PRELIMINARY INVESTIGATION AND ANALYSIS OF BUILDING DAMAGE

in

the Villages of

Agel, El Salitre, San José Ixcaniche, and San José Nueva Esperanza

San Miguel Ixtahuacán and Sipacapa Municipalities San Marcos Department Guatemala

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ABSTRACT

Background: Buildings in communities near the Marlin mine in western Guatemala have developed serious cracking in walls and floors. Inhabitants believe that the damage is caused by vibrations from explosive blasting at the mine and heavy truck traffic through their villages. They say that their buildings have not had problems with cracking prior to the mining.

The mining company's environmental impact study and annual monitoring reports give no indication that any preliminary structural assessment of buildings was performed prior to mine construction or that there has been any ongoing monitoring by the company of ground vibrations and building damage.

Objective: The goal of this study was to identify possible causes of the structural damage to buildings and to assess the likelihood of each possible cause.

Methods: Several buildings in villages immediately surrounding the mine and in two control villages farther from the mine and outside its area of impact were viewed by engineers of the study team. Cracks in buildings were measured, labeled and photographed on periodic revisits. Soil samples adjacent to the buildings were taken and tested in a certified laboratory in the United States. The engineering team conducted vibration monitoring of heavy truck traffic and mine blasting. They also observed the local terrain to identify any signs of land instability. Local construction methods were noted and homeowners were interviewed about the damage. The team also reviewed public scientific records of local geology, seismic activity, and soil types.

Results: Most significantly, buildings in the villages near the mine have many more cracks than the buildings in the control villages. Land instability, seismic activity, damage due to underlying soil types, and to faulty construction were eliminated as likely causes of the structural cracking. The type and pattern of most cracks were determined to be those caused by ground vibrations. Vibration monitoring results were not conclusive as to the damage being caused by ground vibrations, but no other possible causes were identified.

Conclusions: By a process of elimination, the most likely cause of the building damage is ground vibrations. There are no sources of vibrations in the area except those resulting from mine blasting and heavy truck traffic; therefore it is very highly likely that the damage in local villages is caused by the mining activity and associated truck traffic.

Recommendations: The engineering team strongly recommends additional monitoring, particularly because the mining company has started mining in a new open pit that is much closer to portions of the affected villages.

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Acronyms

CONRED – Coordinadora Nacional para la Reducción de Desastres
COPAE – Comisión Pastoral Paz y Ecología
EIA&S - Estudio de Evaluación de Impacto Ambiental y Social
MARN – Ministerio de Ambiente y Recursos Naturales
MEG – Montana Exploradora de Guatemala, S.A.
MEM – Ministerio de Energía y Minas
UUSC – Unitarian Universalist Service Committee

INTRODUCTION

An engineering team of international and national experts observed abnormal structural damage in walls and floors of houses, churches, and stores in communities surrounding the Marlin mine. A gallery of photos showing typical cracking damage appears in Figure 1. The Marlin mine is located in the municipalities of San Miguel Ixtahuacán and Sipacapa, of the San Marcos Department, Guatemala. The location of the mine and surrounding villages is shown in Figure 2. Marlin is owned and operated by Montana Exploradora de Guatemala, S.A. (MEG), which is a subsidiary of Goldcorp, Inc., whose headquarters are in Vancouver, British Columbia, Canada.

Local residents requested a study of widespread cracking in more than one hundred buildings in various villages located close to and around the Marlin mine.

The locations of villages with structural damage include the following:

Agel	15 degrees 14.04 minutes north 91 degrees 42.85 minutes west
El Salitre	15 degrees 15.64 minutes north 91 degrees 41.17 minutes west
San José Ixcaniche	15 degrees 15.09 north 91 degrees 40.99 minutes west
San José Nueva Esperanza	15 degrees 13.99 minutes north 91 degrees 41.84 minutes west

The residents report that the damage began to appear with the construction and operation of the mine. They believe that mine blasting and increased heavy vehicle traffic through their villages causes the damage, as the mining is the only new large-scale activity in the area and they have not had this type of problem before. (COPAE and Valiente, 2007). Seismic activity since mining began has been minimal and so is not a possible cause of the structural damage in the area. There have been tremors reported by INSIVUMEH (Instituto Nacional de Sismología, Vulcanología, Meterología y Hidrología); however, they have been at a distance and magnitude highly unlikely to have caused the structural damage.

The Comisión Pastoral Paz y Ecología (COPAE) and volunteer engineers from the Unitarian Universalist Service Committee (UUSC) conducted the engineering study. Appendix A contains biographical summaries of the key participants in the study. COPAE and UUSC prepared a proposal for the engineering study dated October 2007. A pre-assessment of the structural damage was performed in the first week of May 2008. In addition, the engineering team began monitoring

Figure 1a Vertical Wall Cracks in Adobe

Figure 1b Vertical Wall Cracks in Adobe

Figure 1 Typical Structural Damage

Figure 1c Incline Wall Crack in Adobe

Figure 1d Crack in Concrete Block Grout

Figure 1 Typical Structural Damage

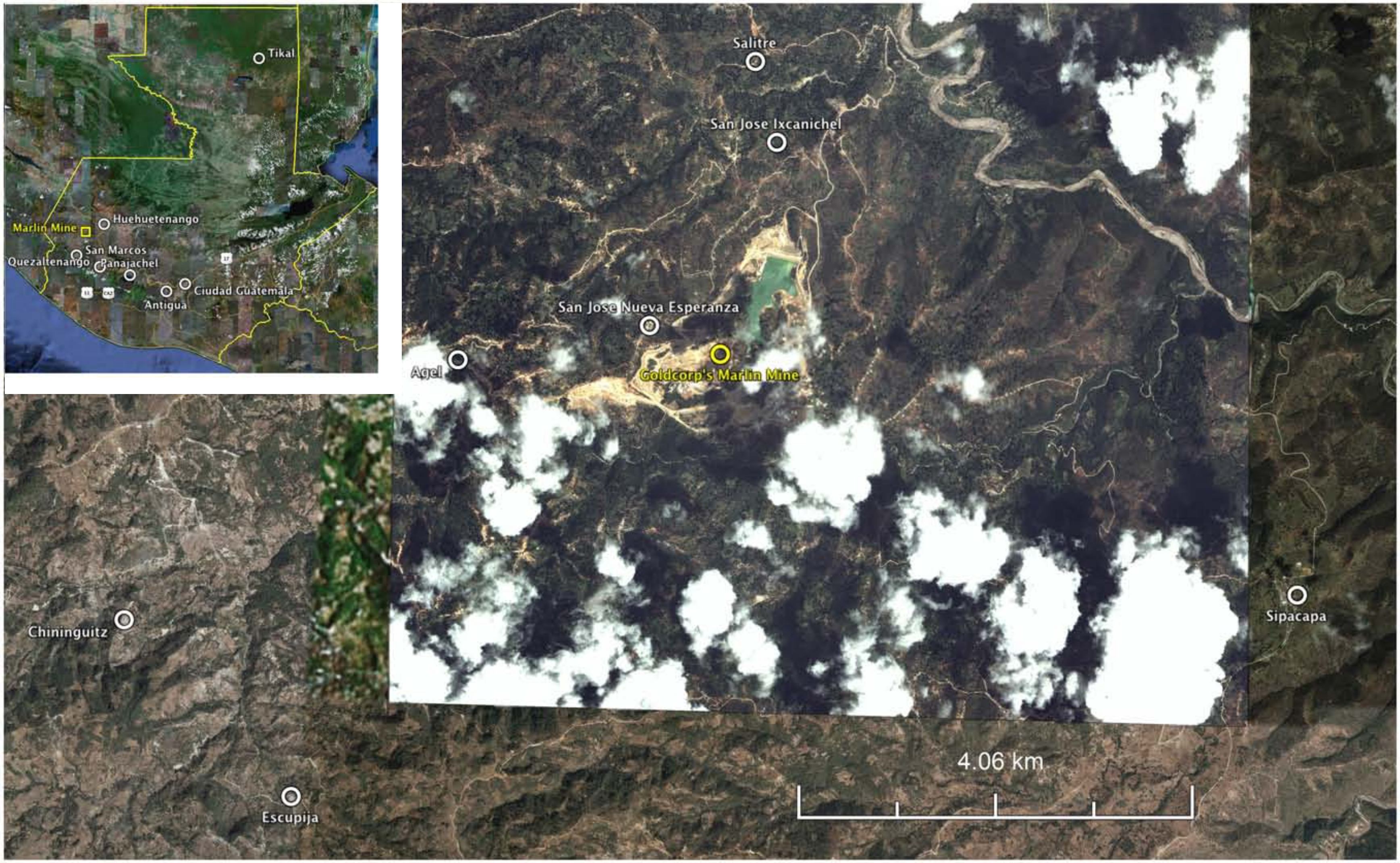

Figure 2. Location Map. © Google Earth and Digital Globe. Inset © Europa Technologies, INEGI, Terrametrics, and LeadDog Consulting.

displacement of 13 cracks in various buildings of the villages. Two further field trips were made to the area in November 2008 and March 2009 to observe the damage and collect data.

