TAIWAN'S 921 QUAKE AND WHAT IT MEANS TO THE SEMICONDUCTOR INDUSTRY

Brian Sherin, CSP, EORM, Inc. and Stacy Bartoletti, PE, Degenkolb Engineers

INTRODUCTION

At 01:47:19 local time on September 21, 1999 a magnitude (M) 7.6 earthquake occurred near the town of Chichi (in Nantou County). The earthquake occurred along the Shungtung and Chelungpu faults as shown on Figure 1. These faults are produced by the intersection of Ryukyu and Manila trenches with the continental margin of Asia (Figure 2).

Within a week of the 921 Earthquake (as it was dubbed by the Taiwan media), Semiconductor Equipment and Materials International (SEMI) dispatched a team of seismic and environmental health and safety (EHS) professionals to Taiwan to survey and document the impacts of the earthquake on the semiconductor industry. The purpose of the investigation was to evaluate how the semiconductor industry fared, with the intent of using this opportunity to learn valuable lessons in preparing for inevitable future earthquakes.

The SEMI team observed a total of five semiconductor facilities, interviewed EHS, Risk, and Facilities managers, and compiled reports on the condition of many other facilities from other industry service providers working at the Hsinchu Science-Based Industrial Park (HSBIP). During the facility evaluations the team observed the production equipment in the cleanrooms, subfabs, and support utilities.

THE QUAKE

Strong ground shaking near the epicenter of the earthquake lasted approximately 30 seconds with recorded peak horizontal ground accelerations ranging from approximately 60 to 100 percent of gravity. One accelerometer, located 10 km from the fault, recorded peak ground accelerations (PGA) of 0.34 g (333 cm/sec^2) in the vertical direction, 0.61 g (598 cm/sec^2) in the North/South direction, and 0.98 g (960 cm/sec^2) in the East/West Direction [1,2]. The ground motion in the epicentral region produced up to an incredible 10 meters (32.8 ft.) of vertical displacement.

Following the main shock, there was a substantial sequence of aftershocks. This included at least four strong aftershocks registering in excess of M6 within the first 24 hours of the main shock. There were another three aftershocks in excess of M6 over the next four days and even another M5.6 event on 22 October 1999, centered approximately 50 km southwest of the Chichi epicenter.

The impact of this earthquake in human terms was substantial. The estimated number of fatalities is 2,400, with approximately 10,000 injured and in excess of 100,000 rendered homeless. Had the quake occurred during the daytime, casualties in the epicentral region may have been considerably greater because of the destruction of workplaces and schools.

Reports of damage to residences occupied much of the local and international media. Over 60 construction contractors (including the chief executives of some very large companies) were detained by authorities, had passports seized, and/or had assets frozen as a result of structural failures that resulted in fatalities. However, the vast majority of structures withstood the ground motion, suffering damage but providing adequate life safety protection. Current estimates of actual physical damage are placed at US$8 billion.

ECONOMIC EFFECTS

The vast majority of the microelectronics industry in Taiwan is located in the Hsinchu Science Based Industrial Park (HSBIP) in the city of Hsinchu. The science park is located approximately 110 km north of the earthquake epicenter as shown on Figure 1. Several of the wafer fabrication facilities are equipped with accelerometers that are used to trigger shutdowns of hazardous gas delivery. Based on acceleration data from these devices, the PGA in the park was on the order of 0.10 g (98 cm/s2) to 0.15 g (147 cm/s2). Figure 3 is a map of the HSBIP with recorded PGA and locations shown.

The Science Park is home to over two dozen semiconductor plants and Taiwan's factories account for more than half of the world's semiconductor contract manufacturing (i.e., wafer foundries) and more than ten percent of the world's silicon area processing capacity. [3] In addition Taiwan produces 80% of the motherboards used in PC manufacturing, and most of the computer keyboards and mice, and a large portion of the video display terminals.

The major impact on the industry was not due to damage to the facilities or the process equipment. Rather, interruption of electrical utilities resulting from damage to Taiwan Power's electrical grid caused electrical outages and rationing for almost two weeks. Although the HSBIP was given priority, power was still very unreliable. While semiconductor facilities have emergency power generation capacity, this is intended for emergency purposes (e.g., running exhaust fans, lighting, life safety systems, etc.) and does not provide a capability to actually run production.

According to local press reports, the overall impact to semiconductor companies was estimated in excess of NT$12.5 billion (US$400 million), eight days after the quake. Of this loss, the actual asset damages (e.g., facilities and equipment) will only be about 5% of the total; the rest will be due to business interruption. In addition to business interruption, there were significant concerns about the possible loss of market share. There was a very real fear that customers, in need of the products produced in Taiwan might have to go to competitors located in other parts of Asia (e.g., Singapore, Korea, etc.). When Taiwan's stock market resumed trading, one week after the quake, financial concerns about the overall impact caused all semiconductor manufacturer stocks to drop the full 2.5% allowed by the stock market each day for three days.

