PERFORMANCE OF WATER SYSTEMS IN THE M_W8.4 ATICO (PERU) EARTHQUAKE OF JUNE 23, 2001

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1.0 INTRODUCTION

This report describes the performance of water systems in the Atico, Peru Mw 8.4 earthquake of June 23, 2001.

The information presented in this report was developed based on a field reconnaissance in Peru conducted by a team fielded by the Technical Council on Lifeline Earthquake Engineering (TCLEE), which is a committee of the American Society of Civil Engineers (ASCE). The team consisted of Bill Byers, Curt Edwards, John Eidinger, Gloria Gee, Anshel Schiff and Mark Yashinsky. A comprehensive report on the performance of all lifelines will be available from ASCE (http://www.asce.org).

2.0 SEISMOLOGY AND GROUND MOTIONS

Much of the country of Peru is located astride the confluence of two great plates: the Nazca plate which underlies the Pacific Ocean, and the South American plate which underlies Peru. This is shown in Figure 2-1.

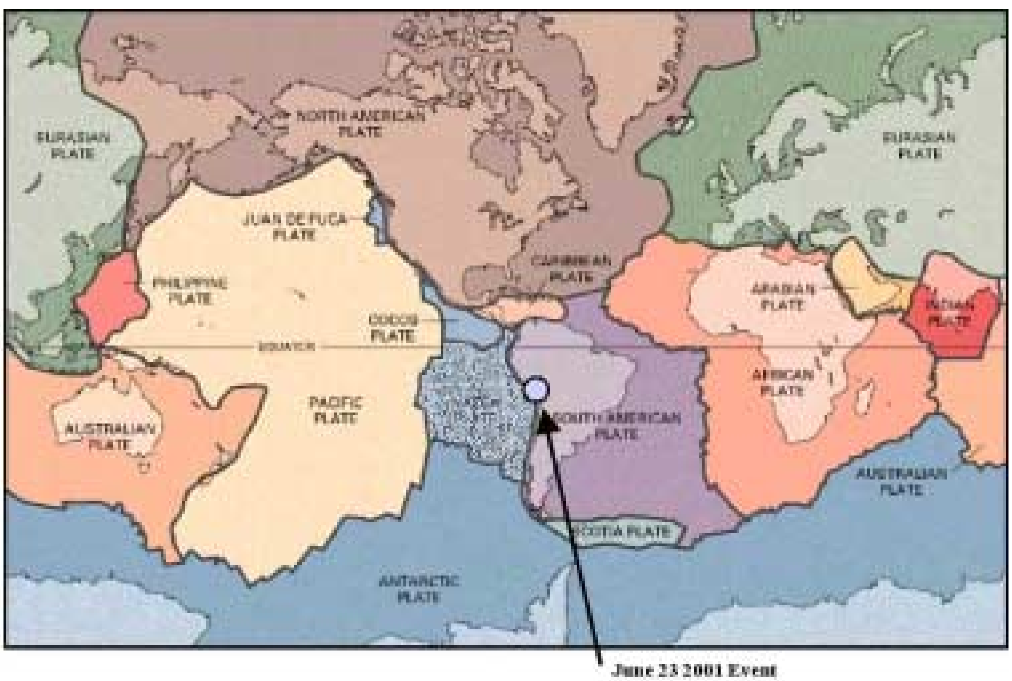

Figure 2-1. Location of the Earthquake

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Figure 2-2 shows a east-west cross section (not to scale) through the Nazca and South American plates. As can be seen, the Nazca plate is subducting beneath the South America plate. The Andean mountains with its many volcanoes are shown schematically.

Figure 2-3 shows a map of Peru. This map the three seismic zones as described in the 1997 seismic design code for Peru. Also shown is the current understanding of the location and extent of the main rupture of June 23, 2001. As can be seen, the epicenter of the earthquake was located in the Pacific Ocean, just to the west of the Peruvian shoreline. The nearest town in Peru to the epicenter was Atico, and hence the name given to the earthquake. Also shown in Figure 2-3 is the understood direction of rupture (from northwest to southeast), and the approximate extent of rupture of the main shock. Most of the rupture plane is located under the ocean, but some of the rupture plane is located under the land mass. Fortunately, most of the land mass underlain by the rupture plane is unpopulated. Also shown in Figure 2-3 are the locations of the main cities affected by the earthquake: Arequipa, Moquegua and Tacna. The various lines shown within Peru represent the boundaries of the various "departments" of Peru – a "department" in Peru is similar to a "county" in California. The capital of Peru, Lima, is located about 400 km northwest of the rupture plane, and was totally unaffected by this earthquake.

