International Conference on Case Histories in Geotechnical Engineering

(2004) - Fifth International Conference on Case Histories in Geotechnical Engineering

14 Apr 2004, 4:30 pm - 6:30 pm

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Joanna L. Meldrum
Exponent Failure Analysis Associates, Inc., Menlo Park, CA

Akshay Gupta
Exponent Failure Analysis Associates, Inc., Menlo Park, CA

Brian McDonald
Exponent Failure Analysis Associates, Inc., Menlo Park, CA

Recommended Citation

Meldrum, Joanna L.; Gupta, Akshay; and McDonald, Brian, "Investigation of Structural Damage in a Corrosive Environment: A Case Study" (2004). *International Conference on Case Histories in Geotechnical Engineering*. 19.
https://scholarsmine.mst.edu/icchge/5icchge/session01/19

Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

Investigation of Structural Damage in a Corrosive Environment: A Case Study

Joanna Meldrum, P.E.
Exponent Failure Analysis Associates, Inc
Menlo Park, CA-USA-94025

Akshay Gupta, Ph.D., P.E.
Exponent Failure Analysis Associates, Inc
Menlo Park, CA-USA-94025

Brian McDonald, Ph.D., S.E.
Exponent Failure Analysis Associates, Inc
Menlo Park, CA-USA-94025

ABSTRACT

This paper presents the methodology and results of an investigation into the causes of structural damage to a reinforced concrete block wall building in Lake Havasu City, Arizona. The structural damage was in the form of cracking and spalling of the lower courses of the block along the building perimeter.

The structural damage to the building had been incorrectly attributed to the Hector Mine Earthquake by another investigator. An evaluation of the response of the building to the estimated level of ground shaking, coupled with site observations, conclusively ruled out the earthquake ground shaking as a cause for the structural damage.

Site observations indicated corrosion of reinforcing steel as the fundamental cause for the cracking of the concrete block. Samples of the block, grout, soil, flatwork concrete, and irrigation water were collected during the site investigation. Chemical testing of the soil and water samples, which indicated high levels of sulfates and chlorides, substantiated the site observations that over time the exposure to the soil and water had resulted in an environment that facilitated and resulted in severe corrosion of the steel.

This case study highlights the potential for serious structural damage in a corrosive environment, and also cautions against reaching engineering conclusions without a holistic understanding of the problem.

INTRODUCTION

Cracking at the base of reinforced concrete block walls is a familiar and well-understood earthquake damage mechanism. Following the magnitude 7.1 Hector Mine Earthquake of October 16, 1999, cracking at the bottoms of relatively narrow concrete block shear walls was observed at a 4-story building in Lake Havasu City (approximately 110 miles east of the earthquake epicenter). The cracking was naturally attributed to the earthquake. This paper presents a case study in which the cause of the cracking was reevaluated considering the damage potential of the earthquake ground shaking as well as other environmental factors.

An inspection of the site identified severe damage in the form of cracking of the base block around the building perimeter. As evidenced by the severe corrosion damage everywhere, the potential for catastrophic failure of the structure could not be ruled out.

ASTM defines corrosion as "…*the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.*" Corrosion proceeds by electrochemical reactions, which involve the transfer of electrons between an anode and a cathode. Corrosion of steel occurs because in the processed form, steel is thermodynamically unstable. In order to reach stability, the iron in steel wants to move back to its native, oxide state. Figure 1 shows the typical corrosion reactions.

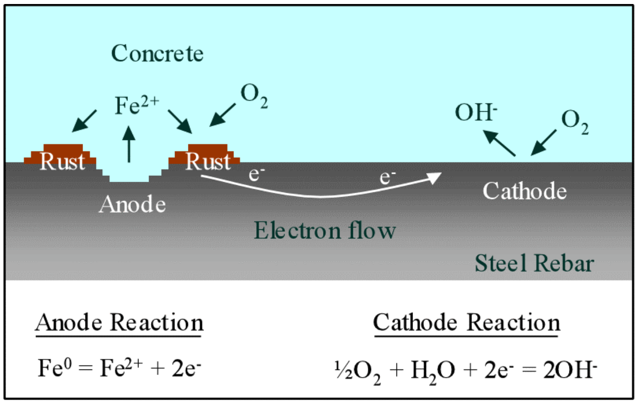


Fig. 1. Schematic showing basic corrosion reactions for steel.