Furthermore, this interruption came at a time when the price of dynamic random access memory (DRAM) was finally starting to rise after the 1997-98 industry downturn. Interruption of the supply of devices, when the supply was already beginning to get tight, caused prices to spike. At the end of June, 64 megabytes of memory was selling for about US$40 on the spot market. One week after the earthquake, prices in some cases were four times that level, hitting the US$160 mark, and finally settling at about US$80 one month after the quake. [4]

The ripple effect to the makers of electronic products, such as personal computers (PC), was also considerable. Companies like Hewlett-Packard announced that fourth-quarter growth would be affected because of the earthquake. CEO Carly Fiorina said, "we said revenue growth would likely be in the 10-13 percent range...With the Taiwan disruption, which effects, most especially, our PC business, we don't think we'll achieve the high end of that range and are more likely to come in closer to the low end." In the weeks following the quake, major PC manufacturers had to significantly revise earnings forecasts. For example, Dell Computer revised its third quarter earning estimate by US$75M, mostly due to the increased RAM prices caused by shortages resulting from the 921 Quake.

PHYSICAL EFFECTS ON THE SEMICONDUCTOR INDUSTRY

Because of the distance of the HSBIP from the epicenter, much of the acceleration was attenuated. As expected for accelerations in the 10%g range, there was very little structural damage. No damage to the exterior window wall systems in the steel frame structures was observed. Similarly no major damage other than minor cracks on the interior partition walls was either reported or observed. Some minor cracking and spalling of the exterior tile on the reinforced concrete structures was observed as shown in Figure 4. This damage was generally caused by the working and cracking of the concrete frame and concrete or masonry infill walls behind the tile facade and was found to be very minor on most buildings.

Reportedly, one complex in the HSBIP did experience some significant damage. Apparently this facility is located on the site of an old lakebed with poor soils. All of the buildings at this site are built on deep pile foundations. Most of the other buildings in the HSBIP are built on shallow spread footing and mat foundations. As reported by the Facility Manager of this site, the seismic joint between the office tower and the lower rise fab support building had significant pounding damage. Unfortunately, this damage could not be observed first hand. However, second-hand reports indicated that there was clearly observable damage to the concrete along the roofline of the support building, with steel rebar seen jutting out from the damaged concrete. It could be presumed that the structural frames in the office tower and fab also experienced some level of structural damage. Unfortunately, this facility did not have an accelerometer on site to record the peak ground accelerations during the earthquake. This information would have been very useful in evaluating the amplification of the rock acceleration caused by the soil conditions at the site.

Very little physical damage or movement of process or facilities equipment was observed. In fact, this investigation team only found one or two pieces of equipment that appeared to move at all during the earthquake. This lack of movement and damage is primarily attributable to the low level of acceleration observed at the site. In most cases that were observed, equipment was either not anchored or was not anchored appropriately. It was reported by other parties, that many pieces of equipment in one facility moved an average of 1 to 3 cm. Furthermore, there were some process tools that suffered damage to the leveling feet on which the chassis stands. These feet are attached to the tool chassis by threaded rods. If the chassis is raised to the point where these rods are only threaded by 2-3 turns, they can be ripped out if the tool shifts laterally. Figure 5 shows an example of a foot that was torn from the chassis into which it was attached. It was observed in the facilities that were visited, that this practice of raising the tools up to the maximum height on these feet is commonplace. In one situation it was even observed that a tool was raised a further few inches by inserting several metal shims between the foot and the floor.

The facility where this tool movement was observed is the same facility that experienced some damage at the seismic expansion joints and potentially some damage to the structural system, as reported above. If equipment in this facility did move, it can reasonably assumed that this facility saw ground accelerations significantly higher than that of most other facilities, presumably due to amplification by the poor soil conditions.

Other sources reported incidents of physical displacement of equipment. One instance involved shifting of a large equipment in a probe test cleanroom up to one meter across the floor. This equipment was located on the upper floor of a seventeen story office tower. In another instance, the ceramic mounts supporting the source chamber in an ion implanter broke, causing the source chamber (which contains hazardous materials) to topple. [5]

Most facilities experienced damage to the internal quartz components of vertical diffusion furnaces (VDFs), in some, more than 90% of VDF quartz chambers were damaged. VDFs are tall pieces of equipment, in some cases exceeding 3 meters in height. It is postulated that there was a sufficient amount of internal shaking to crack the quartz, both at the bottom (which rests on a baseplate) due to stress, and at the top of the tubes due to impact.