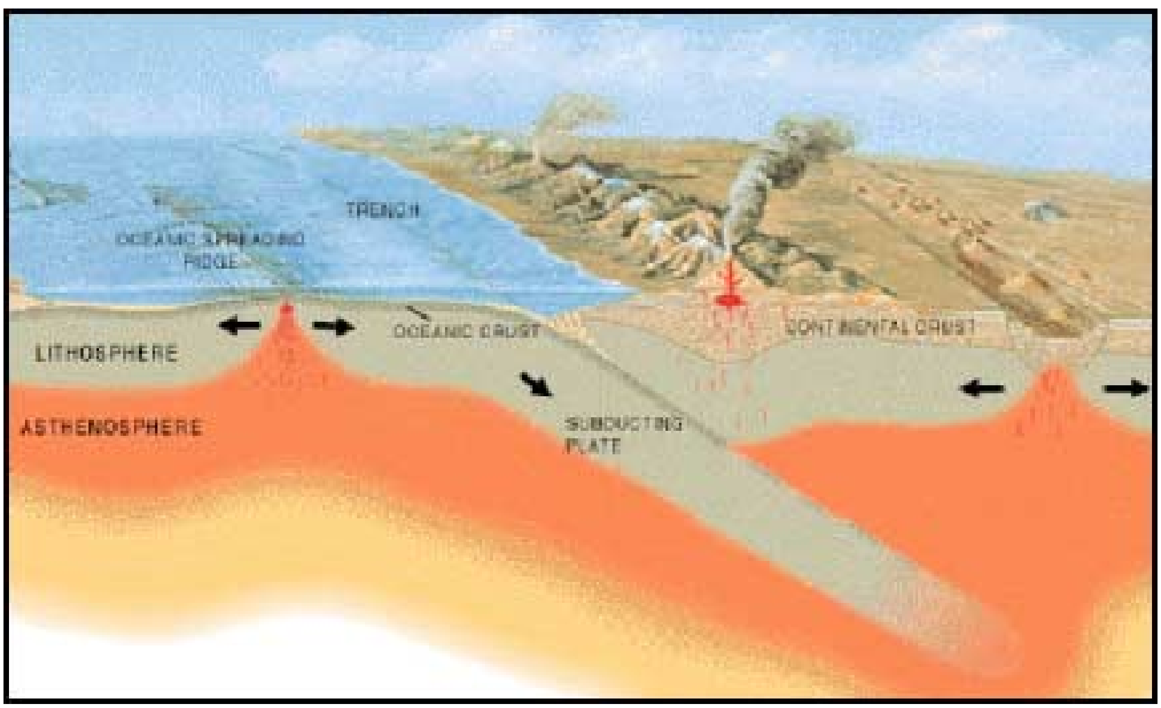

Figure 2-2. Cross Section of Nazca - South American Plates

Figure 2-3. Map of Peru Showing Seismic Zones and Rupture Fault Plane

Figures 2-4, 2-5 and 2-6 show the recorded time histories from the strong motion instrument located in Moquegua. This instrument was located on a deep alluvial site. Highest recorded ground motion in the East-West direction was about 0.3g, with strong motion of 0.05g or higher lasting for more than 50 seconds. Highest motions in the North South direction were about 0.22g, and in the vertical direction about 0.16g. Strong motion instruments in Arequipa and Tacna failed to register the strong motions from the main shock, but did capture strong motions from some of the aftershocks.

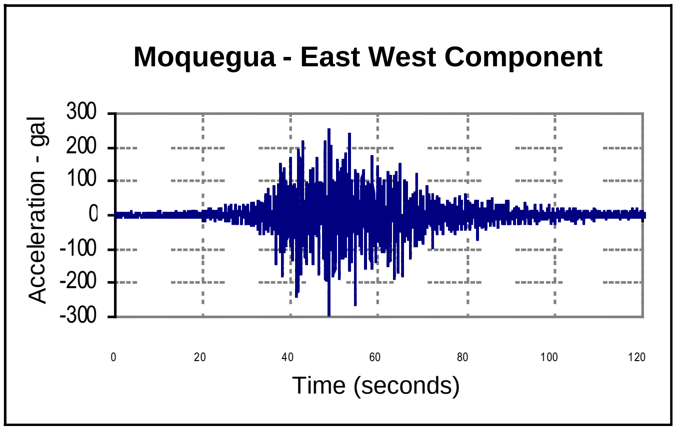

Figure 2-4. Recorded Time History of Main Shock – June 23, 2001 (East West)

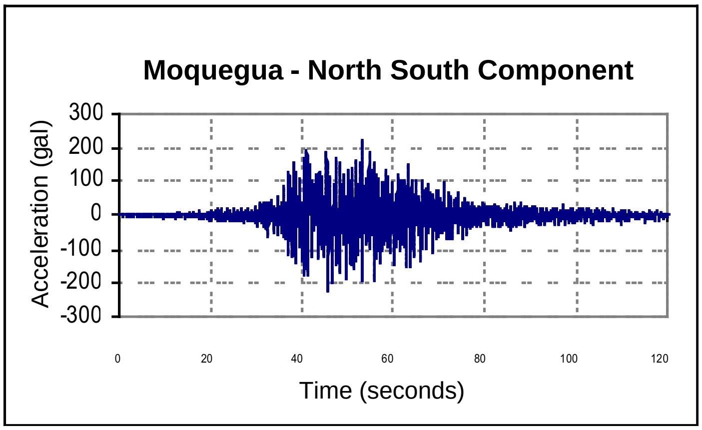

Figure 2-5. Recorded Time History of Main Shock – June 23, 2001 (North South)

