

# **NZSOLD Reconnaissance Report**

## **Taiwan Dams – March 2000**

Peter Foster

*Opus International Consultants*

Grant Campbell

*Contact Energy Ltd*

### **Introduction**

On 21 September 1999, a magnitude  $M_w$  7.6 earthquake occurred on the island of Taiwan with its epicentre adjacent to the town of Chi Chi. Significant ground rupture occurred over a length of 80 km along the Chelungpu Fault. The ground rupture extended through one dam site, and strong ground shaking was experienced at a number of dams and hydroelectric power stations. A very large landslide dam formed at Tsao Ling and works are being undertaken in an attempt to minimise potential downstream consequences if the landslide dam were to fail suddenly. The death toll from the earthquake was about 2,400, with 10,700 people injured and 100,000 homeless.

The authors were sponsored by NZSOLD, and their employers, to visit Taiwan to see how various dams performed during and after the earthquake. We spent a week in Taiwan in March 2000 and we were able to visit a number of dams in the epicentral area of the earthquake. Our visit also included a field trip to the Tsao Ling landslide dam.

The topography of the island is long (350 km) and narrow (140 km) with the Central Mountain Range in the middle (up to 4,000m). The mountainous region with an elevation higher than 1,000m occupies 32% of the total island area, hills and plateaus of 100m to 1,000m cover 31%, and the remaining 37% is coastal plains with an elevation lower than 100m. At 36,000km<sup>2</sup> in area Taiwan is a little larger than Southland. The population of 22 million is largely resident on the coastal plain area. Situated on the Tropic of Cancer it has an annual rainfall of 2500mm with three quarters of that falling in the wet season between May and October. The ratio of wet to dry season precipitation in the northern region is 6:4 and in the southern region 9:1. This creates water resource utilisation difficulties in such a densely populated country. Rivers are short and steep with discharges responding rapidly to rainfall intensity and flood flows usually carry large amounts of sediment. With the rainfall in the wet season coming from storms or typhoons, the intensity can be high - up to 300mm/hr and 1,750mm/day.

Our report presents our findings from the reconnaissance visit, and from data and reports available from others. We discuss briefly the regulatory environment that exists for dam ownership in Taiwan, the dams and power stations we visited, and the Tsao Ling landslide dam. We also discuss issues related to emergency operations and procedures. We conclude with our observations on issues that are relevant to dams and hydro-electric power stations in New Zealand.

## **Dam Safety Management**

Many of the watersheds are steep, with fragile topsoil that can induce siltation problems for reservoirs. Many reservoirs have significant populations downstream of them. The government has realised the importance of reservoirs to water resources utilisation and the importance of reservoir safety to lives and property. During the 1980's the government has successively established the Reservoir Safety Inspection and Evaluation Methods, and Reservoir Safety Evaluation Guidelines. The government also formed the Reservoir Safety Evaluation Group under the Ministry of Economic Affairs (Kuo et al, 1999).

Various safety codes regarding hydrology, geology and seismic impact have been developed. Training courses, seminars and workshops on dam safety evaluation have been held to disseminate the results of government information. Most reservoir agencies follow the guideline requiring safety reviews every 5 years and after strong earthquake shaking or a high water storage level.

There appears to be close collaboration between dam owners, consultants and the universities in the identification, investigation and remedying of problems that could affect dam safety.

## **Chi Chi Earthquake**

The Chi Chi earthquake occurred on 21 September 1999 and resulted from uplift along the Chelungpu Fault. The fault rupture length was up to 80 km and displacements of 10 metres uplift were measured. Within the next month there were many aftershocks, with approximately 14 events that equalled or exceeded Magnitude 6. A number of aftershocks were in the range  $M_w$  6.7 to 6.8.

Taiwan has a coastal plain to the west and uplifted mountains in the central and eastern areas that result from tectonic plate collision at a rate of about 70 mm/yr. Figure 1 shows the tectonic mechanism existing at Taiwan. The Chelungpu Fault located along the western foothill and coastal plain interface had been classed as Category II, namely, a fault that has ruptured in the last 10,000 years to 125,000 years. Figure 2 shows approximately 7 to 8 m of uplift at a new waterfall on the Tachia river, downstream of Shih Kang Dam. The fault trace then changed strike by about 90 degrees and displacement followed the river upstream.