The study consisted of: interviews with building owners and local residents, review of applicable and available technical information, and observation on-site of the structural damage and possible sources of ground movement, including geologic hazards such as land instability, seismic activity, and swelling soils, and other potential causes such as construction practices, mine blasting and heavy vehicle traffic. Most importantly, the engineering team also observed buildings in two control villages, Escupija and Chininguitz, far from the Marlin mine to determine whether the structural damage in the Marlin area typically occurs with local construction practices. The control villages are located in an area geographically similar to the villages near the mine. They are more than five kilometers from the mine, see Figure 2.

Mr. Tim Miller, Goldcorp Vice President of Central American Operations, met with some members of the engineering team on 14 November 2008. The team explained its mission and requested certain baseline information on the Marlin mine, as enumerated in a letter of 8 October 2008, included in Appendix B. The requested information generally is available to the public in other countries. Mr. Miller stated a willingness to provide some of the information so long as the study is accredited, objective, independent, and transparent. On 24 November 2008, Mr. Miller emailed information on the Marlin mine geology, ore treatment, and a report on mine blasting by Ligorría (2008). Mr. Miller did not send all the information as requested in the team's letter.

The engineering team also contacted Mr. Miller on two other significant issues. Firstly, the Marlin environmental impact assessment (MEG, 2003) has two important omissions. There was no inspection by the company of the structural condition of buildings around the Marlin mine prior to the beginning of construction and operation of the mine. The recording of existing cracks immediately before construction and the beginning of mine operations, and of new cracks following these activities, is essential to identify those cracks that are related to the construction or mining. In addition, no inclinometers, precise survey benchmarks, or background groundwater levels were established to monitor ground subsidence. Such monitoring is required in many countries as it provides evidence of impacts from mining activities. (Konya and Walter, 1991, p. 283; Colorado Division of Minerals and Geology, 1980, section 4.08.2.) Secondly, MEG made at least two misleading statements regarding the structural damage. Local villagers gave the engineering team a one page report attributed to MEG (see Appendix B), which concludes that swelling clays cause the structural damage. This report does not identify its source and is based on inappropriate generalities as discussed further in the soils section of this report. In addition, MEG wrote a letter dated 26 July 2006 to Mr. Valentín Melecio Juárez (included in Appendix B) explaining the company's blasting practices, and stating that its blasting could not damage the nearby buildings as the practices are designed to minimize vibrations and the buildings are up-hill from the mine. In fact, blasting vibrations are more likely to persist in up-hill directions, and are concentrated in ridges such as those where the villages lie around the mine. Mr. Miller's response to these issues was to send a one-year record of recent blast vibration monitoring (see Appendix B). He did not respond to the question whether the document on swelling clays came from MEG. The blasting record is incomplete, as there were blasts witnessed by the engineering team that are not in the record, and the record covers only a short period well after the damage complaints began.

Several attempts were made to engage Guatemalan government agencies. One agency responded; Dr. Eugenia Castro, Ministerio del Ambiente y Recursos Naturales (MARN), met with the engineering team on 2 May 2008 for a presentation of its mission. Subsequently, MARN reportedly disclaimed regulatory responsibility for the structural damage of the buildings. In November 2008, the team attempted to again meet with MARN, and to meet with the Ministerio de Energía y Minas (MEM) and the Coordinadora Nacional para la Reducción de Desastres (CONRED). CONRED officials stated they were unavailable for a meeting. There was no response from MARN and the letter to MEM was returned. More attempts to engage these agencies will be made.

Documentation of the contacts with MEG and the government agencies is included in Appendix B.

METHODS

Cracks can occur in buildings from underlying ground movements, extreme air pressure from blasting, and construction practices. Damage from extreme air pressure from mine blasting is rare, as a building must be very close to the blast. This study focused on discovering possible sources for any ground movements and evaluating any faulty building construction. The possible causes of ground movement include subsidence, landslides, and swelling clay soils; and ground vibrations from seismic activity, vehicle traffic, and blasting. Faulty construction comprises inadequate base preparation, the use of defective materials, and poor workmanship.

The study was conducted in four phases, which were (1) inventory and monitoring of damaged buildings, (2) review of literature, (3) field observation of possible causes for structural damage and comparison with the control villages, and (4) analysis and reporting of information collected.

The inventory and monitoring of the abnormal structural damage began in June 2007 (Valiente, 2007), and continues as the buildings are revisited periodically to document any observed changes. More damaged buildings are continually added to the list as residents report them to the engineering team. The team was told that some residents are not reporting damage because of anxiety over conflicts with MEG. Displacement monitoring of a subset of buildings and cracks began in May 2008, and continues on a periodic basis. Crack displacement monitoring determines whether the damage is continuing. Documentation of the damage includes: location of the building; location of cracks within the building and their length and width; type of construction of the building; date of construction of the building; and for a subset of cracks, the displacement. Only cracks that extend through a wall or floor are documented. Superficial or cosmetic cracks are not documented. The information collected also includes accounts of the damage from the owners of the buildings.

Building owners have been interviewed to document the history of the abnormal structural damage and their opinions on the sources of the damage. In addition, area inhabitants have been asked how the recent damage differed from any previous episodes of structural damage from seismic activity. Typical accounts appear in Appendix E.

Literature reviewed includes various documents from MEG (2003, 2006, and Ligorría, 2008), and reports on the local geology, soils, and seismic history. See the list of references.

The engineering team made three trips to the Marlin mine area to collect geotechnical and structural data. The first trip was 1 to 5 May 2008, the second 8 to 15 November 2008, and the third 18 to 23 March 2009. The first trip gave the team an opportunity to view the scale and scope of the structural damage, and provided information to plan the next trip, which focused on more comprehensive data collection. On this first trip mass land movements were eliminated as a cause of the damage, as no recent mass ground movements, fractures, subsidence, or landslides were observed in the area. Fourteen damaged buildings among four villages were viewed and the structural damage inventory was updated.

On the second and third field trips, the engineering team revisited some buildings in the villages around the mine and observed buildings in the control villages of Escupija and Chininguitz. They collected data on soils, sub-base compaction, displacement and structural characterization of cracks, and conducted ground vibration monitoring of heavy vehicle traffic and a blasting event at the mine.

The buildings in the control villages, Escupija and Chininguitz, provide a standard against which the damaged buildings in the villages around the Marlin mine can be compared. The control villages are outside the range of influence of the mine as they are more than five kilometers away and on the opposite side of the Tzalá River valley. The distance and deep intervening valley isolate them from blasting vibrations. In regard to heavy vehicle traffic, the villages are not on a common access route to the mine. The local geology and soils (Simons et al, 1959) are similar to those of the villages near the mine, and the buildings are similar. Building sites are generally ridge top or side hill cut-and-fill, construction materials are most frequently concrete block and adobe, and roofs are lumber trusses and struts covered with either corrugated metal sheets, clay tile, or occasionally thatch.

The data collection was designed to determine possible causes of ground movements underlying the damaged buildings, including displacement from swelling soils, displacement of the ground during the rainy season, displacement from inadequate sub-base compaction, and displacement from ground vibrations. Soil samples were collected and processed in an accredited laboratory. Crack location and displacement were interpreted based on forensic geotechnical literature and the team's training and experience. (See the list of references and biographical summaries of the team engineers in Appendix A.) Qualitative soil compaction was tested with a standard field test. Vibration data collected included records of seismic activity, ground vibration monitoring of vehicles and a mine blast with a certified seismograph, and a report on mine blasting by Ligorría (2008).

MEG did not perform a pre-mining survey of buildings around the Marlin mine, nor was any instrumentation installed to measure ongoing ground movements or vibrations caused by the mine blasting and increased vehicular traffic. This type of background survey and monitoring are generally required by law elsewhere. (Konya and Walter, 1991, p. 283; Colorado Division of Minerals and Geology, 1980, section 4.08.2.) Because this background information is not available, the engineering team had to rely on eyewitness accounts and post-event data collection and analysis to determine the most likely causes of the structural damage. The data collected was analyzed using standard engineering practices, and compared to various engineering failure criteria and regulatory standards of other countries.