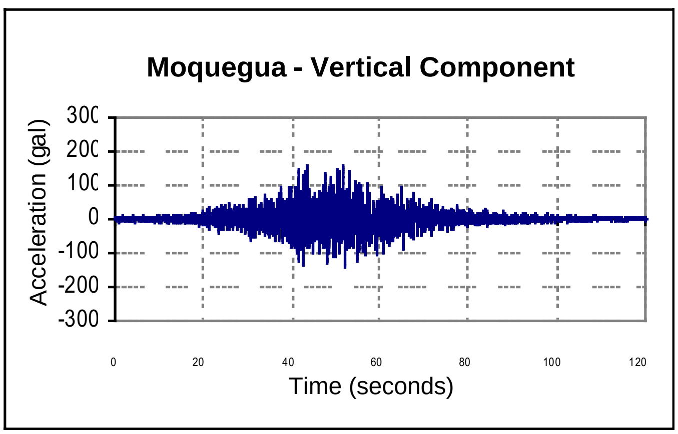

Figure 2-6. Recorded Time History of Main Shock – June 23, 2001 (Vertical)

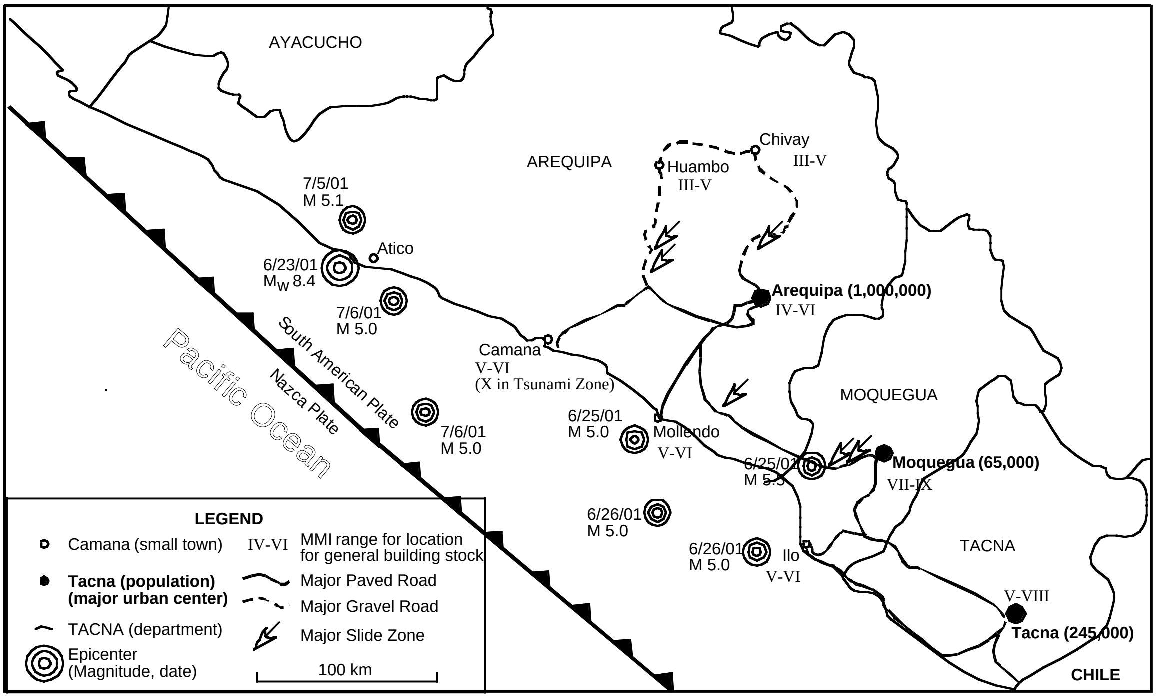

Figure 2-7. Map of the Affected Zone

Figure 2-7 shows a map of the area most affected by the earthquake. Epicenters for major aftershocks through July 6 are noted. Also shown in this map are the highway routes actually traveled by the authors, with major landslide zones notes along these routes. Modified Mercalli Intensity (MMI) values are shown for larger populated towns and cities; the lower MMI value represents the majority of the building stock, while the upper value denotes the areas of the town / city with the most damage. The MMI values shown do not represent damage to lifelines.

3.0 GEOTECHNICAL

The geology of the Pacific Ocean coastal area of Peru can be characterized as a broad alluvial landmass, sloping up from sea level to about elevation 3000 m (10,000 feet) about 150 km inland. Much of the area is arid semi-desert. Most of the "green belts" are those created by small rivers which flow from the Andes southwesterly to the coast, or in irrigated zones.

Figure 3-1 shows the surface geology of the affected area. The light colored areas are relatively flat and arid alluvial plains. The remaining areas are older rock-type formations, generally very hilly.

