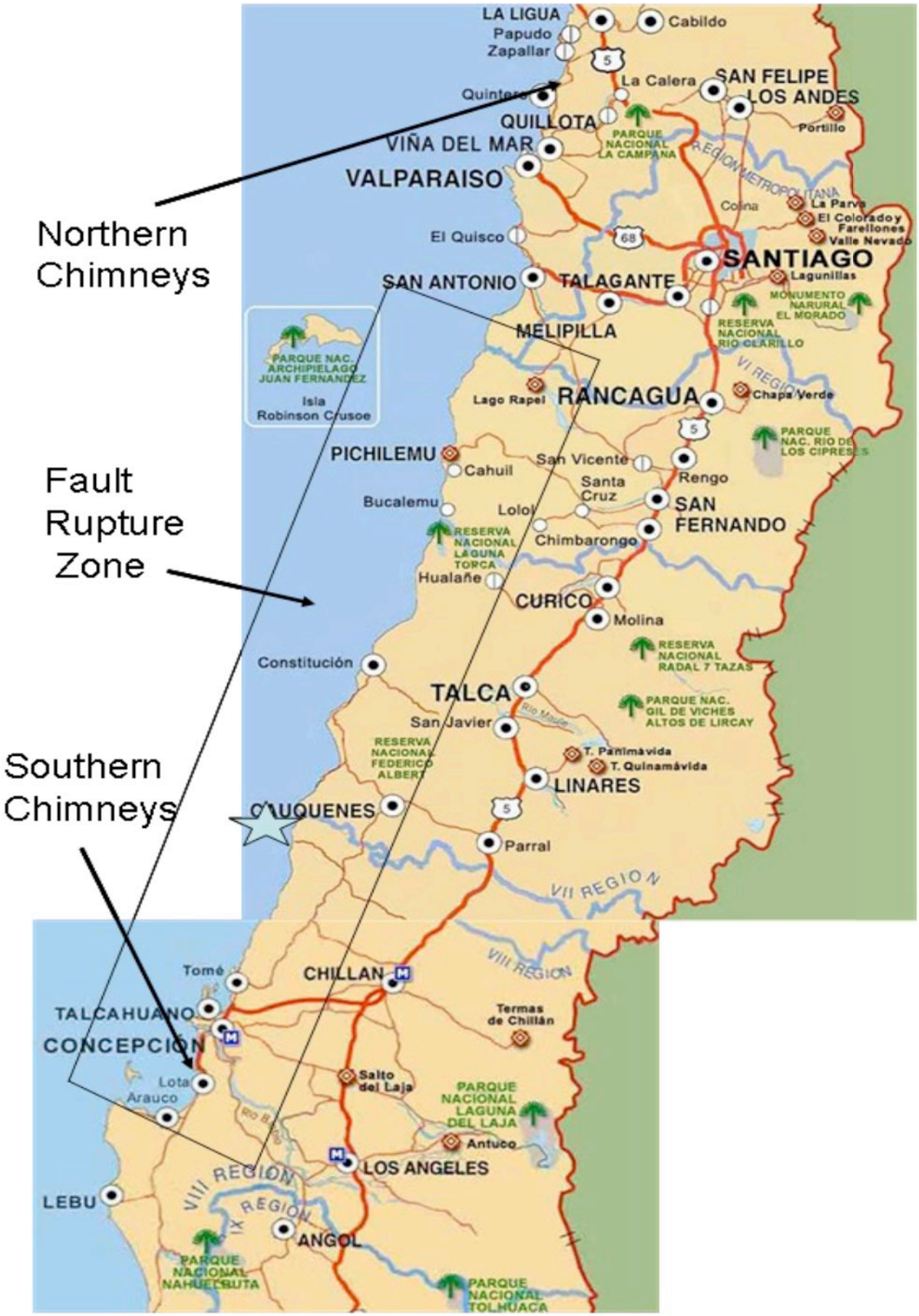


Figure 5: Chimney Locations relative to the fault rupture zone

The Magnitude M_w 8.8 Chilean earthquake occurred on February 27, 2010 at 3:35am local time. This was the fifth largest earthquake recorded in the last 100 years, and occurred directly north of the 1960, M_w 9.5 Valdivia earthquake. The earthquake was a result of the subduction of the Nazca tectonic plate beneath the South American plate (Figures 1 and 2). The rupture zone was estimated to measure 500 x150 kilometres at a depth of 35km with the epicentre 100km NNW of Chile's second largest city of Concepcion (Figure 3). The earthquake lasted longer than 90 seconds with an estimated 60 seconds of very strong ground shaking. Many aftershocks with magnitudes in the upper 6 range were recorded following the main earthquake event (Figure 4). The earthquake also caused a tsunami with a wave peak of 2.4 metres causing significant damage in the fishing village of Talcahuano, approximately 10km north of Concepcion.