The satellite images provided in this report were compiled from Google Earth and Digital Globe. GISCorps trimmed the Digital Globe image, and converted it to a form compatible with Google Earth. The image of the mine and its nearest surroundings was acquired by satellite on 9 August 2007 and the accuracy is approximately 25 meters (Harris, 2009).

SOCIAL SETTING

Prior to the construction and operation of the Marlin mine, San Miguel Ixtahuacán was a quiet and relatively isolated municipality in which most people were traditional small farmers. The local Mam and Sipacapense Mayan people were accustomed to deciding issues affecting their communities through discussion and consultation with all members. This consensus process was guided by the eldest people based on their experience and knowledge.

MEG acquired the right to mine in the area from the national government without consultation with the local communities. MEG did not include the local communities in the decision process for the development of the mine and there was no opportunity for the people to reach a consensus on the mine, the terms and process of mine development, and mine operations. This demand for involvement in the mine decision-making process is not unreasonable or unique. In industrialized countries, mining companies and government agencies are required to consult with local communities, and these communities have authority in some decisions. Many people in San Miguel Ixtahuacán continue to be angered by the lack of local consultations during mine development as well as currently. Protests against the mine are common. Residents often have either no information or incorrect information. There are conflicts between mine workers and other residents, between and within communities and even within families. Village and church leaders are at odds. An atmosphere of mistrust has caused the deterioration of the traditional consultation process with regard to all community issues.

Since the arrival of MEG, approximately 600 families have been displaced from their homes. The land of those who remain has been devalued by the threat of additional displacement, various environmental threats, and the structural damage observed in this study.

Despite some of the residents claiming their rights to the land, a role in decision-making, and a healthy environment, no one has listened to them: not the national or local governments, nor the mining company, though the people are the legitimate owners of the land and have the right to a safe place in which to live and raise their families.

The current situation is becoming worse. Protests against the mine are becoming larger and more frequent. Conflicts between mine workers and other residents are on the rise. People are leaving the area in growing numbers, some saying that they can no longer live in this situation of conflict. The engineering team also suffered from this unrest. One member of the team was attacked and injured by mine workers during the November 2008 field trip. A complaint was filed with local authorities.

Economic development still has not come to the families in the municipality. The vast majority of the profits are exported out of the country rather than being invested locally. Overall, people’s living situation is the same or worse than it was before.

LOCAL CONSTRUCTION METHODS

The area around the Marlin mine is mountainous, and the buildings are constructed on the ridges, hillsides, and in the valleys. On the hillside sites, the hillside is cut away with an excavator on one half of the site, and the material removed is filled on the outer side to create a flat construction surface. The filled portion is compacted by running back-and-forth with the excavator. This construction method is called cut-and-fill. The ridge and valley building sites do not require as much cut-and-fill, but generally require some grading.

Because most of the buildings are on a slope, drainage is generally not a problem. In addition, most buildings have ditches to direct water away from the building. In some cases, wet soil was observed near a building but generally this was merely small spots of surface moisture.

All of the buildings observed are single level.

Adobe and concrete block are the two basic types of wall construction. A more detailed description of the wall construction is provided in Appendix C. Plaster covers most of the walls of both types; it ranges in thickness from 0.5 to 1.5 centimeters. Occasionally the engineering team observed walls made of lumber planking nailed to vertical posts. Lumber has a high tensile strength, and is not damaged by the structural forces in evidence in the villages around the mine.

The buildings have trench foundations. For concrete block, the trenches are filled with large stone concreted in place. For adobe, trenches are filled with adobe. Building owners stated that the foundations were about one half meter deep.

All of the concrete block and many of the adobe buildings have reinforced concrete slab-on-grade floors and a terrace outside the front door. Generally, the slabs are 10 to 20 centimeters thick, while a few are thicker. Some of the adobe buildings have compacted soil floors.

Most of the roofs are supported by lumber trusses set on the walls and tied together with struts. The truss lumber is 5 by 15 centimeters in cross section. A lumber top plate usually but not always is placed on adobe walls as a bearing surface for the trusses. Most roofs are gabled, on either two or four sides. Most have a slope of 1 vertical to 20 – 50 horizontal. A few roofs are made from timber poles. The roofing material is corrugated metal sheets, fired clay tiles, or occasionally thatch or dried fronds. This roofing is layered in such a way as to prevent water leaking into the building. Flashing is placed where roofing material cannot be layered.

No significant roof loading is ever present in these buildings. Water ponding generally is not a problem due to the roof slopes and roofing material. Of course, snow does not exist in the area. Heavy wind loads could occur in hurricanes. Seismic loads are more likely to damage the building walls than the roofs as the roofing material has high tensile strength.

Most buildings are 2 to 2.5 meters to the top of the walls. Doorway openings are typically about 1.8 to 2 meters high. Windows are typically 0.75 to 1 meter square. The tops of the windows are usually a little lower than the tops of the doorways. Both types of openings generally are located within the middle third of the length of the wall.

In adobe houses, the windows and doorways typically have a lumber plate to support the adobe above the opening and also a bearing plate under the window opening. These top and bottom plates extend laterally on both sides into the adobe wall. The support and bearing plates are unnecessary in concrete block buildings.

Occasionally new additions are constructed against one side of an older building. No special measures are taken to join the new addition with the older building.

Adobe and concrete block buildings are particularly vulnerable to vibrations as these construction materials have relatively little tensile strength compared to other construction materials such as lumber and reinforced concrete. Nevertheless, the traditional construction has been adequate until arrival of nearby mining. Figure 22 in Appendix C is a 60 year old adobe building in the municipality of Sipacapa that shows the wear of time and weather but no cracking damage.

The local construction methods and materials are consistent with the Guatemala building code. (Asociación Guatemalteca de Ingeniería Estructural y Sísmica - AGIES, 2001)

STRUCTURAL DAMAGE

Damage Inventory

The engineering team observed the buildings for structural damage, primarily cracks that extended through the walls and floors; and particularly those with displacement. Obvious superficial and contraction cracks in plaster, mortar, and adobe bricks that are considered typical for these construction materials were not recorded. In addition, cracks in construction joints were not recorded. A crack was recorded as impacting the structure if (1) it extended through the wall and could be seen on both sides of the wall, and/or (2) it was in plaster and wide enough to see the wall behind it to visually confirm the presence of the crack within the wall.

The engineering team observed the building site excavation, grading, drainage, base soils and compaction, and construction materials. The building owner was asked the date of construction and the approximate date that structural damage first occurred. A subset of typical structural cracks was marked, photographed, and the initial crack width measured. In addition, some cracks had gauges installed over them. Periodically, the buildings are re-examined to note changes in crack width and displacement and any new damage.

Documentation of structural damage listed in the inventory includes:

- Geographical location of the damaged building,
- Numbering of the cracks for record keeping purposes,
- Record of locations of cracks, and measurement of widths and lengths of select cracks,
- Photographs,
- Building construction method and date of construction,
- Adequacy of drainage around the building,
- Distance to the nearest road and building,
- Building plan showing crack and soil sampling locations.

Appendix D summarizes the inventory data collected in this study. Maps of the locations of the damaged buildings are shown in Figure 3. Preliminary documentation of the structural damage was reported by COPAE (2007) and Valiente de León (2007).

The engineering team made a subjective assessment of the damage, which is recorded in bold type just below the name of the building owner. The damage assessment is a grade between 0 and 10, with 0 indicating no damage, and 10 indicating structural failure. The damage grades were assigned as follows.

- 0 was reserved for buildings with no cracks.
- 1 - 3 were assigned to buildings with cracks having minimal displacement with grade assigned based on number of cracks.
- 4 - 6 were assigned to buildings with at least one crack having obvious displacement but light could not be seen through any cracks. These buildings are unsafe.
- 7 - 9 were assigned to buildings where light could be seen through at least one of the cracks and/or there is displacement of the roof, walls, and/or foundation. These buildings are unsafe.
- 10 indicates a collapsed building.

A total of 33 damaged buildings were observed in the villages surrounding the Marlin mine. Generally, the damage ranges in severity from buildings having one or more cracks with no displacement to buildings with cracks displaced far enough that light can be seen through one or more of the cracks. One building in El Salitre is severely damaged. Table 1 summarizes the damage by village, and

Figure 3. Map of Damaged Buildings in the Villages of Agel, El Salitre, San José Ixcaniche, y San José Nueva Esperanza. © Google Earth and Digital Globe.

shows the distance from the village to the mine and the range of distance of damaged buildings to the nearest road. The last two columns total the number of buildings damaged by grade. Not all buildings were evaluated for damage, and the number not evaluated is totaled in the last row for each village.