The other category of equipment that was reported to have been very susceptible to the shaking was photolithography steppers. Because resolution of the circuit geometry is so fine (e.g., 0.18-0.25 μm) these devices must be very stable and the optics must be protected from vibration. Many of these systems were down because of the need to re-calibrate the optics. Steppers are a critical path item in the production process and interruption in their ability to operate effectively interrupts production.

Similar to production equipment, very little damage to the piping, duct, and fire suppression system was observed. It was reported that several facilities had some breakage of the fire suppression system piping resulting in some amount of water damage. Reportedly, at one facility a photolithography stepper was a total loss from water damage and another was significantly damaged, but recoverable. [5] Sprinkler damage can occur when sprinkler pipes are not adequately braced and the pipes either flex too much, producing leaks at fittings, or if the sprinkler head strikes more substantial objects, and thereby discharging.

There was surprisingly little damage reported regarding the loss of work in process (WIP). None of the facilities reported that containers of wafers were damaged due to falling from storage racks or stockers. However, numerous wafers that were in process equipment at the time of the quake were lost (due to loss of power and breakage). Only Taiwan Semiconductor Manufacturing Corporation (TSMC) reported actual figures for all of their fabs — 17,000 wafers had to be scraped because of the quake. This is equivalent to about 50% of the monthly production of a typical large fab.

There were few, if any, hazardous material discharges caused by the earthquake. There were no reports of hazardous gas releases and reports of only small quantities of liquid spills. All of these were easily controlled. One fab that had several liquid workstations (i.e., wet sinks) lost a substantial amount of the liquids in the chemical baths. However, the liquid was not released into the cleanroom or sub-fab. Apparently, the shaking may have caused the wet sink drains to open, thereby draining the material to the plant's acid waste neutralization system.

The performance of hazardous gas systems in earthquakes is always of key concern. Many, but not all, facilities in the Science Park are equipped with seismic shutdown systems that are designed to interrupt flow of all of the HPM gases at the source if a set-point is exceeded. All of those that had seismic switches reported that they activated and shutdown gas flows. The typical setpoint observed in these facilities was very low — 0.05-0.10 g (49-98 cm/s^2).

Facilities support equipment also came through the event intact. There were no reports of losses of exhaust ventilation, scrubbers, DI systems, boilers, chillers, and so on. However, the same facility that suffered some structural damage and equipment movement, also suffered a fire in the aftermath of the earthquake. Approximately 40 hours after the main shock, a fire broke out in the emergency generator in the utility support building. The CO_2 flooding extinguisher was not sufficient to control the fire and it was finally brought under control through the use of a large number of portable fire extinguishers. The fire destroyed the generator and transformers.

SEISMIC PROTECTION NEEDS

Little physical damage occurred to the equipment in the HSBIP, which was primarily due to the relatively low acceleration experienced in the area. Based upon the recorded PGAs, reports that equipment on upper floors moved (where acceleration is amplified), and past experience, it is estimated that the level of acceleration required to overcome friction between a piece of equipment and the supporting floor may be on the order of 0.20 g (196 cm/s^2). Since the recorded PGA was in the 0.1g to 0.15g range, the local acceleration was apparently not large enough to overcome friction between the equipment and supporting floor.

The accelerations that were observed in the HSBIP are very close to what would be expected from a M7.6 earthquake that occurred more than 100 km away. The relationship between distance from an earthquake fault rupture, the magnitude of the quake, and the PGA can be plotted in what is known as an attenuation diagram. Figure 6 shows an idealized attenuation diagram. The contours from an actual earthquake will be much more irregular, because of inhomogeneities in the earth's crust, non-uniform movements of the fault, and local soil conditions. In addition, the near-field effects can be affected by the depth of fault rupture, the direction of the fault movement, etc.

Based on this, two obvious questions come to mind: (1) Can a comparable sized quake occur nearer to the Science Park, and (2) what magnitude of acceleration might be expected in such an event? In answer to the first question, there has been a comparable sized event in Hsinchu in recent history. On 21 April 1935, a M7.1 quake struck south-southeast of Hsinchu. The epicenter of that quake was about 20 km from Hsinchu, and that fault comes within 15 km of the city. Based on the "idealized" attenuation diagram, the PGA from a M7 quake would be about 35% of gravity and a M7.5 would be close to 40% of gravity. In addition, these values could be considerably amplified by local soil conditions. Furthermore, there are likely other faults located around the Science Park capable of producing sizeable accelerations. As a result, the industry must closely look at the practices and designs being used to reduce the risk of damage in the future.