Corrosion of reinforcing steel in concrete is a concern in a variety of environments. The primary damage mechanism is spalling and cracking of concrete due to the expansion of corrosion products formed as a result of the oxidation of the steel. In order for corrosion of reinforcing steel to occur, two elements must be present – oxygen and water. Reinforcing steel is protected while encased in concrete as the high alkalinity allows for the formation of a protective oxide film on the steel. However, many researchers believe that chloride ions destroy this protective film, thereby making the steel susceptible to corrosion if both moisture and oxygen are present (Kitowski and Wheat, 1997, NACE, 1996).

This problem of poor structural performance in an adverse environment needs to be addressed by geotechnical engineers for both foundation design and failure analysis. Cracking can be caused by a relatively minor amount of corrosion; yet in some cases can seriously compromise the structural performance of a structure.

BUILDING AND SITE DESCRIPTION

Building Description

The subject buildings that were under investigation consist of two 4-story buildings and a 1-story conference area/restaurant building (for confidentiality reasons an overall view of the buildings is not presented in the paper). The buildings were constructed circa 1972. The structures are founded on shallow, spread footings. The bottom floor is concrete slab-on-grade. Lateral load resistance is provided by structural shear walls constructed of reinforced concrete block. Concrete block is sometimes referred to as “CMU,” which is an acronym for concrete masonry unit. The exposed concrete block on the building exterior has an architectural texture and is often referred to as “slumpstone.” The transverse concrete block walls also serve as bearing walls for the precast floor planks.

Of particular interest are the exterior shear walls along the east and west sides of the 4-story buildings. Figure 2 presents an overview of a typical exterior wall.

Fig. 2. Typical narrow exterior wall. Note that previous destructive testing had been performed on the left side of the wall.

These walls are typically 6-feet 8-inches long, with some walls being only 5-feet long, resulting in rather slender walls. The walls are comprised of 4-inch (high) x 8-inch (thick) x 16-inch (long) slumpstone block over a single course of 8-inch base block placed on the cast-in-place foundation. The walls are located at, and typically centered on, the transverse (north/south) walls, thus forming “T”-shaped sections.

Typical vertical reinforcement consisted of two steel rebars at either end of the wall, with rebars also provided at the intersection of the web (north-south interior walls) to the wall. Horizontal reinforcement is present in the 8-inch base block.

Project Site Description

The project site is located in The Basin and Range Province of Arizona. This area is characterized by numerous mountain ranges that rise sharply from plain-like valleys or basins. In general, ranges and associated basins in Arizona trend north to northeast and have through-flowing drainage. The site geology is classified as Quaternary and upper Tertiary sedimetary deposits. These sediments contain gravels, sands, silts, clays, marl, gypsum, and salt that represent combinations of fluvial, lacustrine, colluvial, and alluvial fan deposits (Hendricks, 1985).

The project area is located in a dry region of Arizona; as seen in Fig. 3 the area receives less than 8 inches of rainfall per year.

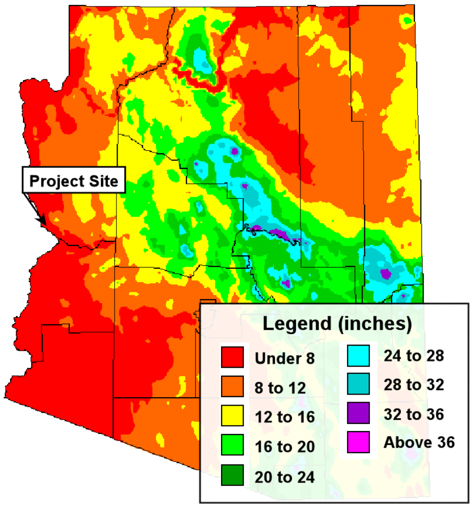


Fig. 3. Annual precipitation map of Arizona (Desert Research Institute, 1997).