The fault rupture caused the first case history of a concrete gravity dam (Shih Kang dam) failing under direct fault displacement. Upstream of Shih Kang dam the Tachia river has been developed with a series of arch and gravity dam structures for hydro-electric power generation. In the epicentral area there are a number of concrete gravity dams and earth dams that experienced ground shaking in the order of 0.4g or higher. Two large pumped storage plants, one of 1000 MW the other 1600 MW were located close to the earthquake epicentre.

In the following section we describe our observations from the dams we inspected and other data we were able to gather.

## Dams

### *Shih Kang Dam*

The Shih Kang dam is a 25 m high concrete gravity dam, with a crest length of 357 metres. It contains 18 spillway bays and two sluice bays on the left abutment. The dam is located on the Tachia river and the reservoir acts as a regulating pool for five hydro stations upstream. The dam is founded on interbedded mudstones, siltstones and sandstones. The reservoir is an important source of water for supply to the Taichung area and for irrigation purposes.

The dam was built in 1977 and designed for earthquake loads using a pseudo-static seismic coefficient of 0.15g.

The dam has had the misfortune of getting a direct hit from the fault displacement associated with the Chi Chi earthquake. Dam blocks 1 to 15 have been uplifted by 7 to 10 metres (Figure 3). A surveyed cross-section about 500 m upstream of the dam had over 5 m of uplift. Dam blocks 16 to 18 were severely damaged by the fault rupture, while the other dam blocks remain essentially intact, (Figure 4). Some photographs we saw of the dam after the earthquake indicated a significant amount of seepage at the toe of the dam blocks to the true right of the fault rupture. This suggests either significant opening of dam block joints or open horizontal cracks in the vicinity of the dam foundation contact. This seepage was in addition to river flows occurring through the vicinity of dam blocks 16 to 18.

At the time of the earthquake the reservoir was about 4 metres below the top level of the spillway gates. Peak rock accelerations at the dam are estimated to have been about 0.5 g horizontal and 0.52 g vertical based on strong motions recorded nearby. An order of magnitude calculation indicates that the gate loads would have been about 55% of the static loads for the full gate situation, and about 45% of the static plus earthquake load considered in the original design.

The Chelungpu fault was known to exist downstream of the dam. The Water Conservancy Agency advised us that there was no record of previous fault movement in the dam foundation. Foundation exposures during dam construction did not identify the fault displacement hazard potential. The faulting in the vicinity of the dam took place on a number of traces, and the water delivery tunnel from the reservoir to the downstream treatment plant on the left abutment was also severed by a separate trace of the fault displacement.

The release of water from the reservoir did not cause catastrophic flooding downstream as the breach outflow was not large relative to flood flows and was thus contained within the river banks.

In the vicinity of the fault rupture, gates 16 to 18 were severely damaged. After the earthquake 3 or 4 of the fourteen gates to the left of the fault rupture did not open. The jammed spillway gates have since been brought back into service. Following the earthquake it was important to be able to operate the spillway gates as a typhoon was approaching. Existing emergency power supplies were used to open as many of the spillway gates as could be operated.

The spillway gates were typical of those seen while in Taiwan. They are robustly made of conservative steel section with adequate cross bracing (figure 5). Music note seals are

attached to the upstream skinplate and run on stainless steel embedded in the pier concrete. The drive mechanism is by wire rope mounted on the pier, connected via sheaves to the gate on the dry side. A connecting rod linked the drive from one side of the gate to the gearbox on the otherside. The buckling of the connecting rod caused three of the gates to be unavailable after the quake. The gate water loads are transferred to the bearing blocks which are attached to the piers via I beams through to the front of the dam (compared to Macalloy stressed bars as commonly used in some New Zealand radially gated spillways.)

The foundation for the main uplifted part of the dam has been both rotated and bent in an upstream direction with relative movement from the original dam axis reaching 353 mm. It was reported that some transverse joints are more open on the upstream side relative to the downstream. Shearing and cracking that must have occurred in the dam foundation has been reflected through a number of dam blocks. We were advised that a number of cracks through various dam blocks for a conjugate set at 45 degrees to the dam axis. Figure 6 shows the view looking across the downstream piers from the left abutment.