Table 1 Observed Building Damage by Village

Village	Number of Cracked Buildings	Approximate Distance to the Marlin Mine (km)	Distance of Buildings to Nearest Road (m)	Crack Damage	
				Damage Grade	Number of Buildings
Agel	12	1	1-300	1	1
				3	3
				5	2
				7	1
				Unev.	5
El Salitre	1	4	25	10	1
San Jose Ixcaniche	15	2.5	5-130	1	1
				2	1
				4	1
				5	2
				6	2
				Unev.	8
San Jose Nueva Esperanza	5	1	3-120	4	1
				Unev.	4
Total	33	1-4	1-300	1-10	

Unev. – Damage Unevaluated.

Of the buildings graded for damage, approximately half had severe damage (a grade of 5 or more) that makes the buildings unsafe. The damage observed in these villages greatly contrasts with the little damage found in the control village of Escupija as discussed below.

Occasionally one or two trusses in the roof of an adobe building were observed rotated out of vertical on their bearing points. This rotation appeared to be within the construction tolerance, and not occurring as a result of any unusual loading after construction was completed. All of these buildings appeared to be built as such, as the adobe mortar encased the beam along either side rather than being locally crushed.

Typical testimonials from local residents regarding the damaged buildings appear in Appendix E. Generally, the residents report that the cracking is coincident with the construction and operation of the mine; in particular, they blame the blasting and the increased heavy truck traffic through their villages. In addition, they make the important point that the cracking did not occur prior to the existence of the mine, even though the villages are in a seismically active area. The residents report that a representative from MEM, Julio Avila, examined the damaged houses. Perhaps the unidentified report discussed in the Introduction and included in Appendix B is a report by Avila. MEM has been unresponsive to the engineering team's requests for information or a meeting.

Crack Analysis

A particular pattern of cracks is evident in the walls of the damaged buildings, and this pattern is a clue to their cause. The cracks are more or less vertical, and usually are located within the middle third of the wall length. In addition, the most frequently cracked walls are those whose ends point toward the adjacent road and/or the mine. Figure 4 illustrates this orientation. This pattern leads to the suspicion that the source of damage is ground vibrations from heavy vehicle traffic and/or the mine blasting, and this suspicion is reinforced in the following sections of this report, which eliminate other sources of the structural damage.

Walls are most stiff in their long dimension, in the plane of the wall, and have some flexibility in their shortest dimension, out of the plane of the wall. The long dimension of the walls in the damaged buildings generally lies in line with the source of the vibrations. This is the wall's most stiff dimension. The stiffness of the wall resists the vibrations beyond the strength of the construction material (the grout between concrete blocks or the adobe), so the material cracks. The walls perpendicular to the source of the vibrations are usually not damaged or have less cracking than the in-line walls because the more flexible side of the walls face the direction of the vibration source. These walls flex in reaction to the vibrations, stay within the failure zone of the construction material, and do not exhibit cracking. Nevertheless, the engineering team occasionally observed walls that failed from excessive flexing; see Crack Type 4 in the next subsection.

In the walls observed, the middle one third of the walls is the most common location of cracks, especially if there is a nearby window or door. A wall is weakest where there are openings, and walls are weakest in their middle one third, as adjacent walls support the ends. Crack location also can be related to a cut-and-fill line underlying the building slab or foundation. Under vibration, the fill side can settle more than the cut side because the two sides cannot be compacted to the same density. Even with modern compaction machines, it is unlikely that the two sides would settle the same amount under a loading event.

Some houses are far away from the road and still damaged. They are most likely not damaged by road traffic. In general, the worst damage in these houses is in the walls perpendicular to the mine blasting.

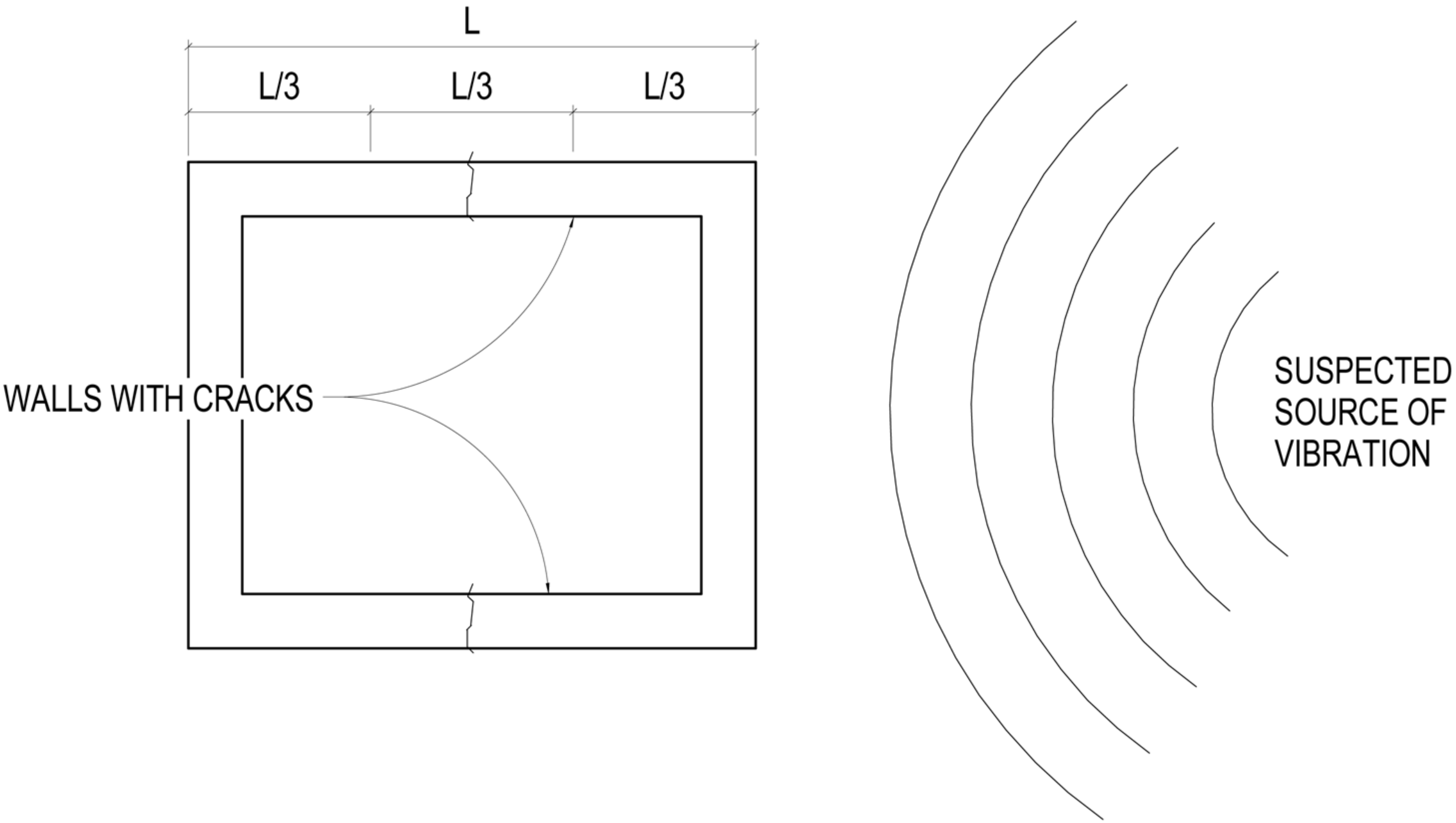

Figure 4. Crack Location Relative to Vibration Source

Generally, cracks caused by vibration do not continue to open or shift even though the source of vibration continues. Once the cracking occurs, as long as the source of vibration remains of consistent strength and location, additional movement of cracks or formation of new cracks will not occur.

Crack Types

The most common cracks found in the damaged buildings appear in several types that indicate their likely cause, as described below and shown in Figure 5. (Day, 1998; Dowding, 1985, p.134; Friedman, 2008.)

Type 1: A more or less vertical wall crack that starts (widest end) at either the top of a wall between roof beams or the base of a wall, and in the case of concrete block walls, extends stair-stepping through the mortar. There is no contiguous crack in the floor slab-on-grade.

This type of crack usually does not originate from differential floor slab movement, or there would be a crack in the slab, and does not originate from excessive bearing pressure of roof beams. This crack type most likely originates from ground vibrations, particularly when it occurs near the middle third of a wall.

Type 2: A crack that starts (widest end) from a doorway or window, usually from one of the corners, and extends upward stair stepping through mortar between concrete blocks or in various orientations through adobe.

Stress concentrations occur at corners of doorways and windows. Ground vibrations can increase the magnitude of these stress concentrations and cause cracking. This crack type is more likely to be caused by ground vibrations if it lies between load points of roof beams.

