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"Performance of Industrial Facilities during 1999 Earthquakes: Implications for Risk Managers"

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INTRODUCTION

A number of damaging earthquakes occurred during 1999 which devastated widespread areas and hit the headlines in the international press. In particular, the Izmit, Turkey Earthquake and the Chichi, Taiwan Earthquake stand out as terrible natural disasters with widespread socio-economic impact.

The effects to the local populations were appalling, and are clearly wholly unacceptable to society. However, the disruption to industry near the earthquake epicentres was also significant, and has been responsible for large financial losses and continuing unsettled local economies.

Following the recent earthquakes EQE engineers visited a large number of industrial facilities affected by the earthquakes, collating data on the performance of the facilities and the damage sustained.

This paper will present some of the key data collected, covering both direct material damage and the associated business interruption. Selected case studies will be presented to illustrate typical experiences. The paper will be concluded by identifying relevant key questions that risk managers should ask to help them prioritise those facilities most at risk and how that risk can be managed through the complex process of cost-effective and systematic earthquake risk management.

BACKGROUND

The experience data collated from the past performance of industrial facilities during catastrophic events is extremely valuable to Risk Managers. EQE International specialise in the gathering, interpretation, presentation and application of such seismic performance data. Over the past 20 years, they have undertaken post-disaster investigations of over 80 earthquakes and some 20 hurricanes. The resulting database contains a vast amount of information documenting good and bad performance of all types of structures, equipment and process systems. A number of lessons have been learned from this information.

Included in this experience data are the recent European and International earthquakes. Eight EQE engineers visited Turkey following the Izmit Earthquake (17 August 1999), and a further six EQE engineers visited Taiwan following the Chichi Earthquake (September 1999). Smaller teams also visited Italy (Umbria-Marche Earthquake, September 1997), Turkey (Adana-Ceyhan Earthquake, 26 June 1998) and Greece (Athens Earthquake, 12 September 1999).

During the above listed investigations, EQE engineers visited many types of industrial facilities, where inspection of the earthquake effects and discussions with the management provided valuable insight into the effects of the earthquakes. Many of the facilities had experienced considerable damage. However, a number had performed very well. To maintain a balanced view of earthquake risk, it is vital to appreciate both good and bad features.

The experience data is used to advise Risk Managers on the distribution and level of risk which they carry, and how to cover this risk through insurance or risk spreading and to identify cost-effective risk reduction measures. This is achieved by focusing on those areas where greatest benefit will be achieved, through improved life safety, reduced damage and enhanced continuity of business following earthquakes.

The implications and lessons learnt from these recent earthquakes can be expressed in terms of the key questions that risk managers should consider when identifying those facilities most likely to be at risk.

PERFORMANCE OF INDUSTRIAL FACILITIES DURING 1999 EARTHQUAKES

The following sections summarise the effects of the Izmit, Chichi and Athens earthquakes of 1999.

Earthquakes of 1999

The principal characteristics of three significant earthquakes which affected both Europe and the Far East are summarised in the following sections. This information will set the scene for more detailed discussions to follow.

Izmit Earthquake, Turkey, August 17, 1999

A 45-second earthquake of Richter magnitude 7.4 (M7.4) occurred in Turkey on Tuesday, August 17, 1999 at 3:01 a.m. local time. The epicentre was approximately 7 miles (11km) south east of Izmit, an industrial city approximately 56 miles (90km) east of Istanbul. The earthquake was felt over a large area, as far east as Ankara, which is about 200 miles (320km) away. Unofficial estimates place the death toll between 30,000 and 40,000. Most deaths and injuries were caused by the collapse of commercial and residential buildings, typically 4 to 8 stories high.

This was one of the strongest earthquakes ever to hit western Turkey and is the largest event on record to have devastated a modern, industrialised area since the 1906 San

Francisco and the 1923 Tokyo earthquakes. The earthquake originated at a shallow depth of about 10.5 miles (17km) and generated strong ground motion (and moderate to high accelerations) in a zone along the Gulf of Izmit of the Sea of Marmara to east of Adapazari. It occurred along the northernmost strands of the North Anatolian fault system, which has produced seven earthquakes with magnitudes greater than 7.0 since 1939.

The North Anatolian fault system is one of the most studied and best-understood fault systems in the world. This earthquake produced spectacular right lateral faulting over at least 37 miles (60km) of the fault. Our team observed offsets greater than 8 feet (2.5) in the region of Golcuk, along the coast of the Gulf of Izmit. Significant vertical offsets along the fault were also observed. In the vicinity of a new automobile assembly plant being constructed east of Golcuk, the vertical offset was about 6 feet (2m). Typically, the ground to the north of the fault dropped with respect to the south. This vertical movement or drop, and accompanying ground settlement and lateral ground flows in soft soils caused extensive and permanent flooding of large areas along the coast.