Cracking went through the number 1 spillway wall and gate guide into the No 2 sluice. (Figure 7). This sluice is still jammed and work was proceeding to try and free this gate when we visited the site. The repair will involve reducing the width of the gate by 1 meter and increasing the pier width. At the number 8 spillway there were shear cracks between the piers and the weir body with the contraction joint having opened up by 50 mm.

The cross- valley earthquake accelerations appear to have cracked a number of the piers, based on our observation of where epoxy mortar had been injected. Downstream of the dam the displacements have also lead to cracking in the stilling basin area. The uplift by the fault will have changed the stilling basin tailwater characteristics and a small weir may be required to ensure satisfactory energy dissipation conditions (Figure 8).

After the earthquake the priorities were:

- Repair the left bank intake and re-establish the diversion of water to the treatment plant
- Repair the No 1 and No 2 sluices and spillway bays 1 to 3
- Repair dam blocks from spillway bay 3 to 15
- Rehabilitate the right bank and spillway bays 16 to 18.

Re-establishing the water supply took about 1 month. At the time of our visit a levee had been constructed upstream of the dam (Figure 9) to direct flow through to the water diversion intake and to sluice No 1. Sluice No 2 was still jammed.

For the spillway bays the cracks within the dam body and piers have been injected with epoxy mortar. The foundation of the dam is being grouted with a cement grout. Borehole cameras and Ground Penetration Radar have indicated some dislocations within dam blocks and in the foundation in the vicinity of the dam base.

A number of secondary grout holes have been drilled and grout takes appear a lot lower than for the primary grout holes. A foundation permeability of less than 5 lugeons is being targeted.

Additional instrumentation is going into the dam to monitor displacements and foundation uplift pressures.

Passive anchors drilled through the dam blocks into the foundation are also being considered, but at this stage they are not being installed.

A number of options have been considered for repair of the right bank. It is proposed that the right bank dam blocks will remain as they are as a memorial to the Chi Chi earthquake. A fishway will be located in this area. A connecting dam will be taken upstream of block 15 and then across the right abutment. This may be a sheet pile structure. The final detail of the dam as it crosses the fault is still under consideration. If future fault movement were to occur the desire is to limit the width of damaged dam and to have a means of repair.

In our opinion the risks posed by this dam are quite acceptable. The likelihood of fault rupture is real but extremely low on an annual basis being in the order of 1 in 10,000. The consequences of release of the reservoir would be relatively minor if the area where the breaching occurs is limited. The river downstream of the dam has a very large flow capacity within its banks.

We did not visit the dams upstream of Shih Kang dam. The Tachia River rises steeply up to elevation 2000 m at the Techii arch dam and access is difficult. However others have informed us that these upstream dams have survived the shaking very well.

The Techii dam is a 185 m high double curvature arch dam. Bed rock accelerations were not measured here but a peak acceleration of 0.86g was measured near the crest of the dam. The crest spillway gates have been tested and these were satisfactory.

#### *Liyutan Dam*

Liyutan dam, completed in 1992, is a 96 m high rockfill dam with a central earthfill core. The dam is 235 m long and is located about 7 km north of Shih Kang dam. The dam is founded on interbedded sandstones and mudstones. Accelerations in the rock base were measured at 0.098g, and at the centre crest of the dam horizontal accelerations peaked at 0.24g.

The earthquake caused 90 mm settlement at the dam. Seepage rose a relatively small amount from 150 cubic metres per day (104 litres/min) to 170 cubic metres per day (118 litres/min) and then returned to normal. Transverse cracking up to 2.1 m deep was detected at the left abutment and this has since been repaired (Figure 10).

At the time of our visit the reservoir was 5% full as indicated in Figure 11. Since the earthquake the reservoir has been drawn down and will not rise until the wet season. Liyutan dam is an off-river storage facility located on a tributary of the Taan River. Water is diverted from the Taan River to the upstream of the Liyutan reservoir.