Figure 3-1. Surface Geology Map of the Affected Zone

Due to the semi-desert conditions, the water table is considered to be quite deep below the ground surface, except immediately adjacent to the rivers. The TCLEE team traveled over 4,000 km of roads, and we were able to discern clear evidence for liquefaction in only two locations: both immediately adjacent to river channels. Figure 3-2 shows the evidence of sand boils caused by liquefaction. We observed little surface evidence of liquefaction in rural areas, and none at all in the inhabited areas of Arequipa, Moquegua and Tacna.

Figure 3-2. Sand Boil in river bed. The boil measures about 6 inches in diameter.

Much of the land terrain in the affected areas is hilly. We observed a great number of different types of rock conditions, ranging from very soft to near granite conditions. In our travels by either road (improved national highways or rural improved gravel roads), there were a great many number of road cuts which exposed the native rock / soil conditions. In about 1,000 km of roadways that we traveled, about 600 km traversed generally flat terrain, and 400 km traversed through very hilly terrain. In the hilly terrain, we observed many hundreds of cuts into hillsides. For the improved national highways, the roads through hilly terrain were generally built by making a cut into the hillside, with a corresponding fill for the outboards part of the road. For the improved gravel roads, the roads through hilly terrain were generally built by making only a cut into the hillside. Hillside cuts were generally graded to about a 50% to 80% slope, indicating a reasonably stable type of rock in most locations. It was not unusual to observe cut slopes with 70% to 90% (vertical) grade.

At the cuts, there were a great many number of landslides, mostly of the rockfall type. Table 3-1 describes our approximate evaluation of the number of landslides at cuts in the hills.

PGA Range	Length of Exposed Road	Length of Exposed Road built in hillside cuts	Number of hillside cuts (average length 100 meters)	Percentage of hillside cuts with rockfalls onto the road
0.0 to 0.10 g	300 km	30 km	300	1%
0.10 to 0.25 g	400 km	40 km	400	15%
0.25 to 0.50 g	300 km	30 km	300	50%

Table 3-1. Roads with Hillside Cuts and Landslides

The data in Table 3-1 is based on a qualitative summary of the landslides at roadways. The main points are as follows:

- At locations with low PGAs (mostly east or north of Arequipa, towards Chivay), there were very occasional rock falls. PGA values were likely under 0.05g in most of these locations.
- At locations with moderate range PGAs (most of the coastal roads, some interior roads), there were a modest number of rockfalls. We estimate the number at 15% of all hillside cuts. This would translate to about 60 rockfalls along 400 km of roads. Many of these rockfalls deposited debris of about 1 to 5 cubic yards, while some deposited 100s of cubic yards of debris onto the road.
- At locations with high range PGAs (some interior roads), it was not uncommon to drive along stretches of road where every hillside cut had failed and deposited debris onto the road. The "50%" failure rate is considered the average.
- It should be noted that much of the rockfall was caused by the initial main shock. However, the continuing sizable aftershocks no doubt activated additional rockfalls.
- For the major highways, the outboard fill sides of the roads suffered about the same number of slumps as the inboard cut side of the roads experienced rockfall debris accumulation.
- For about 80% to 90% of all rockfalls or fill slumps, the road remained passable during daytime driving conditions by passenger car prior to clean up. These roads would be extremely hazardous (typical driving speeds of 100 to 130 kph) for night time driving, and would likely lead to accidents.
- A similar ratio of avalanche-type failures was noted along railway and canal right-of-ways in hillside regions.
- A substantial manpower-intensive effort was required to remove avalanche-deposited debris from roadways, railways and canal right of ways. This is further discussed in other parts of this report.

4.0 POTABLE WATER SYSTEMS

4.1 Arequipa Water Treatment Plant

The Arequipa WTP is located on a hill location above the City of Arequipa. The site is most likely a firm alluvial soil site. Based on the observed lack of any significant damage to almost all residential structures near the water treatment plant (mostly reinforced concrete frame structures with unreinforced masonry infill walls), the site likely experienced ground motions between PGA = 0.10g to 0.20g during the main shock.

Figure 4-1 shows the overall layout of the Arequipa WTP. The Arequipa WTP has a rated capacity of about 1,500 l/s (35 MGD). During the July – August months, the weather in Arequipa is dry and mild (typical daytime temperatures about 70°F), which represents the "low water demand" season. According to the plant manager, during the hot weather months, the demand in Arequipa could reach as high as 4,000 l/s (92 MGD), but there is limited water supply, which leads to occasional water outages in parts of the city. The Arequipa WTP supplies about 80% of the total potable water flow capacity for the city, with the remaining 20% coming from wells.

Figure 4-1. Arequipa Water Treatment Plant

As seen in Figure 4-1, the plant is divided into three main basins. In the foreground is a rectangular set of basins (floc / sedimentation on the right, filters on the left). The first large building is the chlorine building. The next large building is the main operations building. Then there is another rectangular set of basins (filters in the foreground, floc/sedimentation in the background). In the background is a circular clarifier. On the left are two rectangular covered clearwells. There is a pump station building next to the clearwells which pumps potable water to higher elevation pressure zones of Arequipa.