The vast majority of the buildings in the HSBIP were constructed after 1980 and appear to have modern structural lateral force resisting systems. Typical construction in and around the HSBIP appears to be either concrete frame or steel frame. The concrete frame buildings generally appear to be the older low rise office structures and some support utility buildings. These buildings are constructed with concrete columns and beams and either concrete or unreinforced masonry exterior walls. Lateral resistance is generally provided by either concrete shear walls or concrete moment frame action. Many of the new tall office structures in the HSBIP appear to be steel moment frame structures with lightweight, exterior window wall systems.

Most of the fab buildings are constructed at ground level with concrete first stories and steel framing above. The first story is generally a concrete structure with heavy concrete shear walls and a stiff open waffle slab at the second floor to support the fab area. Framing above the waffle slab usually consists of steel columns and braced frames with long span deep trusses to create a large open area for the clean room facility.

From a structural standpoint, most facilities appear to be adequately designed. However, unless a structural engineer with experience in seismic design and mitigation performs an evaluation of each facility and is given access to the as-built structural drawings the likely performance can only be based on visual observations and assumptions regarding typical construction practices utilized at the time of construction.

The majority of the process tools observed were either unanchored or had inadequate anchorage. The exception to this was that almost all hazardous materials storage/dispensing systems that were observed appeared to be well anchored. This included gas cabinets, bulk chemical distribution systems, and bulk gas systems. Inadequate anchorage could generally be categorized as:

- inadequate anchorage feet,
- poor configuration of anchorage feet,
- poor connection of the anchorage feet to the unit,
- or poor connection of the anchorage feet to the access floor system.

The correct design for seismic anchorage of process equipment should ensure that: 1) the equipment is designed to resist the anticipated seismic loads, and 2) the equipment is anchored to structural elements of the building to prevent sliding, overturning, or impact. The Semiconductor Equipment and Materials International (SEMI) organization has published the Safety Guidelines For Semiconductor Manufacturing Equipment (SEMI S2) since 1991, and all of the editions have included guidelines for seismic protection. The scope of SEMI S2 applies to equipment used to manufacture, measure, assemble, and test semiconductors. The guideline is intended to be employed by both the equipment supplier and the user as a reference for EHS considerations.

In the latest revision of SEMI S2 (adopted by the voting membership in October 1999), the stated goal of the seismic protection section is: “equipment should be designed to control the risk of injury to personnel, adverse environmental impact, equipment and facility damage due to movement, overturning, or leakage of chemicals (including liquid splashing), during a seismic event. The design should also control equipment damage due to failure of fragile parts (e.g., quartz-ware, ceramics) during a seismic event.”

SEMI S2 advises that equipment containing hazardous production materials (HPMs), should be designed to withstand horizontal forces of at least 94% of the equipment weight (i.e., 0.94 g [921 cm/sec^2]), and equipment that does not contain HPMs, 63% of the weight of the equipment (i.e., 0.63 g [617 cm/sec^2]. These criteria apply not only to the actual process equipment, but also to subassemblies, such as transformers, vessels, power supplies, vacuum pumps, monitors, fire suppression components, and other items of substantial mass that are attached to the equipment. The criteria also specifies that the design recommendation for determining the force to resist the overturning moment should be based on a value of 85% of the weight of the equipment. This design criteria is based upon the non-structural design requirements of the 1997 Uniform Building Code (UBC) (section 1632.2), which was revised based upon lessons learned from the 1994 Northridge earthquake. [6]

The equipment manufacturer is requested to also provide the following important design information to the end-user:

- A drawing of the equipment, its support equipment, its connections (e.g., ventilation, water, vacuum, gases);
- The type of feet used and their location on a base frame plan drawing
- The weight distribution on each foot;
- Physical dimensions, including width, length, and height of each structurally independent module. These are components that will react to seismic loads by transferring substantially all of the loads to its own anchorages, as opposed to transferring the loads to adjacent modules;
- Weight and location of the center of mass for each structurally independent module; and
- Acceptable locations on the equipment frame for anchorage.

With this information, the end-user has the responsibility to ensure that the equipment anchorage is designed and implemented to withstand the expected forces for their location. Providing this information to a licensed seismic engineer will ensure that appropriate anchorage is designed.

To have a complete system for the seismic anchorage of production equipment, the design and installation of the access floor system must also be considered. This activity should be performed by the end-user's facilities engineering department, or by a licensed consulting engineer. Since most production equipment is mounted directly on top of the access floor system and anchored to the floor for horizontal loading, the access floor must to be able to transfer this load to the waffle slab below. The original design and installation of the access floor system should include a requirement for horizontal loading. This is an extremely critical issue, since failure of the access floor system during a seismic event may result in significant damage to all production equipment mounted on the access floor regardless of how well the individual tools are anchored. It is recommended that access floors be designed and tested for lateral loading to ensure proper performance.