One of the most spectacular aspects of this earthquake is the damage to the buildings inflicted directly by the faulting. This was the first earthquake with major faulting to strike through heavily populated areas. Many, possibly hundreds of buildings which straddled the trace of the fault collapsed because their foundations were torn apart, undoubtedly causing hundreds or more casualties.

Athens Earthquake, Greece, September 7, 1999

An earthquake of magnitude 5.9 struck Athens, the capital of Greece located on the east of the country at 3:00 p.m. local time on September 7th, 1999. The earthquake struck the northern suburbs of Athens, called Menidi (or Aharne).

This earthquake caused over 100 deaths and left over 100,000 people homeless in the direct aftermath. The costs were estimated at $600 million US dollars with a rise in unemployment of up to 30,000 in the area expected.

The Aegean region forms part of the collision zone between the Eurasian and African lithospheric plates, with a level of tectonic activity which is much higher than other regions of this collision zone - the Aegean is the most active seismic area in the Mediterranean.

High ground local accelerations on the order of 0.2g were recorded in the local epicentral region. The resulting damage affected large numbers of residential areas and industrial facilities. Some damage was also noted to historical monuments.

ChiChi Earthquake, Taiwan September 21, 1999

An earthquake of magnitude 7.6 occurred in Taiwan at 1:47 a.m. on September 21, 1999. The epicentre was approximately 7km NW of Chichi; a small town bordering a mountainous resort area, located 155km from Taipei, the capital. The duration of severe ground shaking was about 40 seconds. The earthquake was felt over the entire island. In the 5 days following the earthquake, there were many aftershocks, several from M6.0 to M6.8.

This earthquake impacted on the high-tech facilities that are a crucial part of the supply chain to the world-wide computer manufacturing industry. Large scale power distribution losses due to the disruption of key substations caused significant business interruption all over the island.

This was the largest earthquake to hit Taiwan in recent history. High ground accelerations on the order of 0.5g to 1.0g were recorded in the epicentral region. Significant ground failures of various types were observed. One of the most spectacular aspects of this event was the extreme amount of vertical ground offset observed along the fault rupture. Offsets measured 3m to 6m in many regions. At the dam in Shihkang, nearly 15m of vertical offset were noted, disrupting water supply to Taichung.

Taiwan is located along a zone of collisional convergence between the Eurasian plate and the Philippine Sea plate. On Taiwan, the zone of collusion is marked by NE-trending zones of thrust and strike-slip faulting. A primary zone of thrust faulting follows the Western Foothills of Taiwan, in close proximity to the city of Kaohsiung on the south and the city of Taipei on the north. This earthquake occurred near the centre of this zone.

Summary of Observed Effects to Industrial Facilities

A number of industrial facilities were visited during the various reconnaissance trips conducted to the above three earthquake affected areas. The following table summarises the effects at each site in terms of estimated loss and business interruption periods and notes relevant seismotectonic information such as the distance to the epicentre and the proximity to faulting. Generic information on building type, age and quality are also provided.

Industry	Type of Facility	Distance to Epicentre/ fault	Product Type	Approx pga Soil Type	Building Types and Age	Estimated Loss (% of Insured Value)	Damage and Business Interruption Effects
Izmit Earthquake, 17 August 1999							
Pharmaceutical	Packaging & Storage	50 km/ 25 km	Sensitive to Contamination	0.15 g Soft Rock	Precast Concrete and Steel, masonry infill	Structures <5% Equipment <5% Stock <5%	10mm racking of PC frames, minor cracking of masonry walls, tank bases cracked. Communications down 1 week with Production stopped 2 weeks, then return to full capacity.
Textiles	Manufacturing	50 km/ 25 km	Inert	0.25 g Soft alluvial deposits	Precast Concrete and Steel, masonry infill	Structures 25% Equipment 30% Stock 20%	Widespread cracking of PC columns, damage to floors and cracking to masonry walls. Widespread equipment damage. No power to site for 2-3 weeks, no production for one month, reduced capacity for 2-3 months.
Chemical	Storage	10 km/ 5 km	Hazardous	0.25 g Alluvial deposits	Masonry building and steel vertical storage tanks	Structures 20% Equipment >50% Stock 80%	Cracking to masonry structures and failure of concrete tank support plinths. No business for 2 weeks, then 25% capacity for 3 months, full capacity after 6 months.
Power	Manufacturing	50 km/ 25 km	Sensitive components	0.15 g Soft Rock	Steel portals with light-weight cladding and masonry infill	Structures < 5% Equipment <5%	Minor damage such as broken windows. No reported interruption to business.