Raw water enters the plant from four parallel pipelines located to the right side of Figure 4-1. These raw water pipelines are about 2 km long; one of the 4 pipelines was damaged by the earthquake, and remained leaking and non-repaired as of 34 days after the earthquake. These raw water pipelines range from 14" to 24" in diameter (note that pipe sizes in Peru are commonly denoted in inches of diameter).

Upstream of these 4 raw water pipelines, the raw water is conveyed from the mountains via tunnels and canals. The canal was inundated by landslide debris in one location, and this caused a turbidity spike at the water treatment plant, forcing a 2 hour shutdown of the entire plant.

There was no damage to the reinforced concrete rectangular basins; nor to the concrete troughs in these basins. According to the plant manager, there was wave sloshing in these basins, but the slosh height did not exceed the height of the freeboard in the tanks (Figure 4-2). The sedimentation basins use tube settlers, and some of these (near wall edges) had tilted over in the earthquake, presumably due to water sloshing forces; the settlers had not been repaired 34 days after the earthquake.

Figure 4-2. Arequipa WTP. No damage to concrete troughs, no sloshing over freeboard

Figure 4-3 shows about a dozen small chlorine tanks at the Arequipa WTP. These tanks are used for rechlorinzation at remote reservoir sites, and are often stored at the WTP. As can be seen these tanks are not anchored or chained in any way. During the earthquake, all the tanks tipped over and fell onto the ground. The pressure regulator for one of the tanks broke, and there was a chlorine gas release at the plant. In the cabinet seen in the background of Figure 4-3 are respirators; these were used during the cleanup process.

Figure 4-3. Arequipa WTP. Small Chlorine Tanks

Figure 4-4 shows an Alpaca chained to the raw water gate valve for the plant; presumably, this pet alpaca served as a "canary" – however, it is not known if there were any injuries from the chlorine gas release. Not shown in these pictures are the "ton" chlorine cylinders which are located within the building; all these cylinders were resting on simple roller supports; none were reported to have rolled off their supports during the earthquake.

Figure 4-4. Alpaca at Arequipa WTP – Served as a Peruvian Canary

The circular clarifier did experience a moderate amount of damage. Figure 4-5 shows the radial metal troughs, going from the center column of the clarifier to the outer concrete walls. The volcano in the background is "El Misti" with summit elevation of over 5,800 meters (19,100 feet). the metal troughs were clearly out of alignment after the earthquake, as evidenced by most of the weirs being too far above or below the water line (although this is difficult to see from the picture). This suggests that the steel center column rocked during the earthquake, causing some permanent offsets. Coupled with the other damage to the clarifier, we proposed to the plant manager that the clarifier should be drained and inspected for additional damage from within. The plant manager reported that this was not feasible, as draining the clarifier would reduce plant capacity to below the level of water demand; and seeing as the water demand in July is at the annual low, the plant manager did not have a plan as to how to address the damage to the clarifier.

Figure 4-5. Metal Troughs – Out of Alignment (El Misti in background)

Figure 4-6 shows the exterior wall of the clarifier at the Arequipa WTP. There is a horizontal crack about 4 feet above the ground level, which runs almost entirely around the tank. There are additional cracks near the ground level. These cracks were freshly made by the earthquake, but were not leaking. The three viewing ports seen in Figure 4-6 indicated that the media (clay and sand layers) within the tank were upset, according to the plant manager. Again, as noted previously, taking the clarifier out of service for detailed inspections was not deemed feasible by the plant manager.

Figure 4-6. Clarifier Wall at Arequipa WTP

Figure 4-7 shows the pumping plant building at the Arequipa WTP. About half of the windows (1/4" thick annealed glass panels) were broken; all the glass had been held in place by stiff cement mortar, which explains the high damage rate. Many cracks can be observed in the walls; most of the cracks are located at the interface between the reinforced concrete frame columns and the non-reinforced interior infill walls. The extent of cracking was considered moderate, not indicative of a possible collapse, but warranting either replacement of the infill walls (preferred approach) or a "painting over" (a not unlikely outcome). The extent of the damage suggests that the non-reinforced infill masonry approach yields moderate damage at PGA about 0.15g to 0.2g, and potential collapse at PGA of 0.4g. There was similar types of glass breakage in other plant buildings which had similar levels of damage to infill walls – this suggests that once the infill walls crack, the remaining reinforced concrete frame system becomes flexible enough to cause sufficient story drifts to crack cement-grouted regular glass panes.

No inspections were made of the interior of the two below-ground clearwalls. The heavy concrete roof system is supported by columns on the inside of the reservoir. No rowboat or lighting systems were available to make inspections, and plant personnel had not yet done inspections as of 34 days after the earthquake. It would not be surprising if moderate to extensive damage was found within the clearwells, especially to interior dividing walls.

Figure 4-7. Pumping Plant Building at Arequipa WTP

Figure 4-8 shows the damage to a reinforced concrete walkway leading to the clarifier operating deck. Small reinforcing bars can be seen at the failure location. Figure 4-9 shows the piece of the walkway which has fallen to the ground level.

