The impact of the 12 May 2008 Wenchuan earthquake on industrial facilities

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ABSTRACT

This study describes the results of a field trip to the area affected by the 12 May, 2008, Wenchuan earthquake to analyse its impact on industrial facilities. The damage severity correlates well with the age of the plant, with older facilities having suffered more extensive and severe damage than those built more recently according to the latest design codes. The main cause of worker death and injury was the collapse of warehouses, office and manufacturing buildings. This concerned mostly concrete structures with insufficient confinement or poor reinforcement. The falling debris resulted in equipment damage and loss, as well as pipe severing and crushing. Pipes were also severed or bent when connected tanks were displaced or buildings collapsed. Numerous hazardous-materials releases occurred with spills being the dominant accident scenario. In some sites soil–liquefaction induced damage was evident, highlighting the need to consider potential site effects when selecting the location for a facility. The impact of the Wenchuan earthquake on chemical facilities confirms the findings from other earthquakes in terms of typical Natech damage and failure modes, as well as of hazardous-materials release potential and mechanisms.

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1. Introduction

On 12 May, 2008, at 14:28 local time, a major earthquake devastated the Wenchuan area in Sichuan Province in the heartland of China. The earthquake killed almost 70,000 people, injured over 374,000 and rendered 5,000,000 homeless. It is estimated that over 5 million buildings collapsed while 21 million buildings suffered damage in the earthquake (US Geological Survey, 2008). Severe damage or collapse typically concerned buildings built before the implementation of the updated Chinese seismic code GBJ11-89 issued in 1989 (Wang, 2008a, 2008b) or was due to poor construction choices (e.g. masonry structures instead of reinforced concrete). The economic losses due to the earthquake amount to over 960 billion RMB or about 140 billion US$ (Shi, 2008).

With Sichuan Province being home to a significant proportion of Chinese chemical production, industrial facilities were also affected by the earthquake. In particular, there are numerous companies producing fertiliser in the hard-hit Shifang, Deyang and Mianyang regions due to the abundance of phosphate rock in the area (China Chemical Reporter, 2008a). There is only limited information on the impact of the Wenchuan earthquake on industry as this aspect is overshadowed by the tragic human dimension of the disaster. However, there is concern about earthquake-triggered damage to and destruction of industrial facilities housing or processing hazardous substances and the potential consequences of their release to man or the environment. This type of chemical accident is commonly referred to as natural hazard-triggered technological accident or “Natech” accident (Krausmann & Cruz, 2008; Showalter & Myers, 1994).

In order to understand how well the chemical industry fared in the affected areas and whether Natech accidents were triggered by the unexpected earthquake loads a reconnaissance field trip was organised to Sichuan province from 15 to 21 November, 2008. The objective of the trip was to collect first-hand data on structural and non-structural damage in industry, as well as on possible hazardous-materials releases and their consequences. This work describes the results of the field trip in a qualitative way and provides an example of the industry’s vulnerability in areas prone to major earthquakes.

2. Wenchuan earthquake characteristics

The earthquake that shook Wenchuan County on 12 May 2008 was a major event with MW = 7.9 and a shallow depth of only 19 km (US Geological Survey, 2009). It caused a fault rupture exceeding 200 km in length and affected a total area of about 500,000 km²
The earthquake intensity in the region near the epicentre reached XI, the penultimate level on the Chinese Seismic Intensity Scale (CSIS), which corresponds to widespread collapse of buildings (Chinese National Standard, 1999). The earthquake was accompanied by a number of other geological phenomena, most notably landslides and rock falls. This caused further damage but also hampered search and rescue operations due to blocked access routes to heavily impacted areas.

During the earthquake strong ground motion of over 100 s duration was observed in most areas (Paterson, del Re, & Wang, 2008). Peak ground acceleration (PGA) during the main shock reached values as high as 0.96 g. Fig. 1 shows the PGA contour lines made available by the US Geological Survey (2009). Interestingly, the vertical PGA component exceeded one or both horizontal components for some near-fault records (Li et al., 2008). This is of particular concern as earthquakes usually exhibit larger horizontal shaking which is reflected in current design codes. In fact, the Chinese code assumes the vertical component to be one third of the horizontal ones (Paterson et al., 2008). Large vertical shaking adds to the loading on buildings and if not adequately considered during the design stage can exacerbate damage drastically.