Industry	Type of Facility	Distance to Epicentre/ fault	Product Type	Approx pga Soil Type	Building Types and Age	Estimated Loss (% of Insured Value)	Damage and Business Interruption Effects
Manufacturing	Production & Storage	20 km/ 2 km	Sensitive to Contamination	0.35 g Soft Alluvial Deposits	Precast Concrete with masonry infill	Structures 25% Equipment 35% Stock 20%	Fallen concrete parapets and high level masonry, 50mm racking of PC frames, cracking of columns, secondary damage to ancillary structures and equipment, cranes inoperable, HVAC collapse. No production for one month, reduced capacity for 6 months, ongoing repairs after 9 months.
Petrochemical	Refining and Storage	50 km/ 25 km	Hazardous & Flammable	0.25 g Soft alluvial deposits	RC and steel frames, with masonry infill	Structures 10% Equipment 15% Stock 10%	Cracking of RC elements, silo movement, damage to pipe joints, steel tank roof damage (sloshing), leaking at pipe joints. Facility closed for one week. Return to normal operation within 1 month.
Naval	Manufacturing	10 km/ 2 km	inert	0.35 g Soft alluvial deposits	Very tall Steel braced frame, no cladding	Structures 10% Equipment 15%	Buckling of X braces, elongation of base anchor bolts, rolling of crane, ground subsidence. The facility was not active at the time of the earthquake. Perhaps 6-9 months repairs required.
Automotive	Manufacturing	20 km/	Flammable	0.30 g	Mainly precast	Structures 40%	Widespread structural collapse and

Industry	**Type of Facility**	**Distance to Epicentre/ fault**	**Product Type**	**Approx pga** **Soil Type**	**Building Types and Age**	**Estimated Loss (% of Insured Value)**	**Damage and Business Interruption Effects**
		2 km		Alluvial deposits	Concrete frames with masonry infill, some steel structures	Equipment 25% Stock 10%	cracking, steel connections fractured. Widespread secondary damage to equipment. Extended loss of production during reconstruction works, say 6-12 months.
Packaging	Manufacturing & Storage	30 km/ 0.3 km	Sensitive to Contamination	0.35 g Alluvial deposits	Steel portal frames and braced frames, with lightweight cladding	Structures 15% Equipment <10% Stock 50%	Racking of steel frames, failure of bracing connections, failure of moment connections, no structural collapse. Collapse of masonry fire wall. Equipment generally unaffected. Widespread toppling of stacked product and contamination. No production for 1 week, lost supply for export, full manufacturing capability after 1 month. Repairs almost complete after 9 months.
Petrochemical	Refining and Storage	15 km/ 10 km	Hazardous & Flammable	0.35 g Alluvial deposits	Steel support frames, heavy process equipment, steel storage tanks	Structures 10% Equipment 15% Stock 30%	Collapsed RC exhaust stack, pipework rupture, tank movement, loss of contents, fires following earthquake, other structural damage, racking collapses, loss of water supply, extensive equipment damage. Capacity reduced to 60% for up to 12 months.
Athens Earthquake, 12 September 1999							

Industry	Type of Facility	Distance to Epicentre/ fault	Product Type	Approx pga Soil Type	Building Types and Age	Estimated Loss (% of Insured Value)	Damage and Business Interruption Effects
Food	Production	15km	Sensitive to Contamination	0.25 g rock	Reinforced Concrete and Masonry Infill	Structures 30% Equipment <20% Stock <5%	Damage to older buildings only Pounding between adjacent buildings. Major failure of stairwell walls. Perimeter columns suffered shear failure from short column effects. Misalignment of sensitive machinery from anchorage and sliding failure.
Textiles	Manufacturing	15km	Inert	0.25 g rock	Two Storey Reinforced Concrete with Masonry Infill	Structures 20% Equipment 10% Stock 10%	Cracking of Masonry Walls. Perimeter columns suffered shear failure from short column effects. Misalignment of weaving machinery from sliding.
Construction	Administration	20km	N/A	0.20 g Firm soil	Precast reinforced concrete and Masonry Infill	Structures <40% Equipment <5% Stock <5%	Heavy damage to beam/column connections through bending and shear. Irregular layout, uneven mass and stiffness distribution. Misalignment of sensitive machinery from anchorage and sliding failure.