In low precipitation areas, very litte water is added to the soil through direct rainfall or runoff. As such, insufficient water is added to the soil for leaching to occur. The water that does enter the soil penetrates only a limited depth such that soluble constituents are not removed from the soil profile. In dry areas, such as this project area, the soils typically have high concentration of soluble salts and carbonates (Hendricks, 1985).

OBSERVED DAMAGE

Damage to these walls in the form of vertical cracking (or splitting) of the first few courses of block above the foundation level was reported subsequent to the October 16, 1999, Hector Mine Earthquake. The damage was noticed at the bottom, outboard ends of many of the walls, at or just above/below the soil line (Fig. 4).

Fig 4. Typical damage observed at base of slender CMU wall.

Further inspection revealed that the blocks were spalling (splitting) along a vertical plane parallel to and behind the front face of the wall (Fig. 5).

Fig. 5. Example showing existence of vertical crack in the central portion of a wall. The arrow points to the outer face of the block wall.

The cracks typically "daylight," and are thus visually apparent, only at the wall ends (Fig. 4) and along the lowest mortar joint typically below grade and not visible without excavation.

During the site investigation, the soil adjacent to the walls was excavated (depth ranging from less than a foot to 2-feet) to expose the base block in more than twenty locations around the perimeter of the buildings. It was noted that the cracking extended along the entire length of the wall in all areas where a source of water (sprinkler, spigot, drain, etc.) was identified in the immediate vicinity of the wall. The cracking was also observed along the non-slender north and south walls of the buildings. Figure 6 shows typical cracking noted in the base block of the squat walls.

Fig. 6. Typical cracking of base block. This condition was observed around the entire perimeter.

In all cases, the cracks and spalling of the CMU shells occurred at locations that exhibited significant corrosion of the reinforcing horizontal steel (Fig. 7).

Fig. 7. Example of severe corrosion of reinforcement in concrete. The arrow points to corrosion product as the original steel was completely corroded.

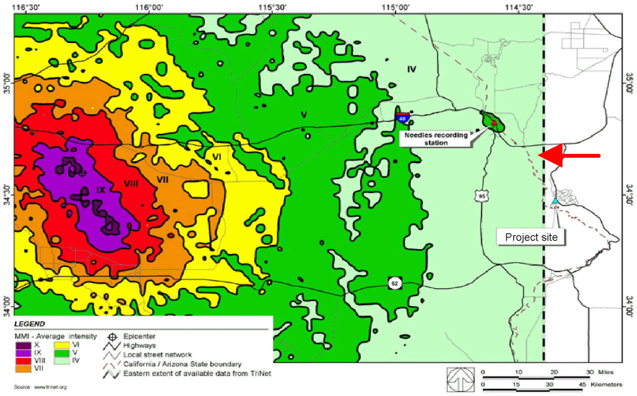
Apart from the severe cracking and spalling at the base of the exterior walls, the building structure was observed to be in relatively good condition. Minor cracking of the interior gypsum wallboard finishes was observed, typically at the reentrant corners above door openings (there are no control joints at these locations). Hairline cracks were observed in the mortar joints between precast ceiling planks, and some short cracks were observed in the block walls at exterior balcony corners.

DAMAGE POTENTIAL OF THE HECTOR MINE EARTHQUAKE AT PROJECT SITE

The magnitude 7.1 Hector Mine Earthquake struck at 2:46 AM (local time) on October 16, 1999. The earthquake resulted from a right-lateral strike-slip on the Lavic Lake fault and central section of the Bullion fault, resulting in 41 km of surface rupture with a maximum surface offset of 5.2 meters. The earthquake epicenter was located about 110 miles west of the project site. No structural damage was reported in the vicinity of the project site or surrounding areas, which is not surprising given the remote nature of the event.