Type 3: A compound crack that includes a crack in the floor slab and a wall crack that originates (widest end) at the intersection of the floor slab crack with the wall and extends upward into wall generally in a diagonal orientation. In this case, the floor has moved horizontally rather than settling downward and the cause is most likely ground vibrations.

Other floor slab cracks with significant displacement that extend into adjacent walls are generally caused by differential settlement of sub-base, resulting from one or more of the following: poor base compaction, swelling clays, land movements, liquefaction, excessive soil moisture, or ground vibrations. In these cases the wall crack is wider at the top than the bottom.

Type 4: A horizontal crack that is usually found at mid-wall in adobe or in the mortar between concrete blocks.

Figure 5a Type 1 Wall Cracks (3 covered with plaster), No Slab Cracks

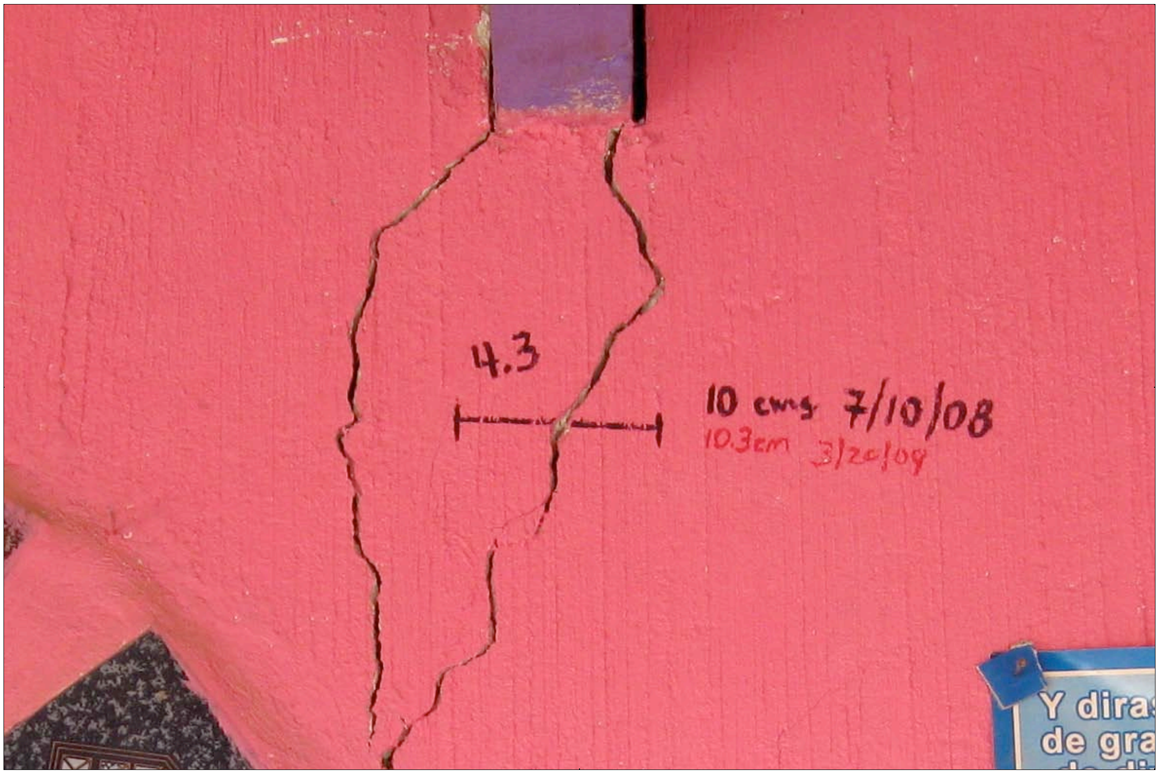

Figure 5b Type 2 Crack from Window or Door to Roof Beam

Figure 5 Crack Types

Figure 5c Type 3 Crack in Wall and Slab

Figure 5d Type 4 Horizontal Crack

Figure 5 Crack Types

Figure 5e Type 5 Wall Crack Below Roof Beam

Figure 5 Crack Types

This type of crack occurs from excessive flexing of the wall caused by vibrations.

Type 5: In adobe only, a crack that starts (widest end) at top of wall under a roof beam and extends downward.

This type of crack can occur if there is inadequate bearing surface for roof beams on supporting walls or if ground vibrations increase the stress on the material under the beam beyond the material's strength. In the buildings observed by the engineering team, the roof beams generally have an adequate bearing surface, as shown by buildings in the control villages. Therefore, these cracks are likely due to ground vibrations rather than inadequate bearing surfaces for the roof beams.

Ground vibrations are likely causes of cracks of types 1, 2, 4, and 5, and ground vibrations are one of several possible causes of type 3 cracks.

The absence of certain types of cracks supports the rationale for deciding on the possible causes of the existing cracks. Cracks seldom or not seen in the damaged buildings include the following:

- Cracks typically related to construction practices include expansion-contraction cracks from temperature changes, shrinkage cracks from curing of concrete or adobe, loading failures at windows and doors, and joint cracks.

  Expansion and contraction cracks are common in concrete and adobe; however, they are generally superficial and do not result in structural problems. In adobe, these cracks seldom extend beyond individual bricks or a layer of mortar. They do not occur in concrete blocks and seldom in mortar between blocks. Cracks in concrete floor slabs with little or no displacement are not uncommon due to contraction in concrete during curing, and diurnal and annual temperature fluctuations. They appear hairline, random, intermittent, multiple, and meandering in the concrete, forming discontinuous cracks.

- Where swelling soils are present, the floor slab will have extensive cracking. The walls also will have cracks if there is much swelling. The slab cracks are usually parallel to the walls, diagonal across corners, or across the narrow dimension of the slab. In extreme cases, the floor heaves. See Figure 9.

- Where cracks arise from mass land movements, there are large ground fractures, hillocks, scarps, and other disturbances around, under, and far beyond the building foundations.

A few construction cracks such as those described above were seen in the villages around the Marlin mine and the control villages. No floor slab heaving was observed except in an area of land instability seen in Chininguitz. In regard to excessive soil moisture, no water stains were observed in any floor slab or walls, no areas of standing water were observed around the damaged buildings, and the building base soils had moisture content typical for other similar soils (4.2 to 42.3 percent, see Table 3).

Crack Displacement

The crack width and displacement of a subset of the cracks listed in Table 1 were monitored over time. This monitoring determined whether the cracks were growing and whether there were changes over the cycle of wet and dry seasons. Generally the wet season is May to late October. Three methods of measurement were used as shown in Figure 6. The first method was simply to measure crack width with a scale at a given location. The second was to mark a line perpendicular to the crack, mark ticks on the line, and measure the distance between tick marks. Different sub-teams of the engineering team used these two methods. The third method was to glue a crack gauge across the crack. This last method gives both the transverse and lateral displacement of the crack. These crack gauges are expensive, and used less frequently than the other methods.

The results of the crack measurements are given in Table 2.

- The first column lists the crack identification and dates of measurement.
- The next four columns list the crack or tick width and the cumulative change in width from the original measurement.
- The last column lists readings from the crack gauges. These gauges have a zero reading when installed; the subsequent readings show the change from the original zero reading.

A crack gauge was placed on SJNE 3.1 in addition to the other methods of measurements; however, it was vandalized.

Thirteen cracks were monitored for displacement. The maximum displacements were small, in a range of 5 to 7 millimeters. Most of the cracks had no or trivial change in width. These results generally indicate that there are no mass land movements, subsidence or swelling of soils under the buildings, and no impacts due to changes in soil moisture from the wet and dry seasons. The one exception could be crack AG 7.1, which was stable from the beginning to near the end of the wet season, narrowed 7 millimeters at the end of the wet season,