Figure 4-8. Damage to Reinforced Concrete Walkway

Figure 4-9. Damage to Reinforced Concrete Walkway

Other damage at the plant included a complete loss of all glassware in the water quality laboratory. The glassware was located in cabinets; the cabinet doors swung open during the earthquake, and about $2,000 worth of glassware fell to the floor and broke. Also in the lab, some of the ovens shifted on the counter tops, but did not move sufficiently to fall onto the floor. This shifting of the ovens suggests a minimum PGA of about 0.15g for the site.

Within the City of Arequipa, there are 1,700 km of distribution pipelines. About 80% of the pipeline inventory is asbestos cement pipe, with the newest 205 of the pipeline inventory being PVC pipe with push-on joints. There were about 40 pipeline failures in Arequipa. These pipe failures lead to water outages in some areas, with some outlying suburbs being cut-off from all water supply for 4 days. The geology of Arequipa suggests that the bulk of the pipeline damage was due to ground shaking, with possibly some landslide-induced damage. There were essentially no urbanized areas of Arequipa subjected to liquefaction.

4.2 Moquegua Water Treatment Plant

Figure 4-10 shows the Moquegua water treatment plant (WTP). This photo was taken prior to the earthquake. The three major stages of treatment are as follows:

- Bottom right of photo. Flocculation basins. Although difficult to discern in this photograph, each basin is subdivided by internal baffle walls. Each baffle wall is constructed from asbestos sheets, hung from lightweight steel channels. The baffle walls are oriented such that the incoming raw water must travel a long path before it leaves the flocculation basin, to give ample time for large particles to settle out of the water.
- Middle of the photo. Settling basins. There are five basins shown in this photo.
- Top of the photo. There are four filters shown in this photo.

Figure 4-10. Moquegua Water Treatment Plant (Prior to Earthquake)

There was a strong motion instrument located about 2 km from this WTP. The maximum level of shaking recorded by this instrument was about PGA = 0.3g (see Figures 2-4 to 2-6). The WTP is located on a gently sloping hill at an elevation several hundred feet higher than most of the city. Most likely, the site could be characterized as being on firm to very firm soil. Based on the observed damage to the plant, the motions at this plant were likely at least 0.25g, and perhaps as high as 0.5g.

This WTP was visited on July 25, 2001, or 32 days after the earthquake. When visited, there plant was operating in "bypass mode". By bypass mode, it is meant that raw water to the plant was going directly to the filters, bypassing the flocculation and sedimentation basins which were out of service. Chemical disinfection, which would normally have been done by an automatic chlorination system, was being manually achieved by adding chlorine bleach to the water. No regular plant staff were at the WTP at the time it was inspected; all staff were reported to be away from the plant due to budget / planning issues. When visited, the plant appeared to be operating at about 25% to 50% of plant capacity, or about 2 MGD.

Figure 4-11 shows the empty floc basins, as seen during the plant inspection. The longitudinal "grooves" at the bottom of the tank form the bottom channels used to maintain position of the baffles (all the baffles have been removed from the tank).

Figure 4-11. Primary Flocculation Basin, Moquegua WTP

Figure 4-12 shows the broken baffles resting next to the floccualtion basin. These baffles appeared to be either corrugated lightweight fiberglass or asbestos sheets. These baffles had been hung in the basin from steel channels. Most of the baffle sheets showed damage to their edges, where they had been bolted to the steel channels. The steel channels in turn had been bolted to steel angles on either side of each concrete basin. At the time of the inspection, all the channels (Figure 4-13) and broken baffles (Figure 4-12) were resting near the basin. The bulk of the damage was to the baffles. It appeared to the inspection team that it might have taken a workforce of about 4 men about 2 days to replace all the baffles and channels, but it was reported that there was neither manpower, material or money available to make the repairs.

Figure 4-12. Broken Baffles, Moquegua WTP

Figure 4-13. Baffle Support Channels – Removed from Service, Moquegau WTP

All settling basins were empty of water during the inspection (Figure 4-14). In the bottom half of the basins were diagonal settlers. About 10% of these settlers were tilted away from their natural angle, which would modestly negate their effectiveness. The settlers had not yet been realigned to their proper configuration. None of the enclosed water troughs at the top of the basis appeared to be damaged.

Figure 4-14. Settlers at Moquegua WTP

The chlorine one-ton tanks were located in small building. This building had a chain link fence as one wall. Figure 4-15 shows the tank configuration. The tank on the left is the spare tank and rests on a wooden "2x4" skid system; this tank was empty at the time of the earthquake. The tank on the right is the active tank, with a "pig-tail" type of hose system attached to the tank at the far side (unseen in this photograph). The empty tank at the left rolled off its supports, coming to rest about 1.5 feet to the right near the active chlorine tank. but as it was not connected, it broke no attached hoses. The active tank at the right did not roll off its supports (note that it is resting on a scale), but showed evidence that it pushed its supports by about an inch or so. It is possible that the sloshing of the chlorine fluid within the tank acted as a "active mass damper", to partially alleviate the dynamic motions of the in-service tank; or possibly it is just luck that this tank did not also roll off its supports; had that happened, it is possible that the attached pig tail hose would have been broken, leading to a substantial chlorine gas release; fortunately, this did not occur. A plant watchman noted that there was a lack of confidence in the chlorine system, and he preferred to use a manual approach of adding chlorine bleach to the finished water. As to the structure of the chlorine building itself – it was moderately damaged (reinforced masonry frame structure with infill non-structural masonry), with through wall cracks (1/16 to 1/8 thick cracks) running diagonally through several of the walls.