Another vulnerable system in the facility is piping and ductwork. In older facilities these were generally supported on individual pipe hangers or small pipe racks with no seismic bracing. In the newer facilities, the sub fab was generally provided with a continuous steel pipe support frame (e.g., constructed of either structural steel or strut framing) that was supported below the concrete waffle slab and attached to the concrete columns in the sub fab. This framing system is generally designed to support the piping and ductwork and deliver seismic loads directly to the building structural system. Most pipes were supported on this type of system. However, where pipes were supported on individual hangers or trapeze supports, very little if any bracing was observed. In addition to the lack of seismic bracing, it was also observed that several facilities had allowed some amount of poor pipe installation practice, which included hanging pipes from other pipes.

Traditionally, the responsibility for design and installation of seismic bracing for pipes and ducts resides with the installing contractor to meet recognized standards. By necessity, the standards are general in nature and cannot account for every situation or material. In fact, most of the standards used in the United States have been established to cover steel piping systems and conventional sheet metal duct systems. Microelectronics facilities use many different pipe and duct materials and situations that are not covered by these standards. It is necessary that a professional engineer be involved in this process and needs to accept responsibility for the design and installation of these systems.

For facilities support equipment, in many cases, there were no lateral restraints (e.g., on fans and scrubbers). Furthermore, in some cases where anchors were present, the bolts used to secure this equipment are often exposed to weather, and/or corrosive liquid. This may corrode the anchorage resulting in a loss of strength. A means of either providing protection or a preventative maintenance program should be implemented.

The seismic performance of facilities support equipment following an earthquake can be as important as the process tools when attempting to return the facility to full operation. Therefore, the seismic anchorage design of facilities should be completed with the same care and attention as the process tools and associated piping and ductwork. Even though SEMI S2 does not cover facility support equipment, the same general principles used in the development of the SEMI S2 guidelines apply. Where SEMI S2 places the burden of designing process equipment to withstand seismic forces on the end user, purchasers of facilities equipment should specify that such equipment be designed by the manufacturer to incorporate the same design specifications. Where SEMI S2 reminds the end-user of their responsibility to ensure that the equipment installation is done correctly, the installation of facilities equipment should also include this level of care. A professional civil or structural engineer should be responsible for the seismic anchorage design of this equipment. Design should be in compliance with local code requirements. Where such requirements do not exist, or where they are insufficient, it is recommended that the UBC requirements be used.

CONCLUSIONS

The effects of the 921 Quake on the microelectronics industry were relatively minimal. The primary impact was due to business interruption due to large-scale utility outages, rather than damage to capital assets. Current estimates place the percentage of financial losses due to damage at only 5% of the total. The observations of the assessment team, as well as those of others involved in the recovery effort was that losses would likely have been far greater had the ground accelerations at the HSBIP been higher. Much higher accelerations can be anticipated in future quakes that occur in closer proximity to this location. Should an event with PGAs of 0.35-0.40g occur, examples of damage that would be likely include (but are not limited to):

- Lateral displacement of equipment in the sub-fabs and fabs on the order of several centimeters to a meter or more on the upper floors (often where assembly, test and measurement equipment are located);
- Overturning of equipment with aspect ratios (i.e., height-to-minimum base dimension) greater than approximately 2;
- Damage to raised access floors;
- Hazardous materials releases from liquid spills in wet benches and possible hazardous gas releases from facilities without seismic gas shutdowns;
- Severe damage to WIP and reticle storage systems resulting in substantial loss of wafers;
- Loss of critical facilities support systems such as scrubbed exhaust, HVAC, DI Water, waste neutralization, etc.
- Severe flooding from damage to inadequately braced sprinkler and process water piping.
- Structural damage in older facilities and potentially new facilities.

Whereas the 921 Quake interrupted the industry for a period of about two weeks, with losses in the hundreds of millions of US dollars, the interruption and losses in this alternative scenario would likely be measured in months, and tens of billions of dollars (including loss of market share that would surely be associated with lengthy production interruptions). More importantly, the 921 Quake did not result in any reported injuries in the Science Park. The alternative scenario would likely be accompanied by numerous injuries and possibly deaths—especially if the quake occurred during the middle of the normal day shift.