3. Data collection

During the field trip we visited 18 industrial facilities in Deyang, Shifang, Mianzhu, Mianyang, Anxian and Dujiangyan, which all lie in areas which experienced high PGA values. We visited 7 fertiliser plants, 1 pharmaceutical manufacturing site, 1 facility producing ethanol and derivatives, 3 cement factories, 1 oil storage depot, 3 factories producing equipment and machinery for various industries, 1 fibreboard plant and 1 facility producing electrical appliances. Plant sizes ranged from about 50 employees up to 3000.

The objective of the field trip was to collect data on the performance of chemical facilities under the experienced earthquake loads. Primarily we aimed at identifying the main types of structural damage and of equipment affected, their failure modes and the resultant consequences. Moreover, we were interested in the performance of active and passive safety barriers. Data was provided by company managers, employees and in some cases residents. Where interviews could not be performed the data collection had to rely on direct observation. In addition, the data collection on hazardous-materials releases was supplemented by a review of the open literature.

4. The performance of industrial structures and equipment

Prior to the Wenchuan earthquake the affected region was considered an area of moderate seismicity with a design intensity of VII on the CSIS as specified in the latest Chinese design code GB50011-2001. This translates to buildings being able to withstand a PGA of 0.1 g, equivalent to an earthquake in the region with a return period of 475 years, with repairable damage. In addition, buildings had to be able to resist a PGA of 0.22 g, equivalent to a 2475 year event, without collapsing to guarantee life safety (Free et al., 2008). The chemical industry follows the basic specifications of this seismic code but is also subject to additional specific...
regulations (Wang, 2001; Zhao, 2009). With the stipulated design levels being lower than those experienced during the earthquake the extent of damage and destruction, in particular in the near-source region, is not surprising. Code GB50011-2001 has been revised after the earthquake and now assigns higher intensity levels to the most seriously affected towns.

While the earthquake impact on the visited facilities was mostly restricted to damage and in some cases injuries, in one completely destroyed plant 75 workers were killed when buildings collapsed during the earthquake. In a neighbouring facility 200 workers are reported to have died (Sino Daily, 2008). Many more were injured, some of them severely. The direct economic losses in the visited facilities are well in excess of 240 million US$. These numbers may only be the tip of the iceberg as many more of the region’s industrial sites were affected by the earthquake. In the less heavily damaged facilities visited the damage to buildings and equipment led to complete plant shut-down and business interruption for up to 6 months for repair and/or reconstruction. Some industrial sites were affected by the earthquake. In a neighbouring facility 200 workers are restricted to damage and in some cases injuries, in one completely destroyed plant 75 workers were killed when buildings collapsed during the earthquake. Plants that were severely damaged had resumed only part of their production six months after the earthquake. In the building sites affected by the earthquake. In the less heavily damaged facilities visited the damage to buildings and equipment led to complete plant shut-down and business interruption for up to 6 months for repair and/or reconstruction. Some industrial sites were affected by the earthquake. In a neighbouring facility 200 workers are restricted to damage and in some cases injuries, in one completely destroyed plant 75 workers were killed when buildings collapsed during the earthquake. In the building sites affected by the earthquake. In the less heavily damaged facilities visited the damage to buildings and equipment led to complete plant shut-down and business interruption for up to 6 months for repair and/or reconstruction. Some industrial sites were affected by the earthquake. In a neighbouring facility 200 workers are

4.1. Damage analysis

4.1.1. Buildings and other structures
Building damage and sometimes collapse were omnipresent at the facilities we visited. As a consequence extensive repair work and rebuilding was still ongoing 6 months after the earthquake. During our site visits, the impact of the earthquake was recorded as a function of the observed damage severity (none, minor, moderate, major, collapse; Sezen & Whittaker, 2006). Table 1 summarises the overall plant damage categories together with plant age and PGA values which were derived by plotting GPS data taken during the site visits over PGA contour line data from the US Geological Survey (2009).