Ground Shaking

A commonly used measure of earthquake damage distribution is the ground shaking intensity. In the United States, the most common measure of earthquake intensity is the Modified Mercalli Intensity (MMI) scale, which is an empirical measure of the effect of local ground motions on structures, contents, people, and the environment. The MMI scale ranges from MMI I (imperceptible) to MMI XII (virtually total destruction). Based on site soil characteristics, recorded ground accelerations, and empirical relationships derived between ground acceleration/velocity and MMI (Wald, 1999), TriNet provides an instrumental intensity (similar to MMI) map for recent and historical earthquake events. Figure 8 presents the instrumental intensity map for the Hector Mine Earthquake based on the TriNet data.



Source: www.trinet.org

Fig. 8. Intensity distribution for the October 16, 1999 Hector Mine Earthquake (based on TriNet data). The arrow points to the eastern extent of the TriNet data.

As seen in Fig. 8, based on the TriNet data, the ground shaking intensity at the project site is estimated to be less than V (more likely IV, but conservatively using V). At Intensity V the shaking is described as *moderate* from a human perception standpoint and *very light* from a potential structural damage standpoint. TriNet also compiles a "felt intensity," which is an intensity measure based on observations made by residents of different areas during the ground shaking. Based on 58 independent descriptions of the ground shaking for the zip code in which the project site is located, TriNet reported the ground shaking "felt intensity" to be IV. At Intensity IV shaking is described as *light* from a human perception standpoint and no structural damage is expected.

The nearest recording station to the project site is located in Needles, California, which is approximately 96 miles east of the epicenter and 28 miles north–northwest of the project site. A peak ground acceleration of 0.071g was recorded at the Needles station (Fig. 9). Again, the peak ground acceleration value suggests a low possibility of any structural damage.

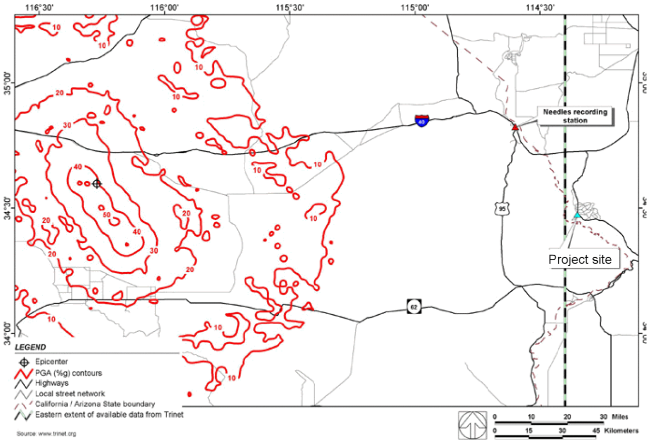


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Fig. 9. Peak acceleration map for the October 16, 1999 Hector Mine Earthquake (based on TriNet data).

The spectral acceleration at a period of 0.3 seconds, at Needles, as reported by TriNet, was 0.138g. Using standard attenuation relationships, the epicenter-to-site distance, and the ground motion parameters reported for Needles, the peak ground acceleration at the project site was conservatively determined to be 0.066g, with a spectral acceleration of 0.12g at a period of 0.3 seconds. These estimated values are consistent with (slightly higher than) the values reported by TriNet, which indicate a peak ground acceleration of 0.053g and spectral acceleration of 0.102g at the TriNet grid point located closest to the project site (the TriNet information geographically stops short of the project site).

These estimates of the ground shaking at the site are far below the thresholds observed for damage to similar buildings in past earthquakes.

Using the obtained ground motion values, a conservative estimate of the interstory drift was obtained as 0.034% (a very low value). As a point of comparison one would expect about the same level of roof displacement for a temperature differential of 20^{o}F (average temperature differential for the City is noted as 27^{o}F). The calculated value of 0.034% is also about 3 times smaller than the threshold value for initiation of interior finish cracking (CUREE) and about 6 times smaller than the threshold value for cosmetic damage to interior finishes (Arnold, 2003).