Chichi Earthquake, 21 September 1999

Industry	Type of Facility	Distance to Epicentre/ fault	Product Type	Approx pga Soil Type	Building Types and Age	Estimated Loss (% of Insured Value)	Damage and Business Interruption Effects
Concrete / Aggregate Plant	Production	<1km	Inert	0.50 g - 1.0 g Soft soil	Steelwork Frames	Structures 20% Equipment >50% Stock <20%	Connection failure of steel frames caused catastrophic failure. Many hoppers/ silos collapsed. (All facilities suffered damage within 40km of epicentre). Anticipated loss of production >6 months.
Port	Storage & Distribution	70km	Sensitive to Contamination	0.1g Reclaimed fill	Reinforced Concrete Buildings	Structures 30% Equipment 40% Stock >50%	Widespread liquefaction of soils caused foundation failure. Sliding/sloshing of tanks caused destruction of tanks. Moderate damage to crane. Expected loss of business >9 months.
Power	Distribution	<10km	N/A	0.5g Soft Soil	Reinforced Concrete with masonry	Structures <10% Equipment 30%	Ground rupture on steeply sloping site caused loss of cables, transmission lines, and busbars. Electrical control equipment toppled. Disrupted power supply about 1 month.
Food	Production & Storage	<10km	Sensitive to Contamination	0.5g Not	Reinforced Concrete	Structures 50% Equipment	Failure of reinforced concrete columns.

Industry	Type of Facility	Distance to Epicentre/ fault	Product Type	Approx pga Soil Type	Building Types and Age	Estimated Loss (% of Insured Value)	Damage and Business Interruption Effects
				known	Frames with infill masonry	unknown Stock >50%	Masonry Wall collapse.

Selected Case Studies of Industrial Facilities Affected

In order to provide the reader with a more in-depth understanding of how the earthquake effects were manifested at individual facilities, three case studies are selected, one from each of the three earthquakes considered.

Case Study No 1 – Production Mill, affected by Izmit Earthquake of 17 August 1999

Description

The southern coastline of the Bay of Marmara, in North Western Turkey, lies only a few kilometres south of the North Anatolian Fault System, which runs under the sea at this point. The coastline is comprised of alluvial and marine deposits, forming a relatively flat, low-lying strip at the feet of the mountainous region to the south.

Several towns and villages are located along this coastline, with a large number of industrial facilities located along the main road in between the towns. Many of the facilities along this coast experienced considerable damage and disruption during the Izmit earthquake.

One such facility was a production mill, which covers a site over 200,000 m^2 and includes many main buildings. Several of the buildings designed to the 1975 Turkish Code experienced damage, while others were unaffected. The structural damage was responsible for secondary damage to process and ancillary equipment. A major extension to the facility, designed to the 1995 Turkish Code and under construction during the earthquake suffered light damage. However, the construction programme for this facility was delayed as a consequence of the earthquake.

Site Input Motion

The site under study is located about 30 km from the epicentre, and less than 5 km south of the western end of the fault rupture. Taking into account the soil conditions at the site, which are alluvial sands and silts, with a high water table, peak ground acceleration of about 0.3 g is estimated.

Damage to Structures

The structures designed to the 1975 Turkish code suffered general damage, more concentrated in some buildings than others. In particular, the mill buildings, which comprised reinforced concrete frames supporting precast concrete roofs and mezzanine floors, experienced permanent frame movements, with the formation of plastic hinges at the lower end of the main load-carrying columns.

These structures also suffered heavy damage to the cladding systems, which included unreinforced hollow-core masonry, cellular masonry (ytong) and heavy precast concrete parapets. The parapet units weighed as much as 12 Te and were ineffectively restrained by small diameter bent reinforcement bars which had been incorrectly installed at the time of construction. The various unreinforced masonry panels suffered cracking or collapse due to amplified shaking up the height of the building. Since the earthquake, the site has implemented a programme of parapet removal and replacing walls with lightweight cladding.

There was considerable secondary structural damage due to the collapse of the precast concrete parapets. In particular, low level workshops were destroyed, along with offices, which were fortunately unoccupied. The switchgear and transformer rooms were also impacted by falling parapet units.

The foundations of the mill buildings performed well, with no significant movement or damage. While the soils are poor, the foundations to the building comprised of a thick reinforced concrete raft, partly to handle operation vibrations from the mill process. The raft will have spread any bearing pressures to very low levels, and will have prevented differential movement of individual columns.

Other buildings, such as the boiler house, experienced almost no damage. This is attributed to their low height and the lightweight steel roof structures.

The new building on the site, whose structural frame was complete at the time of the earthquake, experienced only light damage. The structure had been designed to the 1995 Turkish code and since the structure was partially completed, the mass of the building was lower than assumed in the design. Progress on the construction of the new building was halted for about 1 month, but the final disruption to programme was about 2 months.

Damage to Plant and Equipment

There was complete loss of power to the site for the first day, due to damage to local electricity supply infrastructure. However, the site emergency diesel generator was then started, and this provided power for essential systems such as fire fighting, lighting and immediate repairs.