Assuming a uniform PGA for all visited facilities the damage severity correlates well with the age of the plant (r = 0.79, p = 0.0007), with older facilities having suffered more extensive damage and more severe damage than those built more recently according to the latest design codes. This correlation is, however, somewhat biased due to the limited sample size and as slightly more of the old facilities visited lay in high-PGA areas where a strong PGA effect is to be expected. Nonetheless the influence of the plant age on the observed damage is significant. An example is plant ID 15 which had been built in 1999 to a design intensity higher than that required by law and which suffered only minor damage despite an earthquake loading of 0.6 g. This highlights the importance of seismic design and the implementation of seismic codes.

The main cause of worker death and injury was structural damage to and collapse of warehouses, office and manufacturing buildings. This included roof and wall damage, as well as top-storey collapse and pancaking of floors (Figs. 2 and 3). This concerned mostly concrete structures with insufficient confinement or poor reinforcement that could not withstand the earthquake loads. In some cases we observed stiff-frame configurations which exhibit a high vulnerability to the shaking loads and which in some cases led to near-failure of the building support columns (Fig. 4). In many cases structures toppled when the connection between topsides and their supports broke (Fig. 5). In one of the oldest facilities we observed structural damage to buildings with heavy topsides and slender columns which may have contributed to reducing the resistance of structures. Falling debris from collapsing buildings and other structures was the main source for equipment damage and loss.

In addition to loading by the earthquake forces soil—liquefaction induced damage was evident in some sites. In one facility numerous silos suffered heavy damage (cracks) because of soil liquefaction. Several of them appeared to not have sunk until several days after the earthquake when it was noted that they had inclined. The heavy rains that followed in the weeks after the earthquake may have exacerbated the situation.

Stack towers made of un-reinforced brick typically suffered complete collapse or failure of the upper part where earthquake accelerations were highest (Fig. 6). Several stacks observed during the field visit were cracked but in operation. A flare stack made of steel trusses inclined when steel members too slender to withstand the earthquake loads failed in compression. Glass windows were broken at every site.

### Table 1

<table>
<thead>
<tr>
<th>Plant ID</th>
<th>Year built</th>
<th>PGA [%g]</th>
<th>Damage severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>?</td>
<td>?</td>
<td>Minor</td>
</tr>
<tr>
<td>2</td>
<td>2002</td>
<td>?</td>
<td>Minor</td>
</tr>
<tr>
<td>3</td>
<td>1995</td>
<td>20–40</td>
<td>Minor</td>
</tr>
<tr>
<td>4</td>
<td>1989</td>
<td>20–40</td>
<td>Moderate</td>
</tr>
<tr>
<td>5</td>
<td>1994</td>
<td>40</td>
<td>Moderate</td>
</tr>
<tr>
<td>6</td>
<td>1958</td>
<td>60</td>
<td>Collapse</td>
</tr>
<tr>
<td>7</td>
<td>1950s</td>
<td>60</td>
<td>Collapse</td>
</tr>
<tr>
<td>8</td>
<td>1970s</td>
<td>60</td>
<td>Major</td>
</tr>
<tr>
<td>9</td>
<td>?</td>
<td>40</td>
<td>Minor</td>
</tr>
<tr>
<td>10</td>
<td>1978</td>
<td>20</td>
<td>Minor</td>
</tr>
<tr>
<td>11</td>
<td>?</td>
<td>20</td>
<td>None</td>
</tr>
<tr>
<td>12</td>
<td>1983</td>
<td>20–40</td>
<td>Minor</td>
</tr>
<tr>
<td>13</td>
<td>1984</td>
<td>60–80</td>
<td>Major</td>
</tr>
<tr>
<td>14</td>
<td>1950s</td>
<td>60–80</td>
<td>Major</td>
</tr>
<tr>
<td>15</td>
<td>1999</td>
<td>60</td>
<td>Minor</td>
</tr>
<tr>
<td>16</td>
<td>?</td>
<td>20–40</td>
<td>Minor</td>
</tr>
<tr>
<td>17</td>
<td>2003</td>
<td>20–40</td>
<td>Moderate</td>
</tr>
<tr>
<td>18</td>
<td>1999</td>
<td>40</td>
<td>Minor</td>
</tr>
</tbody>
</table>