Historically, slight damage to structures classified as similar to the structures being investigated is expected at median drift values of 0.27% (HAZUS), which is about 8 times the calculated drift for the structure for the Hector Mine Earthquake.

In addition to the low intensity of the ground shaking and analytical basis for ruling out the earthquake as the possible cause for the observed damage, other aspects of the observed damage clearly indicated that the damage was not a result of the earthquake ground shaking: These observations included:

- The cracking at the outside edges of the walls is principally *vertical*. Based on the historical performance of concrete masonry shear wall buildings, as well as fundamental engineering analysis, earthquake-induced stresses would cause *horizontal* cracks at the bottom corners of the walls associated with the principal tensile stresses caused by in-plane bending.

- Significant cracking was observed in the long squat shear walls (north and south faces of the buildings) supporting relatively light loads. Stresses from earthquake ground shaking would have been essentially negligible in these walls.

- Cracking was not limited to the outboard edges of the walls, as incorrectly claimed by a previous investigator. Cracking was often worse in the center portion of the wall, where earthquake stresses would have been smallest (Fig. 3).

- The condition of the interior and exterior finishes and structural elements was inconsistent from a seismic induced damage pattern. Damage was observed at the base of the exterior walls only; there was no cracking found in any interior shear wall.

- Reported events such as bottles not even falling from shelves indicate that the shaking intensity was low even for content damage, thus the shaking intensity would most likely not result in any structural damage at the site.

LABORATORY EXAMINATION OF SITE MATERIALS

Following the visual inspection of the building perimeter, six locations showing distress (cracking and spalling) were selected for destructive testing as representative of typical conditions. At each location a test pit was excavated, exposing the base block and a portion of the foundation. Soil samples were collected from the immediate vicinity of the foundation, at depths of 2 to 6 inches below grade. Samples of slumpstone, grout, and base block were collected from four of the test pits. At each location samples of corroded reinforcement and corrosion product were also collected. In addition, concrete cores were collected from two locations in the sidewalk. A sample of the irrigation water was also collected.

A total of 22 soil samples were collected for chemical analysis. Thirteen of these samples were analyzed for moisture content, pH, and resisitivity, as well as chloride, sulfate, and bicarbonate ion contents. The irrigation water sample was analyzed for pH, and chloride and sulfate ion content. Relevant test results are given in Table 1.

Table 1. Soil, and Irrigation Water Test Results

Sample number	Sulfate Concentration (ppm)	Chloride Concentration (ppm)	Moisture Content (%)
1	418	31	11.2
2	52	8	7.7
3	219	26	2.5
4	648	33	39.3
5	102	10	16.0
6	576	35	21.1
7	58	11	23.0
8	98	15	17.3
9	66	6	12.8
10	20	3	5.3
11	131	17	1.2
12	109	18	19.4
Water	210	89	n/a

Representative results from the testing of the concrete samples, indicating greater that 1,500 ppm chlorides in 4 of the 8 concrete block and mortar samples are given in Table 2.

Table 2. Chloride Concentration in CMU Block Samples

Sample Type	Sulfate Concentration (ppm)	Chloride Concentration (ppm)
Grout	2500	130
Grout with gypsum and halite deposits	12300	8410
CMU Block	7800	1430
CMU Block with gypsum deposits	11200	ND
Slumpstone	3200	2490
Grout Rubble	2400	300
CMU Block	5300	5330
Slumpstone	2500	6230

Analysis of the water sample collected, and water chemistry results from the City Water Department for the past 12 years indicate the presence of sulfate and chloride ions in the irrigation water as presented in Fig. 10 and Fig. 11.

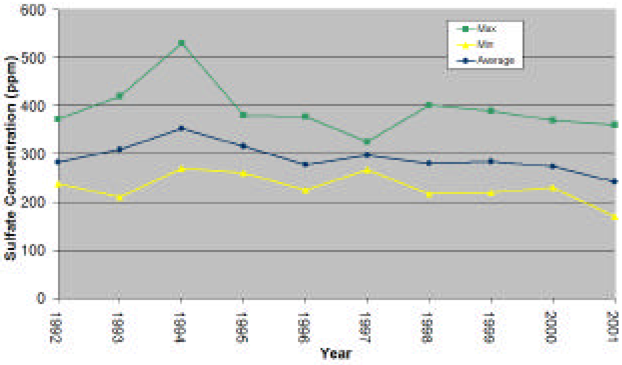

Fig. 10. Sulfate content data from the City Water Department.