The mill units themselves were undamaged due to their rugged foundations and their normal design to resist vibration loading. The mills are bolted to cast-in steel anchor plates. Similar good performance was observed for most of the process machinery, due to their inherent ruggedness. Minor damage was noted to other items of equipment.

The secondary damage caused by toppling cladding included equipment and storage items. While not badly damaged, the electrical switchgear and transformers were affected by impact debris and heavy damage to their structural enclosures. Falling material impacted process tanks causing buckling and loss of pipework connections. In the workshop areas, there was heavy damage to lathes, drills and other items.

Overhead cranes were also affected. The structural movements in the mill buildings displaced the crane rails relative to each other, causing damage to the corbels supporting the crane beams. The movement also jammed the cranes in place, making movement difficult. In the workshop, the collapsing parapet completely destroyed a small overhead crane.

Some HVAC ducting collapsed during the earthquake. The collapsed ducts had then impacted the fire sprinkler system, rendering it inoperable. Emergency repairs to reinstate the fire fighting system were necessary, to guard against the outbreak of fires.

At the new water pump house, there was no damage to the lightweight steel frame, but the 5 metre diameter, 8 metre tall reinforced concrete water storage tanks experienced sloshing of their contents. This sloshing was apparently sufficient to overcome about 2 metres of freeboard, allowing water to spill out onto the adjacent pump house roof.

Business Interruption Effects

Business interruption at the site was limited due to the good performance of the process equipment. The converting processes were recommended after about 4 days, and the mills were restarted about 3 weeks after the earthquake. Completion of structural repairs took about 6 months in total, with some disturbance to production during that time.

Commissioning of the new mill unit was delayed by 2 months, due to both loss of manpower and equipment (cranes etc.) immediately after the earthquake, and due to general labour and material shortages in the months following the earthquake.

Raw materials are imported mainly by road, but raw pulp comes in by sea. Minimal disruption to such supplies was experienced. All export is made via truck, to Turkey and the middle east. Some stock held on site was damaged by exposure to the elements after cladding was lost.

Case Study No 2 – Production Facility, affected by Athens Earthquake of 12 Sept. 1999

Description

The production facility is located within a heavily industrialised area of Athens. The facility contains three main buildings being the old production building, the new production building and the office building. The old production building and the office building were the only structures at the site to suffer significant damage.

The old production building, constructed in 1975, is a two storeys high, reinforced concrete building 80m long by 42m wide and 10m tall. The building is made up of a series of six independent structures with movement joints between each one. The building was observed to have a regular layout of columns and beams supporting a reinforced concrete slab. Internally, the structure does not have any other structural elements other than the two staircases located at each end of the building, which have perimeter reinforced concrete walls. Externally the building has masonry infill panels between the outer columns, with windows running along the length of the building.

The office building and the new production building were similar in construction to the old production building. However the office building had been constructed in the early 1980’s and the new production building in 1993.

The quality of the original construction was found to be good. It should be noted that the buildings would have been designed to the version of the code current to the time of the design.

Input Motion

Based on the proximity of the site to the epicentre and the levels of damage noted it is judged that peak ground accelerations in the order of 0.2 to 0.3g at the site.

Damage to Structures

The buildings had not been designed to the 1995 New Greek Aseismic (NEAK) code, but to the older less onerous codes. This would result primarily in a smaller number of shear/confinement reinforcement links in columns and beams being present. The level of input motion considered within the original design is also likely to have been less onerous.

The old production building suffered a number of failures to the main reinforced concrete members primarily around the perimeter of the building. The reason for these failures was judged to be due to short column effects. The use of short columns does not allow the development of adequate flexibility in the structure, and forces high shear loads to be transferred through the stiffer short stocky columns. The columns have not been designed to accommodate this magnitude of loading and suffered sudden brittle shear failure patterns. The majority of the failures were in the perimeter columns. The limitations of the original design codes are apparent, in that the amount of links present in the short columns is far lower than would be used in modern construction as it has been recognised that that the original designs used do not perform in an adequate manner.

The reinforced concrete walls around the perimeter of the stairwells suffered similar major shear failure. It is judged that the walls acted (unintentionally) as a very stiff element in the load path, and consequently were subjected to high loads.

A number of the external and internal masonry walls cracked. The majority of the failures were as a result of out of plane flexure rather than in plane shear loading. Typically, these were a result of the wall being discontinuous between main columns. However in-plane shear cracking was observed in some panels.

It is noteworthy that much of the damage was caused by unfavourable interaction between what were principally non lateral load resisting members and the main structural frame.

Similar damage was noted to the office building.