![Fig. 2. Top-storey collapse at a factory building.](image-url)
buildings housing machinery. This was brought about either by direct debris impact or by support failure inside buildings. The shaking loads resulted in the breaking of flange connections between pipes or pipes and equipment. Pipes were also severed, bent or crushed when connected tanks were displaced or buildings collapsed, often leaving the disconnected pipe ends hanging in mid-air (Fig. 7). In almost every facility visited we observed damage to pipe and vessel packing (Fig. 8). This was caused by debris impact but was also due to the earthquake forces that resulted in mechanical damage by friction of pipes or vessels against their
support structures. Concrete columns supporting pipes in the open generally performed well. There is evidence of severe cracking in a few cases but this did not seem to diminish their performance. Occasionally pipes were displaced because of damage to the pipe shoes during the earthquake.

Tanks and vessels suffered damage due to debris impact, foundation damage or failure, or toppling under the influence of the earthquake loads (Fig. 9). For full or nearly full tanks (filling level > 50%) liquid sloshing may have exacerbated the earthquake impact (Salzano, Iervolino, & Fabbrocino, 2003). This was observed during other earthquakes where liquid sloshing caused damage to the perimeter seals and leakage from floating roof tanks, sinking of the roof, or ignition of flammable tank contents after creation of sparks from metallic roof seals (Eshgi & Razzaghi, 2005; Sezen & Whittaker, 2006; Steinberg & Cruz, 2004). Several of the tanks observed during the field trip were not anchored to their foundations or otherwise restrained. This makes them vulnerable to sliding or uplifting. Damage to a tank base plate was observed in at least one case. In one of the oldest sites visited there was evidence of tank sliding, as well as severe damage to tank support columns (Fig. 10). In one site we noticed damage to a spherical ammonia tank whose roof packing was lifted up when the staircase curling around the tank suffered twisting by the earthquake. In many cases the structural integrity of tanks and vessels even in heavily damaged plants looked intact. It is highly likely, however, that some leakage of the tank contents resulted due to severed pipe connections.

In several cases we observed displaced grinder cylinders that had been forced out of their oil bearing supports by the shaking loads. Pumps appeared to have resisted the earthquake well when anchored. If not struck by debris anchored equipment generally performed well although occasionally tilting occurred due to straining of the anchor bolts. We noticed that in some cases anchor holes were present but were lacking anchor bolts, which led to displacement of equipment.

4.1.3. Lifelines

The Wenchuan earthquake caused extensive damage to and outage of electric-power, gas and water-supply systems, forcing many industrial plants to interrupt production. Power supply to most of the affected areas was restored within a week of the
disaster. The water-distribution network, which suffered from damage to tanks, reservoirs, and numerous breaks in water pipelines, took two weeks or more to re-establish. Industrial facilities, even if undamaged by the earthquake, could only resume operation once the water supply was restored due to the loss of cooling capacity (Miyamoto, 2008).

During our site visits we noticed damage to and leakage from one transformer, and falling of power poles in the on-site power station. Electrical generators in one site were completely destroyed. In another the power-generating equipment was reported burned (China Chemical Reporter, 2008b). On-site water towers suffered extensive damage or complete collapse. Although we have little information on the emergency response performance during the earthquake we believe that the lack of power and water supply would have hampered efforts to prevent or mitigate earthquake-triggered Natech accidents in the hardest-hit areas.

4.2. Safety measures

The existence and effectiveness of safety barriers varied depending on the age of the visited installation and the PGA the plant was subjected to. We noticed that in the hardest-hit areas safety barriers, in particular in the oldest plants, failed together with the installation. Passive barriers such as catch basins, where existing, or retaining walls were cracked or broken and would therefore have provided little protection from hazardous-materials releases. We could not collect any information on active barriers. However, active barriers that did not have adequate power and water back-up systems were likely unavailable.

We noticed that in many facilities pipes were braced to keep them in place. The bracing was often connected to a concrete beam overhead or to other, bigger pipes that rested in guiding channels to keep them in place on the support columns. The bracing appeared to be effective in preventing pipe displacement but resulted in breaks when the connection between pipes was not flexible (Fig. 11). Many of the storage tanks observed were not anchored but simply rested on their base plate or support columns. In many cases anchoring proved to be effective in avoiding displacement of equipment. Anchor bolts were often strained during the earthquake and subsequently needed replacement. The anchored structures remained, however, intact.