The offtake structure had four sliding gates set at an angle of 45 degrees and located at various depths in the reservoir. Three were operated by cables from winch drums while the fourth which fed a small power plant was hydraulically operated. There were no problems associated with these gates.

The performance of this dam appears to have been satisfactory, as expected for a well compacted rockfill dam on a rock foundation. Other earthquakes around the world have also caused transverse cracking near abutment contacts on similar types of dams.

### *Shuishih Dam*

The Shuishih Dam a 30.3 m high, 363 m long dam founded on rock and located at Sun Moon Lake about 13 km east of the epicentre of the earthquake. The dam was built in 1934 by the Japanese and consists of earthfill shoulders and a central concrete cutoff wall. Upstream and downstream slopes average 4: 1 (Horizontal : vertical). The dam is located about 10 km south of the earthquake epicentre and is estimated to have experienced peak ground accelerations in the order of 0.45g based on nearby strong motion data.

Figures 12, 13 and 14 show the crest, downstream face and upstream face of this dam.

The dam settled approximately 130 mm due to the earthquake shaking and seepage rose from 734 litres/min to 987 litres/min. Seepage subsequently fell to 670 litres/min. It was estimated that seiches in the reservoir reached a height of 2.5 metres.

Prominent longitudinal cracks 30 to 70 mm wide formed along the crest of the dam and extended to a depth of up to 300 to 500 mm. Some smaller cracks were also observed on the upstream shoulder. The central longitudinal cracks are due to settlement of the earthfill shoulder about the concrete core wall. Website [www.liquefaction.com/eq99](http://www.liquefaction.com/eq99) has images of the cracking at Shuishih dam.

After the earthquake the lake was lowered by 6 m as a precautionary measure. The central cracks have been repaired by injecting them at low pressure with a cement-bentonite grout.

At the time of our visit the road surface over the dam crest had been reconstructed. The lake had risen 1.5 m and was to be held at that level for a week before it is raised in 1.5 m intervals back to full supply level. We were advised that piezometric and seepage monitoring downstream of the core wall indicates everything is satisfactory.

Sun Moon lake acts as the top storage reservoir for a number of large pumped storage powerstations including Minchu No2 (1000 MW) and Mingtan (1600 MW). Minchu No 1 is an older (1934) powerstation with 110 MW capacity. These stations operate on heads in the order of 320 m.

### *Mingtán Dam*

Mingtán dam is an 82 m high gravity dam which creates the lower reservoir for the Mingtan pumped storage scheme (figure 15). Ground accelerations are estimated to have been in the order of 0.4 to 0.5g at this dam. It is located about 12 km south of the earthquake epicentre.

The dam appears to have been undamaged by the earthquake. Crest level spillway gates and low level sluice gates are also satisfactory. We were advised that the station goes into pumping mode at about 10 pm at night and ceases pumping at 8.00 am. The water level at the spillway gates when the earthquake struck at about 1.47 am in the morning may have

been at about half height or lower. If the earthquake had struck earlier in the evening the spillway gates may have been subjected to significantly higher loads. If water levels were at or below half height on the spillway gates, the static plus dynamic loads on the gates are unlikely to have exceeded the full reservoir design loads, either for static or earthquake conditions.

At the base of the dam some uplift pressures rose. Extra pressure relief holes were subsequently drilled.

The Mingtan dam is a traditional gravity dam and the good performance of this dam under quite large ground accelerations is encouraging. We hope that one day some back analysis of this dam will be completed and reported.

The dam has a spillway with three radial gates operated by winch drums and four low-level dewatering gates operated by hydraulic rams. Downstream of the dam is a powerhouse with 2 small generators, which provided the residual flow into the river. No damage to the spillway, sluices or residual flow powerhouse was reported.

The main powerhouse is underground and has a capacity of 1600MW (6X 266MW), the largest of its type in Asia. It is a pumped storage station and was pumping at the time of the earthquake.

Noticeable around the Mingtan area was the substantial number of shallow slides in the steep terrain.