Damage to Equipment and Stock

The majority of equipment items performed well, with limited production starting after a few days. A number of unanchored items slid across the floor, including compressors and air conditioning plant. The major concern was for a large critical production machine over 50m long, which had moved as a result of having a limited anchorage and no seismic provisions in its design. The machine had bowed sufficiently to prevent movement of the internal steel conveyor. In order to reintroduce the machine to the production line, the production machine required realignment, and full checks on the internal mechanical components.

Business Interruption Effects

Repairs were started almost immediately to the building to safeguard the building and prevent any further degradation following aftershocks. These involved shoring up the beams adjacent to the damaged columns and applying straps to the main columns. The majority of the columns required the injection of an epoxy resin to seal the shear cracks that have opened up. Other columns require a more thorough retrofitting.

Alignment of the displaced machinery was by specialist technicians who had to be flown in from overseas which both increased the time to start production and the costs of doing so.

Loss of the office building severely interrupted the administration process with significant delays to orders.

After one month 60% of production capacity had been regained with full production regained after three months.

Case Study No 3 – Port Facility, affected by Chichi Earthquake of 21 September 1999

Description

Taichung is a large modern city located on the west of central Taiwan. Taichung harbour on the west coast consists of a number of main piers. Both the structures and plant on one of the piers had suffered significant damage during the earthquake even though it was a considerable distance from the epicentre. The pier is constructed from infill (much of which appeared to be fine sands) retained by a continuous piled wall. Along the length of the pier were a number of wharves linked by road and rail.

There were a number of buildings, storage facilities and major plant items on the site. The buildings are generally noted to be either warehouses or administration buildings. These are of varying construction and but it is likely that they date to the time of construction of the pier. There is a number of tanks and silos used to store a variety of bulk goods. They are either constructed from reinforced concrete or steel. A number of cranes were located on site mainly running along the side of the wharves. In conjunction with the cranes there are a number of conveyor and transport systems for the unloading and loading of cargo.

Input Motion

Based on the distance of the site to the epicentre, about 70km, and the levels of damage noted to other structures in the area it is judged that peak ground accelerations in the order of 0.1g at the site.

Damage to Structures

The main cause of damage noted to structures was the failure of their foundations caused by widespread liquefaction at the site. Liquefaction had caused significant settlement characterised by the presence of large sink holes of up to 20m in diameter and ejection of fine material. Some minor rotation of the quay walls also evidenced causing settlement behind the walls of up to 2m.

Liquefaction at one of the warehouse buildings had resulted in complete loss of support from under the shallow pad foundations. The warehouse was a reinforced concrete portal structure with an arched roof and concrete panel cladding. It was judged likely that demolition of the structure would be required given the gross deformation and loss of foundation support.

One other smaller building had dropped and tilted significantly into one of the sand boils. Again demolition was considered likely.

Damage to Plant and Equipment

A significant failure of a group of tanks containing liquids had occurred away from the area affected by liquefaction. It was observed that these unanchored tanks had slid up to 50mm. This had severed some attached piping and it may be possible that more underground lines were severed. Through sloshing and rapid draw down, the tanks had collapsed. It was noteworthy that some adjacent tanks that were anchored were structurally intact although some local buckling of the tank walls had occurred indicating the high forces involved.

Rail lines were noted as being misaligned due to liquefaction and road/hard standing surfaces were severely damaged.

Overhead conveyor equipment had suffered damage with loss of foundations to some sections. One section almost came off its bearings but had been caught on the column support crossbeam and had not toppled.

It was noted that the weld around one of the bracing members had pulled straight out thus disabling the crane until repairs were undertaken.

Business Interruption Effects

Even though the site was remote from the epicentre of the earthquake this port facility had many structures and plant which were severely affected causing long term business interruption.

The backfill used at the site was extremely susceptible to liquefaction and consideration would need to be given to its suitability and stabilisation for future re-construction.

Those structures which had shallow pad foundations fared poorly during the earthquake with almost complete destruction noted to some requiring demolition and replacement. It is estimated that the lead in time would be greater than six months before they can be replaced with an estimate of up to 2 years possible.

Lack of anchorage to tanks was probably responsible for their failure and only complete demolition and replacement would be possible.

Lessons for Risk Managers taken from Case Studies

Using the above information, coupled with experience of other earthquakes around the world, key lessons are extracted under several major headings. The authors believe that consideration of these lessons are invaluable for managers dealing with facilities in areas of high seismic risk.