Some visited companies had started to retrofit their installations to make them more earthquake-proof. One company used jet grouting to reinforce the foundation of its structures to shaking-induced soil liquefaction. While repairing the damage to concrete columns and beams, steel braces had been bolted around them to strengthen their resistance to future earthquake loads. With the updating of the design intensity for the area an intensity of 8 is now used for the construction of new facilities. One company visited voluntarily uses design intensities higher than those stipulated by law.

4.3. Hazardous-materials releases

There is contradicting information on hazardous-materials releases and company managers were reluctant to discuss this issue. However, with the vast number of damaged and broken flanges, pipes and vessels it is highly likely that some of these materials were spilled. In fact, during our field visit residents of two visited fertiliser plants reported breathing difficulties and a pungent smell emanating from the facilities shortly after the earthquake. It is conceivable that the hazardous-materials releases continued for days after the earthquake until the amount of materials available for release was exhausted.

Only limited public information on earthquake-triggered hazardous-materials releases is available from official sources and newspaper articles. Two neighbouring fertiliser plants visited were heavily damaged and are reported to have resulted in significant ammonia, sulphuric acid and other releases that polluted a river (China Chemical Reporter, 2008b; Ministry of Environmental Protection, 2008). According to El Moudjahid (2008) these releases necessitated the evacuation of 6000 residents. In one of these sites liquefied ammonia leaked because the pipes connecting the pumps on the ammonia storage tanks had cracked during the earthquake, releasing around 1100 m$^3$ of the substance. In the neighbouring plant one source reports an ammonia leakage of 80 tons (China Chemical Reporter, 2008b) while the newspaper Caijing (2008) mentions 150 tons. In addition to ammonia leakage sulphuric acid was spilled from damaged tanks into the soil in both fertiliser plants. The exact amount released is unknown; one source reports at least 1000 tons (Caijing, 2008). In the same plants stored sulphur caught fire and exploded, wrecking the sites and destroying a significant part of the chemical inventory (China Chemical Reporter, 2008b).

At least three other plants (2 fertiliser plants, 1 meat factory) are reported to have experienced ammonia leakage triggered by the earthquake (China Chemical Reporter, 2008b; Green Cross, 2008; Ministry of Environmental Protection, 2008). Phosphorus burning was reported after the collapse of a chemical factory (Green Cross, 2008). The observed occurrence of fires in chemical facilities after the earthquake in Sichuan Province is in accordance with the conclusions of a recent study that indicates that the ignition probability of a flammable substance is rather high upon release during an earthquake (Campedel, Cozzani, Krausmann, & Cruz, 2008).

The immediate impact of the hazardous-materials releases on-site is unclear. Workers are reported to have died when acid burst from broken pipes in one facility (The Times, 2008). There is also little knowledge on off-site effects. In one incident an ammonia cloud is reported to have drifted down a valley, engulfing villagers and injuring or even killing them (The Times, 2008). The flora in the area was heavily affected and nearby crops and vegetation (including an entire mountain slope) were chemically burned (China Chemical Reporter, 2008b).

5. Conclusions

Lessons learned from this reconnaissance field trip confirm the devastating impact that natural disasters can have on industrial facilities. In addition to casualties and environmental harm the economic losses due to damage and business interruption are often disastrous. While we only visited a small sample of the affected
industrial establishments we believe that our results can be extrapolated to other sites in the earthquake area. In general, newer buildings and structures that had benefited from some seismic design performed better than older ones, stressing the importance of implementing seismic building codes. These need to be based on a realistic assessment of the expected earthquake severity and the resultant loading on structures. Building damage and collapse was widespread in the hardest-hit areas where PGA values were highest. This and the generated debris was the main cause for worker death. Equipment damage dominated in the areas subject to lower PGA. Numerous hazardous-materials releases were triggered by the earthquake with spills being the dominant accident scenario. In some cases fires and explosions occurred when flammable and explosive materials were released and found an ignition source or reacted with other materials. In some sites liquefaction-induced damage was evident, highlighting the need to consider potential site effects when selecting the location for a facility. The findings from the field trip confirm the observations made during other earthquakes in terms of typical Natch damage and failure modes, as well as of hazardous-materials release potential and mechanisms.

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