Around 500,000 homes were damaged, 400 people killed and insured losses in the order of US$6 billion were substained. The intensity of ground shaking was very strong with a Modified Mercalli Intensity of around MMI 9 estimated in the fault rupture zone (peak ground velocity PGV=360mm/sec). The city of Concepcion with a population of 220,000 people and located within the fault rupture zone, was shifted 3 metres vertically and 3m horizontally in a westerly direction according to GPS data records. Overall, it was estimated that around 1.2 square kilometres additional land in Chile was reclaimed from the earthquake. The capital of Chile, Santiago, with a population of around 5 million people was north of the fault zone, but experienced shaking of intensity estimated to be in the order of MMI 7-8 (PGV=90-180mm/sec).

The four chimney structures inspected in the study tour, consisted of two chimneys north and two chimneys south of the earthquake epicentre (Figure 5). The two northern power station chimneys (Campiche and Ventanas power stations) each of height 95m were around 100km north of the fault rupture zone (and north of Santiago) and subject to ground shaking of Modified Mercalli intensity estimated to be of the order of MMI 7 (PGV around 100mm/sec). The two southern power station chimneys of height 130m (Colbun power station) and 100m (Bocamina power station) were located at the southerly end of the fault rupture zone and subject to ground shaking of Modified Mercalli intensity estimated to be of the order of MMI 8-9 (PGV in the range 180-360mm/sec).

2. Estimated Earthquake Ground Motions

The earthquake ground motions were recorded at different locations using both analogue and digital recorders and preliminary reports have been released by the University of Chile (Refs 5-6). However, no digital recordings have been released to the public, as calibration and verification checks are still being undertaken. Prof Ernesto Cruz has carried out some preliminary response spectra calculations using some of the recorded motion at San Pedro in the Concepcion area, on a site believed to be classified as stiff soil. From an inspection of this

Figure 6: Campiche 95m tall Chimney

Figure 7: Ventanas 95m tall Chimney

response spectra it was estimated that the peak response spectral acceleration, velocity and displacement was in the order of RSA=1.5g, RSV=800mm/sec and RSD=250mm. This earthquake motion corresponded to a peak ground velocity of around PGV=400mm/sec or Modified Mercalli Intensity of around MMI 9 and could be described by the following response spectral acceleration relationships:

RSA = 1.5g	T<0.3secs
RSA = 0.5g/T	0.3<T<2.0secs
RSA = 1.0g/T^2	T>2.0 secs

This basic data has been used in this report and scaled by a factor of 0.25 for the northern power station chimneys (PGV in the order of 100mm/sec) and a factor of 0.5-0.75 for the southern power station chimneys (PGV in the order of 200-250mm/sec).

3. Northern Power Station Chimneys

The northern power station chimneys consisted of the Campiche Power Station (still under construction with work suspended due to a legal dispute, but chimneys completed, refer Figure 6) and the Ventanas Power Station (being commissioned at the time of the earthquake and now in operation, refer Figure 7). The ground shaking in this region was estimated to be in the order of 100 mm/sec, based on an intensity of around MMI 7. Such an intensity appeared consistent with the level of ground shaking experienced by the people interviewed, the level of damage experienced in this region and the considerable distance of around 100km to the zone of fault rupture. For example, one of the construction engineers experienced quite violent shaking on the 11th floor of his apartment which lasted over 60 seconds, pictures fell from the wall, a TV fell off a table, he had difficulty standing which would have been compounded by the darkness associated with the electricity blackout. However, in the morning there was only very minor cracking in the building joints between the walls and windows suggesting drifts in the order of 1/750 and ground motions with a PGV in the order of 100mm/sec, which would create velocities around 300mm/sec at the top of the building.

Damage to the power station structures was reported to be only minor to one of the main bracing connections in the boiler house structure and some pressure pipes in the membrane wall of the boiler. No damage was reported in the Turbine House, Bunker Bay, Precipitators, Transformer Bay and Switchyard. No cracking was reported in the Ventanas chimney whilst minor cracking was reported in the Campiche chimney at a height of around 45-55metres, including fracture of the externally mounted copper lightning conductor. The chimney designer recommended that the minor horizontal cracking in the Campiche chimney be repaired with epoxy injection.