Recently, the industry in Taiwan has begun to expand to the southern part of the island, to a new science park located in Tainan. It should be noted that this too is a seismically active region, where an earthquake with a magnitude of 7.0 occurred on 18 January 1968. Therefore, design of these new facilities clearly must incorporate the best practices mentioned in this report. Several of the new fabs being constructed in that area are being built using the latest seismic design considerations, going beyond what is used in the United States as code requirements. It must be noted that the UBC is a minimum code, whose basic objective is to ensure that the facility will not collapse and threaten life safety in the event of an earthquake. It is not the intent of the code to ensure that the facility will easily return to operation, or may even be salvageable. The determination of what level of design, above the basic safety objective, needs to be made on the basis of risk-benefit. Because of the tremendous capital investment in new fabs (e.g., estimated to be US$2-3 billion for a 300 mm fab), facility owners are deciding on performance-based designs equivalent to essential facilities, or safety/critical facilities (e.g., hospitals); i.e., 1-2 levels higher than the code minimum.

Seismic performance of microelectronics facilities, is not an issue that only applies to Taiwan. In October 1999, the U.S. Geological Survey released a fact sheet (#152-99) "Understanding Earthquake Hazards in the San Francisco Bay Region: Major Quake Likely to Strike Between 2000 and 2030." [7] This report concludes that there is a 70% probability ($\pm$10%), that a M6.7 or greater quake will occur somewhere in the San Francisco Bay Area over the next 30 years. A report by the Association of Bay Area Governments (ABAG) predicts that this event could produce accelerations in the range of 0.34-1.25 g's. [8] What should be obvious by now, is that a damaging earthquake <u>will</u> occur in areas where the semiconductor industry operates. As such, the users of semiconductor processing equipment should ensure that purchasing specifications for this equipment meet the design guidelines of SEMI S2.

However, as was seen in the 921 Quake, a major portion of the business interruption may occur not from damage to assets, but due to infrastructure interruptions. In addition to looking for alternative utility sources (e.g., some Taiwanese companies are looking to independent energy providers as a backup to the state-run utility), semiconductor operations must also develop and implement response strategies. These strategies should address problems that arise immediately after the earthquake, and in the business recovery phase during the following days and weeks. Facilities should have internal emergency response teams (ERTs) trained to deal with the earthquake and ensuing emergencies that may arise from the earthquake (e.g., medical injuries, fire, chemical spills, etc.).

Facilities should also develop crisis management plans that provide procedures to (1) address the immediate emergency (i.e., the ERT response), (2) the initial damage assessment phase (i.e., evaluation of structural integrity and of the facility and production equipment), and (3) the recovery phase (i.e., requalification and recovery of the equipment and processes).

The majority of the world's semiconductor production, and semiconductor equipment manufacturers are located on what is sometimes referred to as the "ring of fire" where the Pacific Plate comes into contact with the adjacent plates of the Earth's crust —Taiwan, Japan, California, and Oregon. Although in some of these locations, much effort and expense has been expended on seismic preparedness we need to continue to learn from previous earthquakes as we prepare for the future events.

REFERENCES

1. IRIS/CWB: *REPORT #1 on the Chi-Chi (Taiwan) Earthquake*, W. H. K. Lee, Dr. K. W. Kuo, Director of the Seismology Center, Central Weather Bureau (CWB), Taipei, Taiwan; http://www.iris.washington.edu/taiwan/chi-chi1.html
2. IRIS: *REPORT #4 on the Chi-Chi (Taiwan) Earthquake, Tectonic Setting and Regional Geology of Taiwan*; J.G. Liou and L.Y. Hsiao, Dept. of Geological and Environmental Sciences, Stanford University, Stanford, CA 94305 (Oct. 1st, 1999); http://www.iris.washington.edu/taiwan/chi-chi4.html
3. CNET News.com: *Dell feeling effects of higher memory costs*, Michael Kanellos, October 19, 1999; http://news.cnet.com/news/
4. CNET News.com: *PC industry hit by Taiwan quake aftershocks*, Brooke Crothers, October 1, 1999; http://news.cnet.com/news/
5. Swales, Bruce; Asia Regional Director, Relectronic-Remech Pte. Ltd., personal communications
6. UBC: Uniform Building Code, 1997 edition; International Conference of Building Officials; 5360 Workman Mill Road, Whittier, California 90601-2298, USA
7. USGS: U.S. Geological Survey, MS119 National Center, Reston, VA 20192, USA, http://quake.usgs.gov/media
8. ABAG: Association of Bay Are Governments, website. Full descriptions are from: Richter, C.F., 1958. Elementary Seismology. W.H. Freeman and Company, San Francisco, pp. 135-149; 650-653. http://www.abag.ca.gov/bayarea/eqmaps/eqmaps.html

ACKNOWLEDMENT

The authors would like to acknowledge the assistance provided by the following in the gathering of information for this paper: Mr. Richard Kaplan and Mr. Eric Sklar of Applied Materials Product Safety, as well as all the other members of Applied Materials Post-Quake Assessment Team; Dr. Lone-Yee Ye and Ms. May Ho of Applied Materials Taiwan; Mr. Eric Pai of Rinne & Peterson; Mr. Bruce Swales of Relectronic-Remech Pte. Ltd; The ESH & Facilities Departments of Winbond Electronics Corp.; Mr. Kean Wah Kong, of United Microelectronics Corporation (UMC); and Mr. Jonathan Davis, Ms. Aimee Bordeaux, and Dr. Murray Bullis, of SEMI.