#### *Minchu 1 Power Station*

This station has 5 x 22MW pelton driven generators. The water source is Sun Moon Lake where the offtake is a tunnel through a mountain to five penstocks. These emerge from the mountain side and drop 300 meters to the station which is positioned on the river bank. At the time of the earthquake the station was running but tripped off due to power outages elsewhere. Part of the intake tunnel collapsed and it has taken six months to repair and get the station back on line. The exposed penstocks were hit by some small rock falls which caused little damage, although an auxiliary cooling line close to the station was severed (Figure 16). Transformers 4 and 5 had moved on their bases and required repair.

#### *Minchu 2 Power Station*

Adjacent to the above station is an underground powerhouse with four pumped storage units rated at 250MW each. These were installed in 1983. At the time of the earthquake the station was in pumping mode and tripped offline. When a restart was attempted it was noted one machine had a sharp rise in the guide bearing temperature. The unit was shut down and opened up for inspection. The bearings were adjusted and the shaft realigned which fixed the problem. Above ground the gas insulated switchgear (GIS) lines, which lead to the transformers, suffered leaks and needed repairs.

A concrete gravity dam impounds the small reservoir, which is used for the pumping cycle. It has 2 spillway gates and 2 low-level dewatering gates. These gates, typical of those seen in Taiwan, were quite robust. No problems were experienced

### *Jen-I–Tan Dam*

This dam is located 50 km south of the earthquake epicentre and received shaking in the order of 0.19g during the Chi Chi earthquake. A month after this earthquake a Magnitude 6.4 earthquake caused acceleration up to 1.0 g. We are not sure of the exact location of the strong motion instrument. These accelerations may have been recorded near the crest of the dam either in an administration building or on a ridge. The control room contained a seismic recorder which was alarmed at 4 points. The degree of alarm indicated what type of checks needed to be undertaken following an earthquake.

The dam is a 1.5 km long, earth rockfill structure with a height of 20 m (Figure 17). Settlement of the main earth dam was small. There was a gradual increase in seepage which then returned to normal.

Between the main dam and the spillway is a narrow natural ridge which has had fill placed downstream. Settlement over a 10 m long 3 m wide strip occurred after the Chi Chi earthquake. Cracks were 12 mm wide near the spillway. The October aftershock increased the settlement by 220 mm and widened the cracking to 160 mm width over a length of 113 metres. (Figure 18)

The ridge has always had seepage passing through it and a weir monitors the flow. Current seepage was small and the water was clear. Repairs will entail recompaction of the fill near the crest of the ridge. It appears the cracking was primarily in the ridge/fill interface area.

### *Lian Tan Dam*

This dam is a 28 m high earthfill structure with a concrete core wall. The original reservoir goes back to the 17<sup>th</sup> century and is associated with the Dutch. The dam today was built by the Japanese and heightened 3 m in 1987.

Longitudinal cracking up to 650 mm deep appeared along the crest of the dam. This, like the Shuishih dam, followed the concrete corewall. The cracks have been infilled and the road surface repaired. Figures 19 and 20 show the crest of the dam and the upstream face, respectively.

## **Tsao Ling Landslide Dam**

Tsao Ling landslide is located approximately 40 km south of the epicentre of the Chi Chi earthquake. Earthquakes and heavy rainfall have triggered previous landslides at the same location. The landslide dams have formed due to block slides along interbedded mudstones and sandstones. An earthquake in 1862 led to the formation of a landslide dam that later failed in 1898.

An earthquake in 1941 led to another slide and formation of a dam 140 m in height and 48 million cubic metres in volume. Rainfall in 1942 led to a further slide increasing the dam height to 217 m and forming a lake with a volume of 157 million cubic metres. The dam failed in 1951 after 776 mm of rainfall fell in 5 days. The resulting flood killed 154 people.

In 1979 rainfall triggered a further slide and a dam formed 90 metres in height with a lake volume of 40 million cubic metres. This dam failed 9 days later after 624 mm of rainfall in 2 days.

The current landslide volume is estimated to be in the order of 150 million cubic meters. Water is impounded to a depth of about 55 m and the reservoir has a volume of about 43 million cubic metres. The distance along the river from the toe of the landslide to the upstream is about 5 km. The toe of the landslide is about 135 m lower in elevation than the upstream end. The steepest part of the landslide is the downstream 1.5 km section where the gradient is about 1 in 5.