Facility Location

1. Building on or near faults typically increases seismic risk to an unacceptable level. Ideally, a minimum distance of 10km to a major active fault should be ensured. However this in itself does not remove the risk it only reduces it.
2. Building on soft soils, typically found along coastal regions or rivers, can result in increased levels of damage. If poor foundation conditions are unavoidable, suitable foundations are required.
3. Following a major earthquake, road and rail systems may be heavily damaged. Facility locations that are dependent on a limited number of access routes should be avoided or should have emergency preparedness plans.

Building Type and Condition

1. For the countries presented, buildings constructed post 1980 present a lower seismic risk, due to continued improvements in code design requirements. Pre 1970 structures should be treated with extreme caution.
2. Steel framed structures typically avoid collapse, but extensive damage is possible, particularly at welded locations.
3. Reinforced concrete structures are very reliant on the quality of construction. Good performance is achievable, but if the pedigree of construction is questionable, then the seismic risk may be high.
4. Precast concrete structures are typically very high seismic risks, due to the poor connectivity between structural elements, and should generally be avoided.
5. The potential for adverse interaction between stiff cladding and the main reinforced concrete frame is often overlooked during the design.

Equipment Arrangements

1. Rugged anchorage of equipment items to adequate foundations is central to minimising damage to processes, which in turn will help reduce business interruption.
2. Potential interaction movement/pounding between adjacent items of equipment should be carefully considered since this can result in secondary damage due to impact, cable damage and pipework leakage.

Storage Arrangements

1. Storage racks should be adequately braced and anchored. Heavy items should be stored on lower shelves and items should be restrained on shelves by stops or chains.
2. Storage tanks should be anchored at their base and flexibility should be provided to pipework connections, to avoid rupture and loss of contents.
3. Care should be taken not to stack pallets too high, since toppling may damage or contaminate finished products. Typically, stacks of 2-3 pallets high would remain stable, but depending on geometry.
4. Heavy items should be stored individually, and not stacked, with restraints as necessary to prevent movement. The potential for secondary damage to adjacent essential equipment should not be overlooked

Firefighting Capability

1. Firefighting systems should be self-contained with respect to their function after the quake and should not be totally reliant of public supply for either power or water.
2. Pipework should be adequately braced and sprinkler systems designed to avoid accidental damage.

KEY QUESTIONS FOR RISK MANAGERS

When the past performance of industrial facilities is studied, EQE believe that the apparently wide ranging business functional implications can effectively be addressed through consideration of five main questions, for which general information, at least, should be readily available.

If each of these questions is investigated, the risk manager should rapidly be able to build up a feel for his likely level of seismic risk exposure at the facility in question. However, the extent of the risk profile for the facility thus depends on the depth of the investigation performed.

The flow chart on page 21 is intended to be a quick easy to use screening tool for risk managers to assess if the facility is at risk from seismic hazard. The chart is intended to help the risk manager ask the following questions.

Question: Where is the facility?

Armed with this basic knowledge, the risk manager can use anecdotal information or readily available reference texts to decide if earthquake risk is relevant to the location. There may even be records at the site of past earthquakes. If in doubt, a quick question to the site manager typically provides the necessary information. All of the sites discussed in this paper are in regions of historical earthquake activity, and there was little excuse for not being prepared.

Question: How is it built?

Based on EQE's observations, the way the facility is developed and built is of paramount importance to deciding the level of risk. Older facilities, or those where there has been a history of poor maintenance, are particularly exposed. A common problem area is where existing sites have been acquired, particularly for facilities with lacking records or details. The risk manager should check the scope of any due diligence study. The more information obtained on this subject, the better.

Question: What type of facility is it?

The performance of different key process equipment facilities contributes to the overall risk. For example, while structural damage often occurs, it is rarely responsible in itself for major business interruption. Large business interruption losses are more likely to occur due to failure of process equipment that requires a long lead-in time for replacement. Business interruption can also be aggravated by failure of raw material storage arrangements, leading to loss of market share. Hence, seismic considerations to key process items are essential as production facilities can be at very high risk. Storage or distribution centres should be treat differently.

Question: What product does it handle?

If the facility handles toxic or hazardous materials, then the risk can increase dramatically, due to potential for escalation of loss and injury following the earthquake through fire, toxic release or explosion. Facilities may be involved in high value products e.g. pharmaceutical or advanced electronic products, where loss of production capacity and/or stock could be very costly. Facilities relying on single source local supply facilities are also notable for being very high seismic risks.