The earthquake caused a loss of offsite power to this WTP. The WTP has a standby diesel generator, seen in Figure 4-16. With the exception of the battery, the generator was otherwise well anchored. The battery fell over in the earthquake, and spilled acid on the floor. The generator was presumed not to be operational immediately after the earthquake. Reportedly, offsite power was restored to the WTP prior to repairing the emergency generator, and it is not known if this generator was ever used during or after the earthquake. The battery remained unanchored in its repaired state.

Figure 4-15. Chlorine Tanks – Moquegua WTP

We were unable to obtain an estimate of water distribution system pipeline damage in Moquegua. Based on extra pipe available at the water treatment plant site, the most recent distribution pipe installations were typically 6" diameter PVC pipe with push-on joints. Older distribution pipe is most likely asbestos cement. It is likely that there was some damage to distribution pipes, either due to landslide (a substantial portion of the city is located on moderately steep slopes), subsidence (the city is underlain by alluvial soils which in some locations might be underlain by loose soils) or strong ground shaking. The extremely dry local conditions suggest that liquefaction was either non-existent or extremely rare in the locale of the city.

Figure 4-16. Emergency Generator – Moquegua WTP

4.3 Tacna Water Treatment Plants

The city of Tacna has two water treatment plants. While there were no strong motion recordings in Tacna from the main shock, it is estimated that the level of ground motion at the two WTPs was in the range of PGA = 0.02g to 0.10g, considering observed damage (mostly lack of damage) to nearby structures.

The main water treatment plant has two clarifiers. Some minor damage to metal troughs where they are connected to the center islands and the outer concrete walls occurred; this damage was not sufficient to hamper plant operations.

The operations building suffered slight to moderate structural damage, at non-reinforced infill masonry wall locations. This damage was not serious in terms of an immediate collapse hazard; however, the structural integrity of the entire building would be seriously challenged should the Tacna portion of the Nazca fault break.

A partially buried reinforced concrete clearwell (Figure 4-17) at one of the water treatment plants was inspected from the outside. This reservoir used a heavy concrete roof system, support on interior columns, with lateral resistance provided be exterior concrete walls. The bottom of the reservoir used a concrete lining. It was evident from the outside that the roof system had been damaged, likely from sloshing wave action on the inside, coupled with modest inertial forces (PGA at the side was in the 0.10g range). There were several portions of the roof system which had visible settlements on the order of 4 to 12 inches. The outside reservoir walls, above the ground surface, were cracked, likely from excessive shear forces during the earthquake. Outside the reservoir, there was a pile of remnants of liner damage (about 100 pieces, total volume about 2 cubic yards). The water utility had yet to make a comprehensive inspection of the reservoir from the inside, although they expressed concern about the damage.

Figure 4-17. Tacna WTP – Damage to Walls of Reinforced Concrete Clearwell

The plant also had numerous non-structural seismic deficiencies such as non-anchored equipment, unanchored batteries, unanchored chlorine tanks, etc., but the low level of shaking did not lead to any serious problems.

4.4 Water Storage Tanks

The cities of Arequipa, Moquegua and Tacna have relatively few above ground potable water storage tanks. In Tacna, we observed a few elevated reinforced concrete tanks, which we could observe no damage (PGA under 0.1g). There were similar elevated concrete tanks in Ilo which were undamaged (PGA 0.15 to 0.25g range).

In a small farming community between Ilo and Tacna, along the Pacific Ocean coast, we observed one elevated concrete tank which had been taken out of service. The small pump building at the base of the tank was collapsed; there was spalling of concrete at some of the reinforced concrete beam-column joints. At the time of the earthquake, the tank was empty, due to the prior failure of the pump to fill the tank.

In all cities, we observed a great number of small (100 gallon to 500 gallon) water tanks situated at the top of residential and commercial buildings. We made no detailed reconnaissance of these tanks; in only unusual cases (under 5% of the total tanks observed) did we observe any movement to these tanks. However, any damage to these tanks was likely repaired by building owners by the time we made our reconnaissance.

At Ilo, we observed three at-grade welded steel water storage tanks at a power plant. Each of these tanks was anchored to a concrete ring girder using eight 1.5 inch diameter anchor bolts. Figures 4-18 and 4-19 show one of these three tanks, along with a typical anchor bolt. This tank had capacity of about 1,500,00 liters of water, and was full at the time of the earthquake. The tank dimensions were height 12.2 meters, diameter 14.5 meters, water level at the time of the earthquake 11.6 meters. Each of the 8 anchor bolts stretched out of the foundation by about 1.5 to 2 inches. None of the attached pipelines (side entry) were damaged, although each pipe was long enough before its first support to likely be able to accommodate a few inches of vertical movements. There was no evidence of elephants foot buckling on this tank.