During the study visit, the Campiche chimney could only be inspected at the base with no cracking evident. Access up the chimney was prevented due to a legal dispute that had suspended construction of this power station. Similarly, no cracking over the lower half of the Ventanas chimney was evident during the study visit, although access above the platform at mid-height level was not permitted due to operational constraints.

Both chimneys were identical and 95metres tall and with a constant outside diameter of 5.150m. The thickness was a constant 350mm over the bottom 30m and then a constant 225mm for the remainder of the height, whilst the vertical reinforcement ration varied from 0.43% in the upper regions to 1.7% at the base. The chimneys were founded on a circular raft foundation 16.0m in diameter. The site consisted of deep estuary fine sands with an SPT in the range 30-60 (dense sand) and a depth to rock greater than 40 metres. The chimneys were originally designed using the response spectra specified in the construction contract which was generally consistent with the Chilean earthquake design code for industrial structures (Ref 3) with a structural reduction factor of R=3. The design moments were then scaled by a factor of around 1.5 to achieve a minimum base shear force of V=10%W, although the resulting rebar ratio specified in the chimney provided a nominal ultimate base shear capacity of V=15%W (maximum strength with over-strength in the order of V=20%).

An analysis of the chimney indicated that the response of the structure to earthquakes was dominated by the first 3 modes, with the contribution from the second mode being very significant. The analyses clearly indicated that cracking was twice as likely to occur at the base of the chimney as compared with the upper levels due to the constant diameter configuration of the chimney (refer Figure 8 which compares the ratio of the bending moment demand with the cracking moment capacity). Hence from the calculations, if cracking did not occur at the base, then it was not likely to occur at the upper levels. The calculations indicated that the chimney was on the verge of cracking at the base with the estimated ground motion of PGV of around 100mm/sec. The level of ground shaking experi-

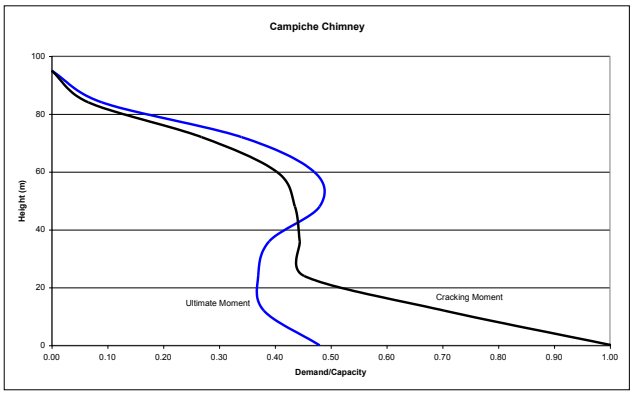


Figure 8: Demand/Capacity performance of Campiche chimney (PGV~100mm/sec)

enced was estimated to be around 50% that needed to develop the ultimate strength capacity of the chimney (refer Figure 8 which compares the ratio of the bending moment demand with the ultimate moment capacity). This result was consistent with the no cracking observations for the Ventanas chimney and the base of the Campiche chimney. However, the calculations were not consistent with the minor horizontal cracking reported at the mid-height of the Campiche chimney, indicating a more detailed study would be required to understand this observation.

No damage was reported to the 'Pennguard Block' lining system in either chimney indicating excellent performance to this relatively strong ground shaking, with maximum chimney drifts in the order of 0.1-0.2%.

4. Southern Power Station Chimneys

The southern power station chimneys consisted of the Colbun Power Station (still under construction, but the 135m tall chimney completed as shown in Figure 9) and the Bocamina II Power Station (still under construction, but the100m tall chimney completed as shown in Figure 10). The ground shaking in this region was estimated to be in the order of 200-300mm/sec, based on an intensity of around MMI 8-9. Such an intensity appeared consistent with the location of the site being around 35km south of Concepcion and on the southern edge of the fault rupture zone. Damage in the surrounding area of the power station appeared less than in the city of Concepcion and more consistent with an intensity of around MMI 8 or slightly higher.

Some damage was reported to the Colbun power station but mainly in equipment that was not fully erected, such as the Steam Turbine, Air Heaters, FGD components, Bunker Bay, and other minor equipment that was not fully anchored at the time of the earthquake. Non piled foundations, underground ducts, including pits suffered some damage due to differential settlements. The primary steel and reinforced structures performed relatively well and remained in sound condition overall, except for some cracking in partitions such as brick walls that were not fully isolated from the main structure.