Sulfate is classified under the secondary maximum contaminant level (SMCL) standards by the Environmental Protection Agency (EPA). The SMCL for sulfate in drinking water is 250 milligrams per liter (mg/l), sometimes expressed as 250 parts per million (ppm). Secondary Standards are based on taste, odor, color, corrosivity, foaming and staining properties of water. As shown in Fig. 10, the average sulfate concentration in the Lake Havasu City water exceeds the EPAs SMCL.

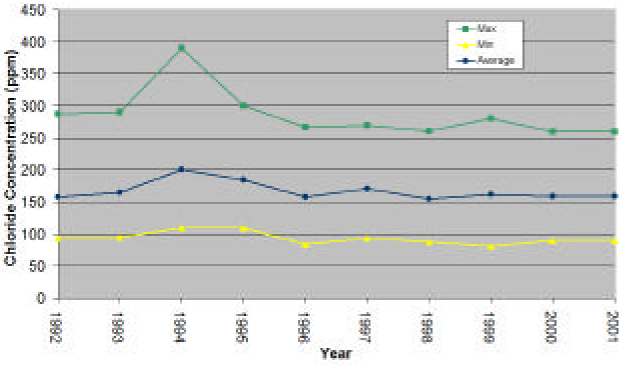

Fig. 11. Chloride content data from the City Water Department.

The SMCL for chloride in drinking water is also 250 ppm. As shown in Fig. 11, the average chloride concentration in the Lake Havasu City water is lower than 250 ppm, however maximum levels exceed the EPAs SMCL.

Scanning Electron Microscope (SEM) and Energy-Dispersive Spectroscopy (EDS) on three reinforcement and corrosion product samples was carried out to determine the elemental composition of the corrosion products. The results of the EDS analysis detected chloride ions on the corroded reinforcement samples and in the corrosion product (Fig. 12).

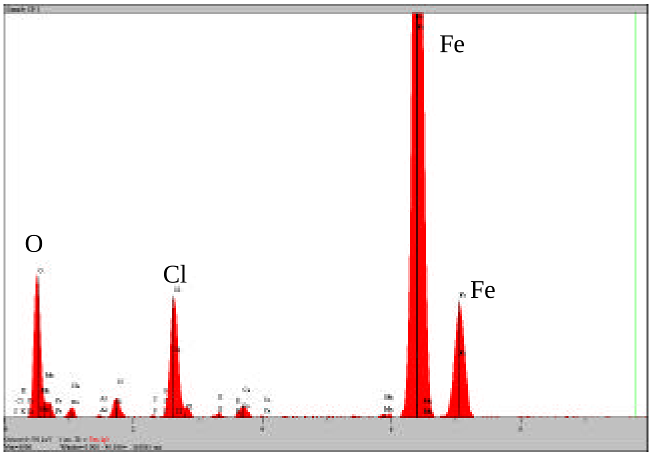

Fig. 12. Example of Electron Dispersion Spectroscopy (EDS) result for corroded reinforcement specimen

ANALYSIS OF ENVIRONMENTAL FACTORS

Corrosion of Steel Reinforcement

Chloride ions are aggressive and are known to cause corrosion of reinforcement in concrete. The National Association of Corrosion Engineers (NACE) Standard "Recommended Practice for Design Considerations for Corrosion Control of Reinforcing Steel in Concrete" (NACE RP0187-96) states

> "*Corrosion of reinforcing steel in concrete is a serious problem in certain environments. The major cause of this corrosion can be attributed directly to the presence of significant amounts of chloride or other aggressive ions at the surface of the steel.*"

Both the chloride and sulfate concentrations in the collected soil sample were low. The sample of irrigation water had concentrations of both chloride and sulfate ions that was consistent with the data obtained from the City Water Department. Irrigation sprinklers, spigots and other sources of water were observed in direct correlation with the location of corroded rebar

In addition to chloride ions, water is a necessary ingredient for corrosion of reinforcement to occur. Water is present in soils from irrigation as seen by the moisture content data in Table 2. Corrosion was only observed in the vicinity of identified water sources.