Figure 21 shows the upstream section of the landslide and spill channel, looking downstream. The source of the landslide material is indicated on the right bank. We observed sufficient material at the top of the slide to possibly cause another landslide dam at the same site.

Figure 22 shows the next section downstream. Overshot material can be seen on the left bank. A reasonably wide spill channel exists in this section of the landslide dam.

Figure 23 shows the downstream section of the landslide dam. This is the steepest and most critical section of the landslide. Earthworks is ongoing in this area in order to widen and armour a spill channel.

Figure 24 shows the toe of the landslide dam where a large amount of rip rap has already been placed.

The estimated 2 year flood could produce a flow of about  $1000 \text{ m}^3/\text{s}$  over the slide. At the time of our visit the flow over the landslide was less than  $10 \text{ m}^3/\text{s}$ .

Approximately \$NZ 20 million of works are committed prior to the rainy season commencing in May. It involves earthworks and channel protection works to create a flood channel to accommodate flows in the order of  $1000 \text{ m}^3/\text{s}$ .

The aim is to get an armoured spill channel in place before the rainy season to lower the likelihood of rapid erosion.

Check dams are also being constructed downstream in order to limit the amount of debris reaching the lower reaches of the river.

Emergency procedures are in place in case there is an uncontrolled release of the reservoir behind the dam. Order of magnitude dam break studies have been completed. Instruments are monitoring rainfall, lake levels and flow in the channel. Closed circuit television is also monitoring critical sections of the landslide dam. All information is telemetered to the Water Authorities central control and is also made directly available to the police and emergency services. A notification plan is in place for those who may be at risk of inundation.

A three-level warning system has been developed based around rainfall and the volume of overspill.

A permanent solution to remove the inundation hazard would require about 8 km of tunnels to draw the reservoir down. This is not practicable in the short term with the rainy season imminent.

Incidentally a dam site was investigated upstream of the Tsao Ling landslide. A 40 m depth of lake bed sediments at the valley floor deemed the site too difficult to build on.

## **Emergency Response**

Taiwan is familiar with dealing with emergency responses on an annual basis. In the last 100 years there have been 350 typhoons and over 1000 storms. These events usually cause flooding, landslides, subsidence and sedimentation problems. In the same period there have been 18 earthquakes recorded as being disasters, ranging in magnitude from 5.5 to 7.6. On a more frequent basis, damage by fire causes \$300M loss annually due possibly to the high population and hence building density. Perhaps because of this it falls to the Fire Department to coordinate disaster relief.

Three years ago the Central Weather Bureau completed a six year seismic instrumentation program, giving Taiwan the most intense network system in the world. The following instruments are in place,

- a) a real-time digitally telemetered seismic network of 80 three-component, short period stations
- b) a rapid earthquake information release system based on 61 real-time telemetered digital accelerographs
- c) 700 digital accelerographs in free field sites
- d) 56 real-time strong-motion arrays in buildings and bridges.
- e) Many other sites in critical locations such as dams, power stations and structural facilities.

For the Chi Chi earthquake the Rapid Earthquake Release System automatically determined the location and magnitude for the mainshock. Within 102 seconds after the event a shake intensity map was prepared. This information was then sent out by pager, e-mail and by fax to interested parties such as Water Resources Department which has responsibility for many dams in Taiwan. The earthquake occurred at 1:47am and by 2:30am ministry officials had gathered at the National Fire Headquarters in Taipei and communications were established with local agencies in the most severely affected areas. By early on the morning of the earthquake the government had released a paper outlining the priorities for response and recovery. In order to expedite disaster assistance a six month State of Emergency was declared four days later.

Taiwan has an armed force of over 400,000 personnel with modern equipment and facilities. The Fire Department was able to call on this resource to assist in the days following the earthquake. They were specifically used to support central and local government efforts in search and rescue, relocation and shelter of victims, demolition of dangerous structures and clearance of debris. They also assumed much of the responsibility for recovering the dead. Within 24 hours of the earthquake international search and rescue teams from 21 countries arrived and were assigned locations by the Fire Department.

## **Lifelines**

Major life-line supplies were effected such as electricity, water and gas.