Figure 4-18. Water Tank Near Ilo

Figure 4-19. Stretched anchor bolt – 1,500,000 tank near Ilo

The two other water tanks at this site were larger diameter (18 meters), with somewhat lower height (9.5 meters). These 2 water tanks did show evidence of anchor bolt stretch. There was also a 5,000,000 liter at-grade welded steel diesel fuel tank at this site; with dimensions of 21.3 meters, height of liquid 15.6 meters, and height of roof 16.3 meters; this tank also did not show evidence of anchor bolt stretch. (All three tanks had eight anchor bolts into a circular ring girder or concrete mat foundation). The site PGA was likely in the 0.15g to 0.5g range, and more careful study of this plant is likely warranted.

5.0 CANAL WATER SYSTEMS

The climate of much of southern Peru is very dry. As the prevailing wind direction is east to west, the western exposures of the Andes get little rainfall. Annual rainfall over much of the coastal region is just several inches per year (desert-like). Going inland, the rainfall amounts increase to moderately low amounts at the higher elevations of the Andes foothills (up to about 3000 m elevation), increasing to very high amounts on the eastern faces of the Andes mountains.

For these reasons, there is a great need to transport water from the higher elevations of the Andes (about 150 km inland) to the urban and agricultural areas further to the west. Since the early 1970s, there has been a substantial effort to build aqueducts to transport this water. Most of the aqueducts are either water tunnels or water canals – very little of the aqueducts are pipelines.

In the region northwest of Arequipa, the canal system is dominated by the Majes – Siguas aqueduct system. This system includes 88 km of tunnels and 13 km of canals. System capacity of Q=34 m^3/sec (23 MGD). According to the operator of this system, there was no damage from the earthquake; however, inspections of the tunnels have not yet been performed. The bulk of this system is located between 75 and 150 km east of the Pacific Ocean coastline; and PGA levels were likely in the 0.01g to 0.05g range.

Immediately north and east of Arequipa along the Chili River is a system of tunnels and canals which provide water to five hydroelectric power plants (total capacity about 160 MWe) and which also serve as the raw water supply to the Arequipa WTP. The canal portion of the system traverses of steep canyon, flowing downslope along the topographical contour lines. In at least one location, a landslide deposited debris into the canal. Workmen repaired this damage location in about 2 hours. This caused a turbidity spike in the raw water that eventually entered the Arequipa WTP. The PGA at the landslide location was likely in the PGA=0.05g range. Further upstream (and further from the earthquake) there is a 13 km long water tunnel (PGA range about 0.01 to 0.04g). The power plant operator reported that there was no damage to this tunnel, although it had not been inspected since the earthquake.

In Moquegua Department, the canal system is dominated by the Pasto Grande aqueduct system. Design of this system began in 1987, with construction originally scheduled to be completed in 2002. The bulk of the system had already been built by June 23, 2001, including the Moquegua WTP. This system includes (from west to east) the Moquegua-to-Ilo canal; the Otora-Torata canal; the Humalso canal, the Jachacuesta Tunnel, the Pasto Grande Canal, the Cuetire Tunnel and six hydroelectric power houses en-route.

There was no reported damage to the tunnels; although these had not yet been inspected, and PGA values were likely in the 0.01g to 0.05g range. However, the Otora-torata and other canals suffered serious damage, including about 106 locations where landslide debris entered the canals (Figures 5-1 through 5-4). Substantial lengths of canals were exposed to ground shaking levels in the PGA = 0.10 to 0.30 (or higher) range. In at least a few locations, the landslide debris also damaged the reinforced concrete canal walls. It required a workforce of 60 men a total of 35 days to perform emergency repairs to the canal system and restore water flows.

Figure 5-1. Landslide Debris in Canal Near Moquegua

Figure 5-2. Landslide Debris into Canal Near Moquegua

Figure 5-3. Landslide Debris into Canal Near Moquegua

Figure 5-4. Landslide Debris into Canal Near Moquegua

6.0 CONCLUSIONS

This report presents a summary of damage to water systems in the Atico, Peru M_w 8.4 earthquake of June 23, 2001. The damage to water systems can be grouped into three areas: slight to moderate damage to water treatment plants, slight damage to distribution pipeline systems, and heavy damage to canal systems.

The level of ground shaking was very long in duration (over 50 seconds of strong ground motion). The lack of liquefiable soils over most of the urbanized areas prevented the widespread destruction of underground pipelines. There was widespread evidence of landslides, and these had serious impacts on canals, as well as other lifelines such as highways and railroads.

The damage to water treatment plants included some potentially life threatening damage to chlorine systems. We observed a great many seismic deficiencies at the water treatment plants, and future earthquakes, such as along the Tacna segment of the Nazca – South America plate interface, could cause more serious damage. Generally, reinforced concrete structures performed well at the water treatment plants, but infill wall structures (the most common style of construction in southern Peru) were consistently damaged, even under moderate levels of shaking.