Damage was also recorded at the Bocamina II power station including damage to the water intake structures from excessive foundation movement. Interestingly, an old lightly reinforced concrete chimney around 30m tall servicing the Bocamina 1 power station was significantly damaged in the earthquake. The chimney was shrouded in scaffold to enable the wide circumferential cracks to be repaired. Details of the chimney were not available, but the damage and age of the chimney indicated that it was probably designed using the 'working stress method' which would result in a very under-reinforced and less ductile chimney than that recommended in a contemporary code such as CICIND (Ref 1).

4.1 Colbun Chimney

During the study visit, the 130 m tall Colbun chimney was inspected over the lower half and no cracking was observed. Access to the upper half of the chimney was denied due to some access safety concerns, however, the power station contractor confirmed that no cracking was observed in the upper half of the chimney following an earlier post earthquake inspection they had completed.

The Colbun chimney is 130 metres tall, with a constant outside diameter of 5.90m and thickness of 250mm over the upper 50m and flaring to a diameter of 11.0m and a thickness of 400mm at the base. The chimney is generously reinforced with vertical reinforcement ratios varying from 1.0-2.0% over the

Figure 9: Colbun 130m tall Chimney

chimney height. The chimney is founded on a circular raft foundation 26.0m in diameter directly onto soft rock. The chimneys were originally designed using the response spectra specified in the construction contract which was generally consistent with the Chilean earthquake design code for industrial structures (Ref 3) with a structural reduction factor of R=3. The design moments were then scaled by a factor of around 1.9 to achieve a minimum base shear force of V=15% W, although the resulting rebar ratio specified in the chimney provided a nominal ultimate base shear capacity of around V=30%W, thus creating a very strong chimney with excellent post cracking performance.

An analysis of the chimney indicated that the response of the structure to earthquakes was dominated by the first 3 modes, with the contribution from the second mode being very significant. The analyses clearly indicated that cracking was more likely to occur in the upper levels between 60-110m compared with the base due to the tapered configuration of this chimney. The calculations indicated that the chimney was on the verge of cracking in the upper levels with an estimated ground motion of PGV of around 200mm/sec. The level of ground shaking experienced was estimated to be around 50% of that needed to develop the ultimate strength capacity of the chimney. This result was just consistent with the no observed cracking in the chimney from the field studies, although cracking was expected to be very close to occurring.

Importantly, no damage was reported to the 'Pennguard Block' lining system indicating excellent performance to this strong ground shaking, with drifts in the order of 0.15%.

4.2 Bocamina Chimney

During the study visit, the 100m tall Bocamina chimney was inspected over the full height and many fine cracks were observed as follows; one circumferential crack at the base, 6 circumferential cracks between 35-50m and around 50 circumferential cracks between 50-90m. All cracks were very fine and did not exceed 0.2mm in width (Figure 11).

The Bocamina chimney is 100 metres tall, with a constant outside diameter of 6.25m and thickness of 250mm over the upper 60m and flaring to a diameter of 10.50m and a thickness of 350mm at the base. The chimney is generously reinforced with vertical reinforcement ratios varying from 1.0-2.0% over the chimney height. The chimney is founded on a circular pile cap with piles passing through 10m of soft clay before being socketed into the soft rock below. The chimneys were originally designed using the response spectra specified in the construction contract which was generally consistent with the Chilean earthquake design code for industrial structures (Ref 3) with a structural reduction factor of R=3. The design moments were then scaled by a factor of around 1.2 to achieve a minimum base shear force of V=15%W, although the resulting rebar ratio specified in the chimney provided a nominal ultimate base shear capacity of around V=30%W, thus creating a very strong chimney with excellent post cracking performance.

An analysis of the chimney indicated that the response of the structure to earthquakes was dominated by the first 3 modes, with the contribution from the second mode being very significant. The analyses clearly indicated that cracking was likely to occur between the base and level 75m, with a heavier frequency of cracking around levels 25-65m with an estimated ground motion of PGV of around 250mm/sec (refer Figure 12 which compares the ratio of the bending moment demand with the cracking moment capacity). The higher PGV at Bocamina compared with Colbun can be explained due to the presence of

Figure 10: Bocamina 100m tall Chimney

a 10m soft clay layer that would tend to amplify the ground motions compared with a rock site. The cracks were considered fine with a maximum crack thickness of around 0.2mm. Local yielding of the reinforcement would not be expected from this level of shaking which was estimated to be around 60% of that needed to develop the ultimate strength capacity of the chimney (refer Figure 12 which compares the ratio of the bending moment demand with the ultimate moment capacity). This result was generally consistent with pattern of cracking observed from the field study.