ABOUT THE AUTHORS

Brian Sherin, is a co-founder of, and a Managing Principal in, the firm of Environmental & Occupational Risk Management, Inc. (EORM). Mr. Sherin's experience is in safety engineering and management and emergency preparedness and response within the semiconductor and electronics industries. He has a B.S. in Genetics from the University of California, Davis and a Master's Degree in Biology/Toxicology from San Jose State University and is a Certified Safety Professional (CSP). He was the Working Group Leader for the development of the Seismic Section of the SEMI S2 Re-write (SEMI Doc. 2614D), and is also a professional member of the SSA, SFPE, NFPA, and ASSE. He is a Lecturer in the Environmental Studies Department at San Jose State University, and an industry advisor to both the Environmental Studies and School of Engineering EHS degree programs. In his "spare" time, he is a volunteer fire fighter in the Loma Prieta Volunteer Fire and Rescue Department.

Stacy Bartoletti is an Associate with Degenkolb Engineers in their Portland, Oregon office. Mr. Bartolleti's experience is in the structural and seismic engineering fields. Mr. Bartoletti has a B.S. in Civil Engineering from Purdue University and a M.S. in Civil Engineering from the University of Texas, Austin. He is a registered Professional Engineer in California, Oregon, and Washington and a registered Structural Engineer in California. He has provided input to SEMI on the development of the seismic provisions for SEMI Doc. 2614D and is a member of the Earthquake Engineering Research Institute, Structural Engineers Association of California, and the Structural Engineers Association of Oregon

FIGURES:

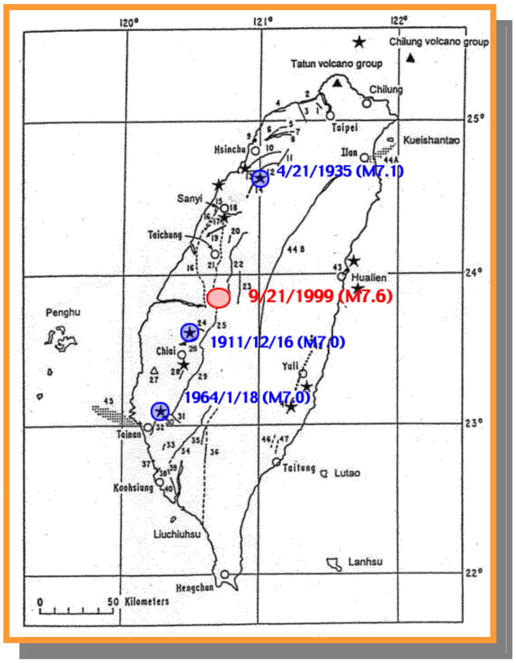

Figure 1. Map of Taiwan showing the epicenter of the 921 Quake and several other notable quakes in the past 100 years, including one outside of Hsinchu in the north and one outside of Tainan in the south (both semiconductor industry locations).

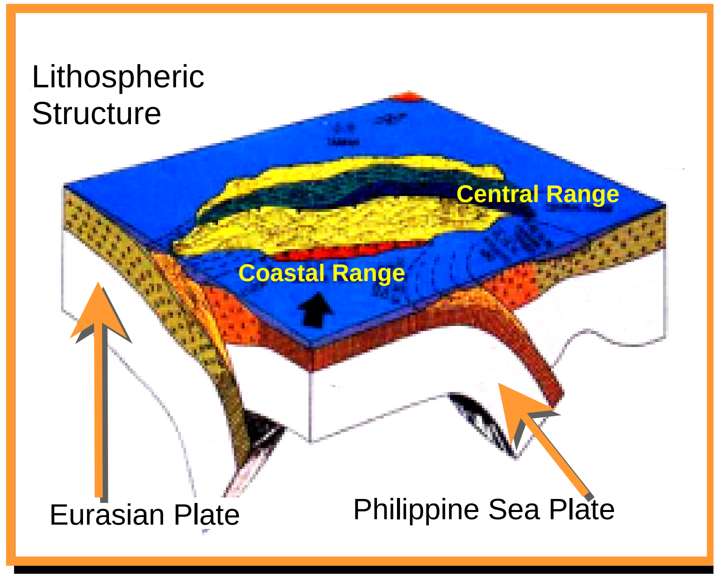

Figure 2. Diagram showing a cross section of the plate tectonics that form Taiwan. Typically, plate boundaries either slide against each other (strike-slip) or subduct (thrust). Taiwan's complicated seismic structure includes two subduction boundaries (Eurasian into the Philippine Plate and the Philippine into the Pacific Plate). The Central Range (location of the 921 Quake) is formed by material that piles up (accretion) as the Eurasian plate dips down below the Philippine. This geology produces parallel bands of seismic activity on both sides of the island.