Water in direct contact with the foundation exposed the concrete to chloride and sulfate in sufficient concentrations over time to allow these aggressive ions to accumulate. High amounts of soluble salts can accumulate readily in concrete because as water evaporates, the soluble salts that it carried remain in the concrete. Over time, fairly large accumulations of soluble salts accrue by this process.

An often-cited threshold value of chloride in concrete to cause corrosion is 1,500 ppm (ACI, 1984). However, in zones of cyclic wetting and drying, the chloride threshold for corrosion is significantly lower. The maximum measured chloride concentration at the site (grout sample) is as high as 8,410 ppm.

Sulfate Attack of Concrete

Sulfate ions in contact with concrete can cause the cement component of concrete to degrade, resulting in a more porous concrete (Fig. 13). This facilitates ingress of water, oxygen, and aggressive ions. The moderate levels of sulfates in the irrigation water are sufficient to cause mild sulfate attack. (ACI, 1992). Some evidence of sulfate attack was also noted in the petrographic analysis of the concrete samples.

Fig. 13. Example of deteriorated concrete located next to a source of water.

In summary, corrosion of reinforcement and resulting cracking of concrete block is consistent with long-term exposure to the environment at the site (water, oxygen, sulfates, and chlorides along with repeated wetting and drying cycles). The necessary ingredients for corrosion of reinforcement in concrete exist at the project site.

Chloride levels in the concrete materials were well above the corrosion thresholds established by the American Concrete Institute. In addition, chlorides were evident in the corrosion product and on the corroded reinforcement surface. There is evidence of sulfate attack of the concrete, which allows more water, oxygen, and chloride to reach the steel, thereby facilitating increased corrosion.

CONCLUSIONS

Evaluation of structural damage requires a holistic understanding of the behavior and response of not only the structure, but also its constituent elements and materials, as clearly evidenced in the case study described above.

The earthquake ground shaking being a cause of the damage was conclusively ruled out based on:

1. Characteristics of the ground motion at the project site (Intensity, peak ground acceleration, spectral acceleration, etc.).
2. Low damage potential of the earthquake ground shaking as evidenced by the structural analysis. It should be noted that the structural analysis does not need to be complex for this type of assessment.
3. Assessment of behavior and response of the structure (cracking pattern inconsistent with seismic loading, even content damage not occurring at the site, concentration of damage on the exterior, among others).

The damage was clearly identified as being a result of ongoing long-term corrosion of the reinforcement steel due to the presence of water, oxygen, sulfates, and chlorides in the environment. Presence of all these elements, coupled with the wetting and drying cycles, resulted in the damage to the slumpstone and base block. Observations of damage included:

1. Splitting of the concrete block in all cases was associated with corrosion of the reinforcing steel. The volume of the corrosion product that is formed as the reinforcement corrodes is several times that of the original (uncorroded) steel. As the corrosion product expands, it stresses the surrounding concrete, eventually leading to cracking of the concrete block. In some locations the steel reinforcement was observed to be entirely corroded.
2. Cyclic irrigation draws water into the concrete, the chlorides in the concrete then concentrate with repeated water inlet and evaporation. This makes the environment at the subject property conducive to steel corrosion.
3. Poor placement of the reinforcing bars facilitates the corrosion (at many exposed locations it was observed that the reinforcement was not adequately embedded in the grout thereby facilitating exposure of the steel to the elements).

This investigation highlights the important issue of geotechnical engineers properly considering the environmental effects on the performance of the structure, as corrosion can result in to significantly poor structural performance.

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