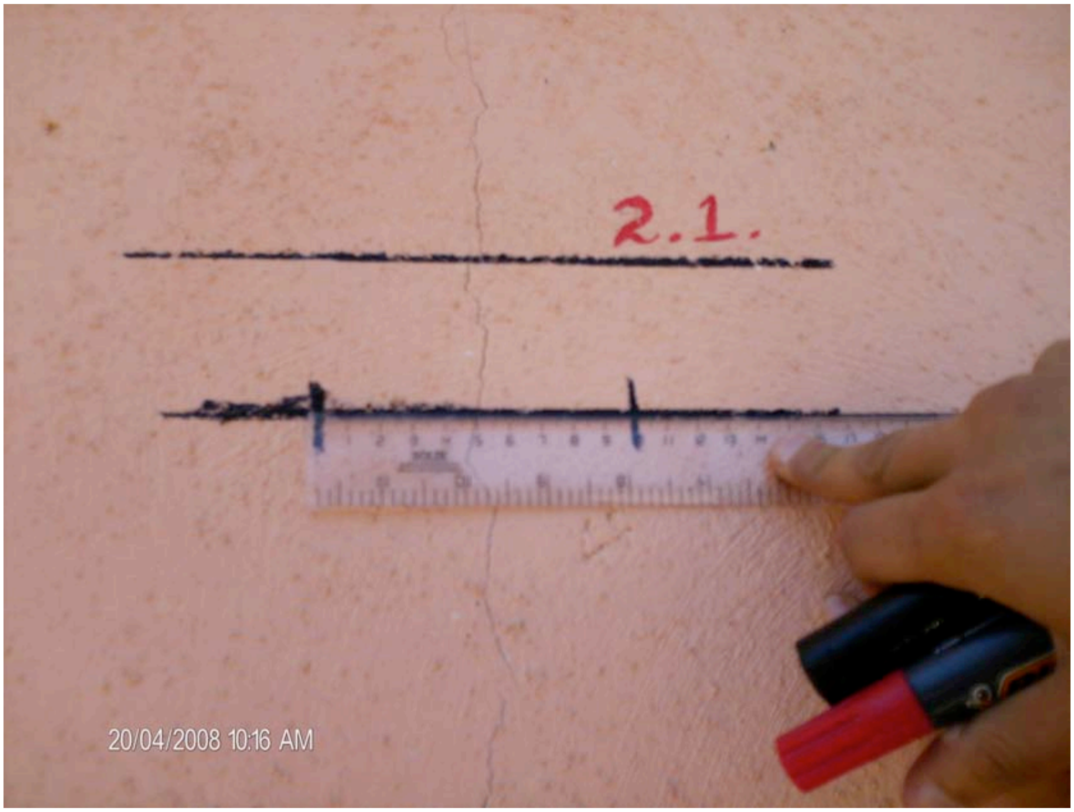

Figure 6a Measure Crack Width on Upper Line and Measure Width of Tick Marks on Lower Line

Figure 6b Crack Gauge

Figure 6 Methods of Crack Measurement

and then widened 7 millimeters in the dry season. However, there could be an error in the 11 November 2008 reading of 63 millimeters as all the other readings are a consistent 70 millimeters. This crack could be monitored through the 2009 and 2010 seasons to determine if movement is related to seasonal causes.

Table 2. Crack Displacement

Crack-Date	Crack Width (mm)	Change (mm)	Tick Width (mm)	Change (mm)	Gauge (mm)
AG 1.1- 20.04.08	6		100		
07.10.08	6	0	100	0	
19.03.09	7	+1	101	+1	
AG 1.2- 20.04.08	4				b
07.10.08	4	0			0
19.03.09	4	0			T-0.1 L+0.1
AG 2.1- 02.05.08	1	b			
07.10.08	1	0			
19.03.09	1	0			
AG 2.2- 02.05.08	1	b			
07.10.08	1	0			
19.03.09	1	0			
AG 7.1- 02.05.08			70		
07.10.08			70	0	
11.11.08			63	-7	
19.03.09			70	0	
AG 7.2- 02.05.08					0
11.11.08					T-0 L-4
19.03.09					T-0 L-5
AG 8.1- 02.05.08					b
10.11.08					T+0.5 L+4
19.03.09					T+0.5 L+4
AG 10.1- 04.05.08			90	b	
10.11.08			91	+1	
19.03.09			91	+1	
SJI 2.1- 02.05.08			100		
07.10.08			100	0	
20.03.09			100	0	
SJI 10.1- 02.05.08			96	b	
07.10.08			97	+1	
11.11.08			97	+1	
20.03.09			97	+1	

Crack-Date	Crack Width (mm)	Change (mm)	Tick Width (mm)	Change (mm)	Gauge (mm)
SJI 13.1- 03.05.08			88		
07.10.08			91	+3	
20.03.09			94	+6	
SJI 13.3- 07.10.08			100		
20.03.09			103	+3	
SJNE 3.1- 02.05.08	5				
07.10.08	8	+3	105		
20.03.09	10	+5	107	+2	

SJI = San José Ixcaniche
AG = Agel
SJNE = San José Nueva Esperanza
b = base measurement
T = transverse measurement
L = lateral measurement

COMPARISON WITH CONTROL VILLAGES

The engineering team selected two control villages for comparison of any building damage with the structural damage in the villages surrounding the Marlin mine. The two villages and their locations are:

Escupija	15 degrees 11.61 minutes north 91 degrees 43.81 minutes west
Chininguitz	15 degrees 12.54' minutes north 91 degrees 44.74 minutes west

The villages are each approximately 5.5 kilometers from the mine and across the Tzalá River, as shown in Figure 2.

Escupija

The engineering team made two trips to Escupija to observe the village buildings, 12 November 2008 and 21 March 2009. In addition, an engineer and technician visited the village on 29 January 2009 to observe additional buildings.

A total of 52 buildings were observed for cracking and other damage, as tabulated in Appendix D. The building locations are shown in Figure 7. Documentation of the buildings observed includes photos. Out of the total 52 buildings observed, 38 had no cracks, and the remaining 14 had no more than one or two cracks each. None of these buildings had crack damage that would rank above 2 in the grading defined in the above Damage Inventory subsection. In the villages of Agel, San José Ixcaniche, and San José Nueva Esperanza,

Figure 7. Map of Buildings Observed in Escupija. © Google Earth and Digital Globe.

near the Marlin mine, every building observed has at least one and usually multiple cracks.

The observations in Escupija indicate notable differences between the degree and type of damage there and the degree and type of damage in the villages surrounding the Marlin mine, as documented in the preceding section.

- The difference is not the local construction practices and materials, as these are similar throughout the area.
- The difference is not the damaging presence of water. There was more evidence of damp soils in Escupija than in the villages around the mine.
- The difference is not in geology and types of soils.
- The difference does not seem to be age, as there is little damage in Escupija regardless of building age, and in the villages surrounding the mine, cracking damage occurs in buildings of various ages, see Appendix D.
- The seismic history is the same.

The obvious large and new difference between Escupija and the villages around the Marlin mine is the mine, with its associated increased heavy vehicle traffic, blasting, and other mining operations.

Chininguitz

The engineering team made two visits to Chininguitz, 11 November 2008 and 20 March 2009. In addition, an engineer and technician documented structural damage in the village on 17 December 2008, see Appendix D.

There is considerable building damage in Chininguitz, but most of this damage is concentrated in a small valley, shown in Figure 8. The damage in Chininquitz differs from the damage seen in the villages surrounding the Marlin mine. It is the result of mass land movements. In Figure 8, the white area is a landslide scarp and the broad area of lighter colored land enlarging in a trend from the lower left toward upper right is the unstable and moving ground. There are extensive fractures in the area that extend several hundred meters including one just to the left of building CH 6 and another in the lower right corner of the image.

The building in Figure 9 demonstrates damage from landslides. Note the gaping hole in the wall (rubble has been removed), and large crack on the left end. In side there is extensive cracking, heaving, and subsidence of the floor. This subsidence overlies a ground fracture (indicated with arrows) and moisture that extends some 50 meters into an adjacent football field. In the surrounding small valley, the engineering team observed numerous similar fractures. This fracturing is typical of mass land movements. In addition, the team observed other extensive evidence of mass land movement including a 400-meter fracture

Figure 8. Map of Buildings Observed in Chininguitz. © Google Earth and Digital Globe.

Figure 9a Damaged Building (note hole in wall, left arrow points to wall crack, right arrow points to fracture that extends into foreground)

Figure 9b View From Building in Figure 9a (Fracture in foreground is same one shown in Figure 9a and it extends to person. Fracture difficult to see as it is partially filled with soil)

Figure 9 Land Instability in Chininguitz

Figure 9c Escarpment (left arrow) and Recent Landside (right arrow)

Figure 9d Arrows Show Part of a Fracture that Is 400 Meters Long

Figure 9 Land Instability in Chininguitz where the semi-circular valley floor meets the hillside, several fresh landslides, and hillside escarpment (Figure 9), which are also visible in Figure 8.

Local residents told the team that the area was temporarily evacuated during one particularly rainy period in the 2008 wet season because of the risk of landslides.

A soil sample was taken and analyzed, with results shown in Table 3. The sample indicated that swelling clays are not present.

The two control villages of Escupija and Chininguitz provide a good contrast with the villages around the Marlin mine. Escupija shows little structural damage, and Chininguitz contrasts damages from mass land movements with damage caused by ground vibrations.

GEOLOGY

The following geological summary (in italics) has been abstracted from MEG (2003, sec. 4.0). From observation, the engineering team regards the MEG geology description as adequate for this report.