No damage was reported to the 'Pennguard Block' lining system, except locally at the duct opening interface with the windshield, indicating excellent performance to this strong ground shaking, with chimney drifts in the order of 0.3-0.4%. The expected concrete strains experienced by the 'Pennguard' adhesive would probably be in the order of 0.2%, assuming a maximum crack width of around 0.4mm during the earthquake. The localised damage (cracking of the 'Pennguard' block) observed at the interface between the duct liner and the windshield at a chimney opening, was suspected to have been caused by the vertical excitation of the steel cantilevered ductwork, causing some local overstress at the connection interface. These cracked 'Pennguard' blocks at the base of the openings would need to be repaired, with access easily provided from within the ductwork and flue base.

5. Overall Performance of Chimneys

Overall the 'New Chimney Design' consisting of a moderately ductile reinforced concrete windshield lined with the 'Pennguard Block' lining, performed very well under extreme

earthquake ground shaking associated with the 2010 M_w 8.8 Chilean earthquake. The two northern power station chimneys were subject to ground shaking with a PGV in the order of 100mm/sec, whilst the two southern power station chimneys were located directly within the fault rupture zone region, with PGV in the order of 200-250mm/sec. Interestingly, the northern chimneys were around 50% the strength of the southern chimneys (V=15%W versus V=30%W) and experienced around 50% the level of ground shaking, resulting in similar overall performance for all four chimneys. All chimneys performed very well, with either no cracking or minor circumferential cracks with a maximum thickness of around 0.2mm. The peak concrete strains experienced by the 'Pennguard' adhesive was estimated to be around 0.2%, which is significantly less than the 1.0%-4.0% strain needed to crack the blocks from previous experimental tests, as reported in Ref 2. This suggests that the chimneys could have experienced much greater ground shaking, including yielding of the windshield reinforcement without damaging the 'Pennguard' block lining system.

Figure 11: Circumferential Cracking to Bocamina Chimney

An alternative flue lining system to the 'Pennguard Block' lining system would be to install an acid resistant brick flue liner. Such a flue system would require intermediate corbels to support a number of flue lengths up the height of the chimney to cater for the thermal movements expected. Brick flues tend to be heavy and brittle, which are two undesirable characteristics in relation to earthquake excitation. The southern power station chimneys experienced horizontal velocities and accelerations in the order of 800mm/sec and 0.9g near the top and localised drifts in the order of 0.5% which would have resulted in severe damage and probably collapse of any traditional brick flue liners during this earthquake.

Another alternative could be steel flue liners, depending on the flue gas temperatures and level of acidity. Such flue liners tend to have a high diameter/thickness ratio and consequently have a tendency to buckle under excessive internal moments caused by a combination of the windshield drift and flue inertia forces, particularly if they are bottom supported and in net compression. Alternatively, if the flues are top hung, they would perform better under earthquake excitation although local buckling at the lateral restraint positions could be a problem.

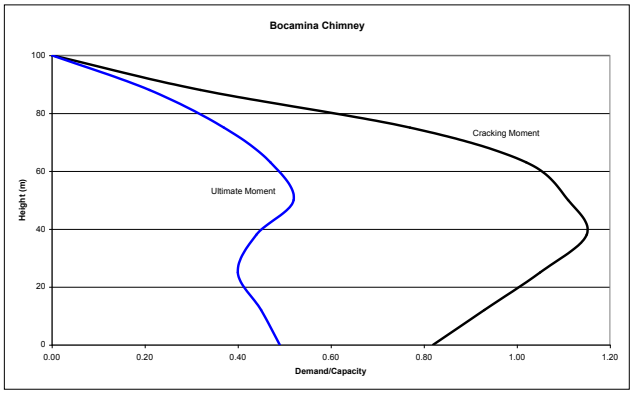


Figure 12: Demand/Capacity performance of Bocamina II chimney (PGV~250mm/sec)

In summary, the four chimneys that were reviewed in this study demonstrate that the 'New Chimney Design' consisting of a moderately ductile reinforced concrete windshield lined with the 'Pennguard Block' lining system, performed very well under extreme earthquake ground shaking associated with the 2010 M_w 8.8 Chilean earthquake. The 'New Chimney Design' has created an integrated and efficient chimney system, particularly suited for regions of high seismicity.

6. Acknowledgements

The study tour involved representatives from Hadek (Netherlands-Johan Lautenbach), Exponent Industrial Structures (Germany-Markus Rost), and Swinburne University of Technology (Australia-Prof John Wilson) together with the photographer Huib Nederhof (Netherlands). The study tour was undertaken 30 May-3 June 2010, and involved a one day session with Prof Ernesto Cruz (Catholic University of Chile and Chilean earthquake expert) and site visits to all four chimney structures.

7. References

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