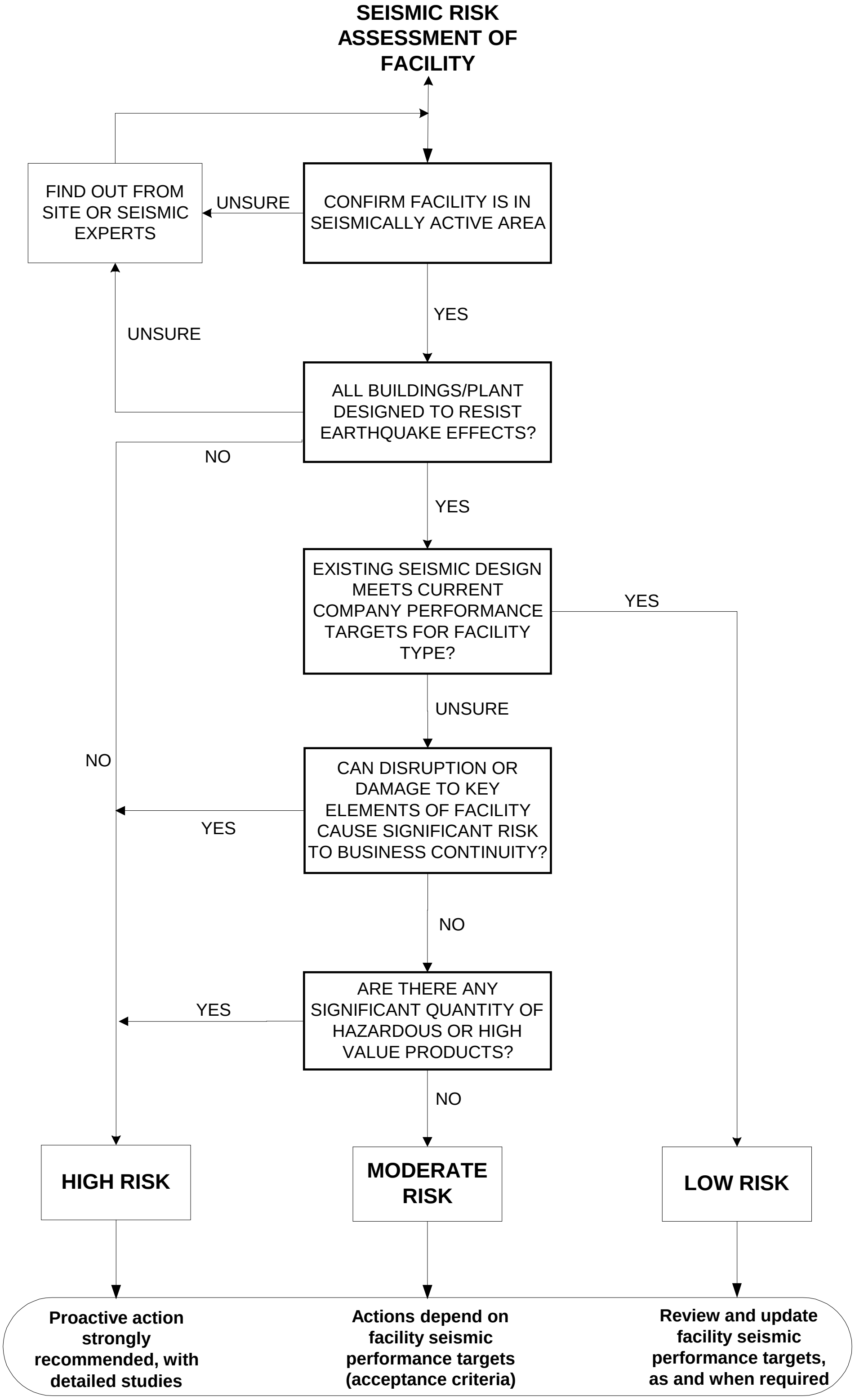
Question: What action should be considered?

The risk manager has a number of approaches that can be used to manage the corporate risk posed by the earthquake threat to the facility or inter-related facilities. Traditionally managers have transferred these risks through a well designed insurance programme supplemented as required by conventional safety and loss prevention/ control programme. Another approach is to implement a seismic risk reduction procedure to proactively manage the issue by determining the actual risk and undertaking positive action to reduce it. The third option is to combine the two above methods to provide the most informed and cost effective programme of earthquake risk management.

CONCLUSIONS

The implication of the 1999 earthquakes for risk managers is that industrial facilities within seismically active zones are at risk from severe disruption and that in most cases the risk from the earthquake is underestimated. When the past performance of industrial facilities is studied, EQE believe that the apparently wide ranging implications of earthquake risk can effectively be addressed through consideration of five main questions, for which general information, at least, should be readily available.

Armed with this information the risk manager is in a stronger position to manage the corporate risk posed to the business. Through insurance or risk spreading and to identify proactive risk reduction measures the risk manager focusing on those areas where greatest benefit will be achieved, through improved life safety, reduced damage and enhanced continuity of business following earthquakes.



Seismic Risk Assessment Tool – Key Stages