Continental plate movement has extensively affected the regional area around the Marlin mine. The shifting of these plates has developed major east-west faulting just to the north of the mine and a multitude of lesser faults through the mine area. The mine lies within the central mountain area of Guatemala with a chain of volcanic mountains to the west. The central mountains principally consist of Paleozoic metamorphic rocks.

According to the historical record of the last 19 years, in the region around the Marlin mine, there have only been four earthquakes of magnitude 5 or greater on the Richter scale with an average depth of 33.5 kilometers. These earthquakes did not cause any visible damage in the area. Earthquakes of 7.1 or greater on the Richter scale in the last 35 years were more than 120 kilometers away. [In 2007, after the date of the EIA&S, an earthquake of magnitude 6.7 Richter occurred 202 kilometers away.] *Older local residents report that past earthquakes have not caused significant damage.*

LAND STABILITY

The largest scale recent disturbance of the land around the Marlin mine is, of course, the mine itself. However, the open pit part of the mine is not yet large enough to destabilize or undercut the land of the surrounding villages. The underground mine is too deep and small to destabilize the land.

The open pit and underground mine are probably lowering the water table. Local residents report that some of their springs are drying up, particularly in Agel. Dewatering by the mine and subsequent lowering of the water table possibly could cause some subsidence of a large area around the mine or localized areas. However, the engineering team did not observe any tension fractures, which are evidence of subsidence.

Standard engineering practice for measuring subsidence is to install precise survey stations and to monitor groundwater levels around the mine. The EIA&S (MEG, 2003) does not report installation of inclinometers, precise survey benchmarks, or background groundwater levels prior to mining. In addition, the MEG Annual Monitoring Reports (2004, 2005, 2006, 2007) do not report groundwater levels in the monitoring wells surrounding the mine except for those immediately adjacent to the tailings storage facility.

MEG states that there is a very low risk of landslides due to the fact that the surface is mostly volcanic and there are no clay layers. The area has been shown to be resistant to earthquakes of 7.5 magnitude Richter scale and up to 38% soil moisture (2003, section 4.4.3). Nevertheless, the engineering team also looked for evidence of natural slope failures or landslides. In the villages with structural damage, none of the following evidence of recent land instability was observed:

- Shear displacement, either surficial slope failure along slip surfaces or gross deep-seated shear zones.
- Debris flows or soil with entrained water and air moving as a fluid.
- Creep, generally seen in downward and outward movement of soil that forms into large hummocks.
- Anomalous surface patterns such as open fractures, scarps, bulges or jumbled topography.

The presence of water often is a cause of land instability. The only significant local water hazards observed are springs and the annual rainy season. Local residents reported that springs are avoided as building sites as the springs are a primary source of water. The observed buildings generally had good drainage to divert surface water around the buildings, and the base soils were generally free draining (see the Soils section). The engineering team occasionally observed damp areas around buildings. These were noted. Because there were very few buildings with damp areas, this hazard was discarded as a cause of the extensive structural damage.

SOILS

The goal of the soil sampling and testing was to determine if soil properties might have caused the building damage observed in villages around the Marlin mine.

The behavior of soils, particularly swelling soils, has been shown to have a direct effect on the structural performance of buildings.

Related Reports

Three reports on local soils were reviewed for information relevant to the building damage, as follows.

Two reports (Ministerio de Agricultura, pp. 203-231 and MEG, sec. 5.6.11.2, 2003) classify and describe soils from an agricultural and reclamation perspective. Their soil descriptions generally coincide with the soils sampled by the engineering team. The reports do not mention the presence of swelling soils or other soil characteristics that might cause damage to buildings. However, MEG (2003, Cuadro 5.6-21) provides data on the clay content of local soils, which were found to range from 14.7 to 54.6 percent. Soils with clay content less than 50 percent are not likely to cause significant damage to buildings due to swelling (Nelson and Miller, 1992).

The third document, titled "Informe de Causas Generales de Rajaduras en Construcciones, en Guatemala: 'Comportamiento de Estructuras en Suelos Arcillosos' " (Appendix B) was provided to the engineering team by community representatives who stated that they received the document from MEG. The copy given to the engineering team does not show a date or author. This document includes some misleading generalizations that do not apply to the area around the Marlin mine, as follows.

- The first sentence of the document states that "Clay is a material that, when it gains water, its volume increases, and, when it loses water, its volume decreases." ("La arcilla es un material que cuando gana agua aumenta su volumen, cuando pierde la misma lo disminuye.") This statement is true only for some clays. Montmorillonite clays are very prone to volume changes with changes in moisture content, while kaolinite clays are relatively unaffected by changes in moisture content (Holtz and Kovacs, Section 4.2, 1981). In fact, as discussed below, sampling results show that some of the soils in the area around the Marlin mine are affected by changes in moisture content and others are not.

- The document describes differential settlement ("asentamientos diferenciales") caused by swelling clays as the cause of damage to houses built on clay soils. This statement is not strictly correct. The term 'differential settlement' is most often applied to differences in settlement from one part of a structure to another. Such differential settlement is most often caused by soils with different load-bearing characteristics underlying different parts of the foundation. When discussing damage due to swelling soils, the term 'differential swelling' would be more appropriate.

- The document concludes: "All of the houses that are built on clay soils without slab foundations have at least one crack caused by differential settlement; the houses built in the area around the Marlin mine are over clay soils." ("Todas las viviendas que están edificadas en suelos arcillosos sin losa de cimentación, tienen al menos una grieta debido a asentamiento diferencial; las viviendas edificadas alrededor de la Mina Marlin están sobre suelos arcillosos.") This statement is overly broad and misleading. The results below clearly show that not all buildings around the mine are built on clay soils, and that some buildings built on clay soils show little damage, while others show significant damage.

Soil Sampling and Testing

Seven soil samples were collected in villages around the Marlin mine at the locations shown on Figure 10. Samples were collected at a depth of approximately 15 centimeters. Six samples were taken on the building sites of damaged buildings in the villages of Agel, San Jose Ixcaniche, and San Jose Nueva Esperanza. For comparison, one sample was taken at the control village of Chininguitz. A second sample was collected at Chininguitz, but this sample did not contain sufficient soil volume. Immediately after collection, the samples were sealed in watertight bags, and each bag was labeled with a sample number and the date of sampling. The samples were stored at room temperature until delivered to the testing laboratory three days later.

Soil samples were analyzed by CTL Thompson, Inc., located in Denver, Colorado, USA. CTL Thompson is a commercial geotechnical soil lab accredited by the American Association of State Highway and Transportation Organizations (AASHTO) Accreditation Program. For each soil sample, lab-testing determined the natural moisture content, grain-size distribution, plasticity, and soil classification. In addition, one clay soil and one granular soil sample were selected for swell potential testing. Testing results are summarized in Table 3. Lab data sheets and data summaries are included in Appendix G.

In addition to the lab-testing, a simplified field density test determined the relative density of the soil. The test consists of hammering a 10-millimeter diameter rebar into the ground with a 2.5-kilogram hammer. See Figure 11. The number of blows required to penetrate a given depth was recorded, see last column of Table 4. The test does not give quantitative results, but does generally indicate the relative soil density at the various locations.