The major area of damage to the electricity system was in the switchyards and transmission lines. The fault rupture went through Chung-Liao switchyard, which was a nodal point for the whole transmission system. Damaged substation components included circuit breakers, lightning arrestors, ceramic insulators, gas insulated line relays and gas circuit breakers. This resulted in power blackouts throughout much of the northern island for 24 hours. Rationing was put in place and lasted for two weeks in Taipei. Emergency repairs involved installing a bypass transmission line around the substation. Other damage included large transformers (oil leakage and bushings), transmission towers (13 collapsed, others were tilted or had insulator problems) and distribution facilities (871 transformers damaged, 2,100 poles damaged, 4,400km of lines affected).

Several major water facilities were damaged, including Shih Kang dam which was the offtake for water supply to treatment plants serving Taichung city (pop 2M). As well as the dam breaching on the right side the offtake pipe on the left side of the dam was severed by a rupture. One of the downstream treatment plants was also severely damaged. While other water supplies and pipelines were affected 70% were operational again 10 days later. Emergency water supplies were delivered by trucks to affected areas.

Gas supplies throughout the island were turned off immediately after the earthquake to prevent secondary problems. While there was severe damage along the rupture area, sectionalisation allowed gas to be restored to the majority of uses in the following two weeks. Most of the damage was at connections to gas.meters.

## **Lessons and Thoughts for New Zealand**

The Chi Chi earthquake provides a significant case history regarding the performance of dams and hydro-electric power stations during and subsequent to a very large earthquake. It has relevance to New Zealand as we have known active fault systems adjacent to hydro developments along the Clutha River, within the Waitaki valle, and along the Waikato River. We should also not overlook the potential for faulting along the Hauraki graben adjacent to the Hunua dams that store water for Auckland, and in specific locations such as at Matahina dam on the Rangitaiki River.

It is encouraging to see that well constructed earth and concrete dams can survive ground accelerations in the order of 0.3g to 0.5g without serious damage. It was direct displacement that caused one dam to fail. It is important that seismotectonic studies consider both the shaking and ground displacement hazards at any dam site.

The Chelungpu fault was classed as having ruptured in the last 10,000 to 125,000 years, but its time came around ahead of more probable faults. The next major earthquake in New Zealand may not be on the Alpine or Wellington fault, but could be one of the faults close to a major dam. Dam owners should consider this in any emergency planning and plan for the worst.

Damage to spillway gates was mainly due to ground displacement effects at Shih Kang dam and not as a result of shaking. However the fact that some key reservoirs were not at full

supply level, significantly lowered the potential load on the gates. In New Zealand, where hydro lakes typically have very little operating range, the forces on gates from a near field earthquake may be relatively much higher than the design static loads. In Taiwan the examples we saw had relatively low loads due to the reservoirs been partially lowered when the earthquake struck.

Most of the damage that occurred at the various dams was detected by visual inspection. Post-earthquake inspection procedures are therefore important for assessing damage at dams and alerting dam owners to potential problems.

Hydro plants in the vicinity of a major earthquake may not be able to generate for some time. It is imperative that spillway and sluice gates have a number of independent power supply or hydraulic lifting systems to ensure flow can bypass the powerstations after an earthquake without the risk of the dam overtopping.

When there are a number of dams in the epicentral area a heavy demand is placed on technical resources to inspect dams and interpret the results from gathered data and visual inspections. It could be worthwhile for dam owners to have a register of available engineers to assist in post-earthquake inspections and data evaluation.

## **References**

Japanese Society of Civil Engineers. The 1999 Ji Ji Earthquake Taiwan, Investigation into Damage to Civil Engineering Structures

Kuo Jan Tai, Hsu Shaing-Kueen, Hsieh Cheng-Daw (1999) Dam Safety management in Taiwan. Risk Analysis in Dam Safety Assessment; Proceedings of the International Workshop on Risk Analysis in Dam Safety Assessment, Taiwan.

## **Acknowledgement**

We acknowledge the support of NZSOLD, Contact Energy Ltd and Opus International Consultants in making our visit possible. We are grateful to Professor Jan Tai Kuo for his efforts in arranging our itinerary.