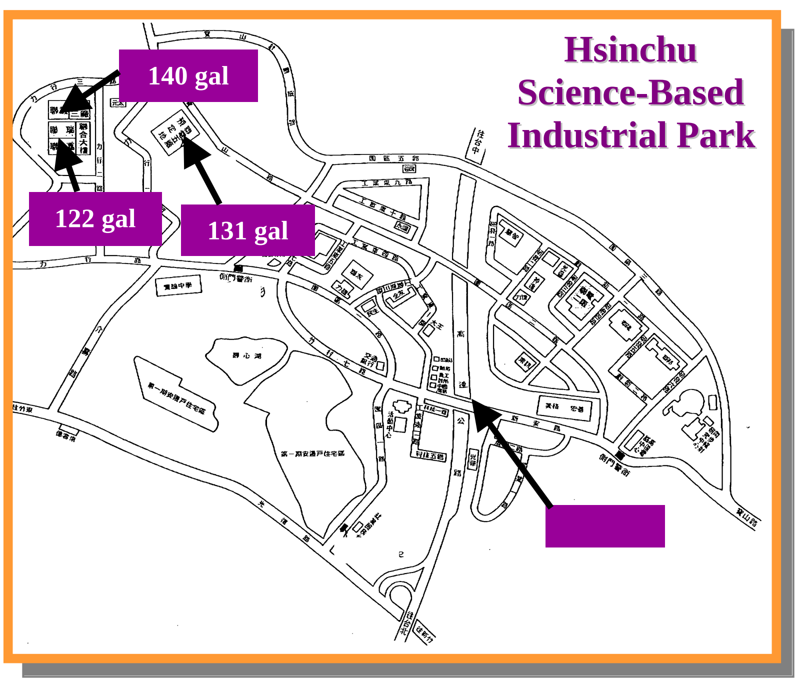

Figure 3. Map of the Hsinchu Science-Based Industrial Park (HSBIP) showing acceleration readings from hazardous gas shutdown switches (accelerometers).

Figure 4. Typical exterior damage observed in the Science Park – spalling or flaking of architectural finish tiles.

Figure 5. Example of process equipment leveling foot that pulled out of the equipment chassis. Note how high up the threaded rod the bolt is located and the stripping of the upper few threads. Raising the equipment up to the maximum height of the foot is a common practice. Equipment makers should provide further guidance on the minimum number of threads that should go into the chassis or re-design the rods to ensure that there

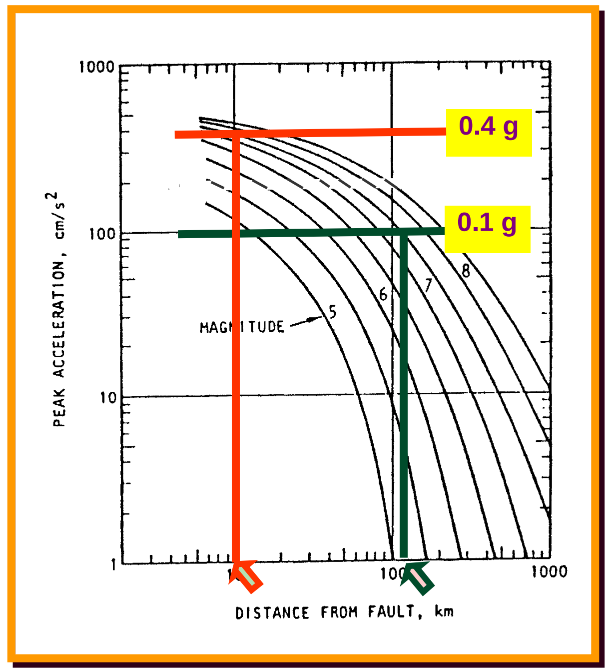

Figure 6. Idealized attenuation diagram showing the relationship between distance from the fault and the expected PGA. Hsinchu is approximately 110 km from the epicenter of this quake; therefore distance would attenuate the acceleration from a M7.5 to approximately 0.1 g which is what was recorded by accelerometers in the Park. If a comparable sized quake occurred on the Hsinchu fault, or another one in close proximity to the Park, acceleration could approach or exceed 0.4 g.