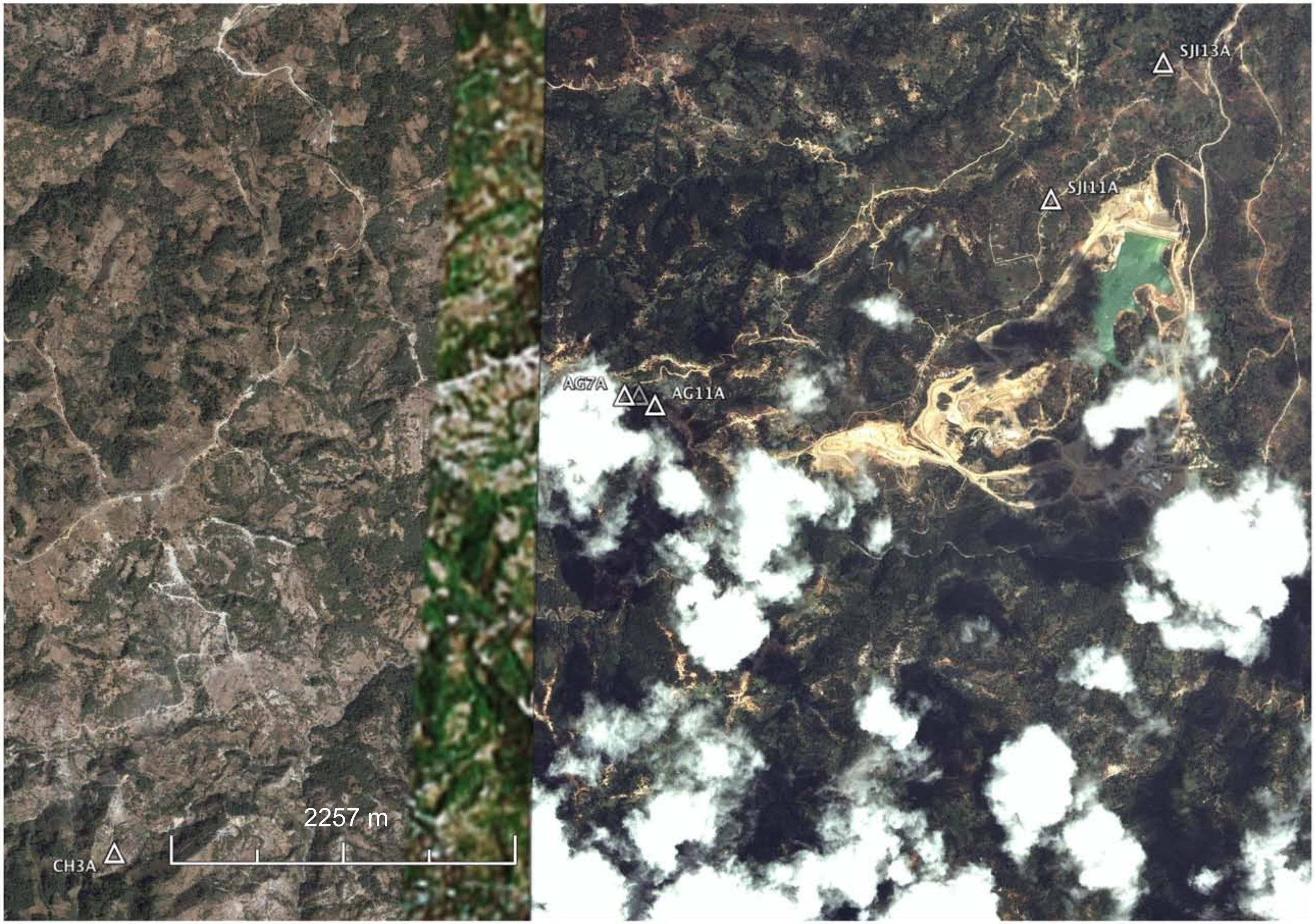

Figure 10. Location of Soil Samples. © Google Earth, Digital Globe, TerraMetrics, and GeoEye.

Table 3. Summary of Soil Properties

Sample Number	Sample Location	Soil Classification (USCS) 1	Natural Moisture Content (%)	Fraction Passing 200 Sieve (0.074 mm) (%)	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index (%)	Percent Swell (%)
AG 1A	Agel	CL	17.2	66.3	23	49	26	1.2
AG 7A	Agel	CH	25.1	78.6	27	71	44	
AG 10A	Agel	CH	9.8	88.5	23	62	39	
AG 11A	Agel	CH	42.3	86.1	35	85	50	9.0
SJI 13A	San José Ixcaniche	ML	24.4	50.4	NP	NP	--	
SJNE 3A	San José Nva. Esp.	GC	4.2	41.5	14	31	17	
CH 3A	Chininguitz	SM	8.9	48.9	25	32	7	

1. USCS = Unified Soil Classification System
CL - Lean clay (or low plasticity clay, liquid limit less than 50)
CH - Fat clay (or high plasticity clay, liquid limit greater than 50)
ML - Lean silt
GC - Clayey gravel (gravel with more than 12% clay sized material)
SM - Silty sand (sand with more than 12% silt sized material)

Table 4. Correlation of Soil Properties and Building Damage

Sample Number	Sample Location	Density Test Results (Number of blows/soil density)	Soil Swell Potential	Degree of Damage[1]
AG 1A	Agel	10 for 8 cm/ very dense	Low	2
AG 7A	Agel	no test	High	7
AG 10A	Agel	no test	Moderate	3
AG 11A	Agel	no test	High	1
SJI 13A	San José Ixcaniche	12 for 13 cm/ dense	Low	3
SJNE 3A	San José Nva. Esp.	12 for 8 cm/ very dense	Low	1
CH 3A	Chininguitz	12 for 5 cm/ very dense	Low	3

Note: 1. Degree of damage is from Appendix D except for Chininguitz.

Figure 11 Field Density Test

Soil Properties

Soil test results, as summarized in Table 3, indicate that soil properties vary widely within the study area. Column 3 describes the soils. The soil types include gravel, sand, silt, and clay. The coarser soils have varying clay and silt contents. This variability explains the variation in natural moisture contents. For different soil types exposed to similar natural moisture and temperature conditions, coarse-grained soils will tend to retain less water than finer soils.

The test known as “fraction passing the No. 200 sieve” - also referred to as the “minus 200 fraction” - is the best indication of the amount of clay-sized material in the soil. The minus 200 test results varied from 41.5 to 88.5 percent. Soils with less than a 50 percent minus 200 fraction are seldom swelling soils. Soils with more than 50 percent may be swelling soils depending on the remaining properties.

Two plasticity tests were performed: the Plastic Limit and the Liquid Limit. These limits are the moisture content of the soil when the soil becomes plastic and liquid with the gradual addition of water. The Plasticity Index is the arithmetic difference between the Plastic Limit and Liquid Limit. All three values indicate the behavior of the clay fraction of a soil as a function of moisture content. Generally, higher Liquid Limit and Plasticity Index values indicate clays that are more prone to volume change with variations in moisture content. Soils that do not display any plasticity are reported as Non-Plastic. These soils do not contain minerals whose behavior varies with changes in moisture content. Values for plasticity tests varied from Non-Plastic for sample SJI 13A to Liquid Limit and Plasticity Index values of 85 and 50, respectively, for sample AG 11A.

The swell potential test consists of placing a soil sample under a load and inundating it with water. The change in sample height as a function of load and water inundation is plotted on a graph. The plots for the two tests performed are included in Appendix G. The results are reported as percent swell on inundation with water under a 48 kiloPascal load. Results for the two samples were 1.2 percent and 9.0 percent. Swell results less than two percent indicate soils that will not swell enough to cause damage to structures.

The soil tests show that, of the seven samples collected, only two have some indication that swelling clays may be contributing to building damage. The test results for sample number AG 11A show the combined characteristics of high natural moisture content, high Liquid Limit, high Plasticity Index, and high minus 200 fraction, which are indicators of high swell potential. Of the samples tested, other than AG 11A, only sample AG 7A shows a similar combination of high natural moisture, high plasticity, and high minus 200 fraction. Although AG 7A was not analyzed for swell potential, it is expected that this soil would show swell potential similar to sample AG 11A.

Based on natural moisture content, plasticity, and minus 200 fraction, the remaining samples show very low swell potential, similar to the results for sample AG 1A.

Sample SJI 13A is Non-Plastic. This result indicates that the minus 200 fraction does not contain significant quantities of clay minerals; the fine fraction is likely composed primarily of silt. Silt is similar in size to clay, but it is composed of minerals that do not exhibit volume change with variations in moisture content. Based on these results, SJI 13A most likely would have a zero swell potential.

The field density test results, in Table 4, varied widely, with the densest soils returning results of 12 blows to penetrate 5 centimeters, while the loosest soils returned results of 2 blows to penetrate 30 centimeters. The results indicate that there is considerable variation in the degree of compaction of the base soils underlying the buildings. This variation in penetration does not correlate with the building damage, so inadequate compaction is not likely the cause of the damage.

Correlation of Soil Properties with Structural Damage

In cases where swelling soils may contribute to building damage, the actual degree of swelling, and subsequent damage to buildings, depends on other factors in addition to the swell potential of the soil. Swelling only occurs when there are particular clay minerals present and there is sufficient change in moisture content and temperature of the soil. Depending on the clay minerals present, changes in moisture content sometimes do not produce changes in soil volume. Changes in moisture content often are caused by migration of moisture under the building due to temperature differences between the soil under the building and the soil surrounding the building (Nelson and Miller, 1992). Such temperature differences are caused by the combination of extreme seasonal temperature variations and any heating and cooling systems of the buildings. Due to the moderate temperatures of the western highlands of Guatemala, ambient temperatures do not vary dramatically, and such internal systems are unnecessary. Therefore, variations in soil temperature, and the related differences in soil moisture, would be minimal in the soils under and around buildings in the area. In addition, many of the buildings observed had soil floors. In these cases, because the interior soils are open to the atmosphere just as the exterior soils are, it is even less likely that significant variations in soil moisture would occur.

Soil sample locations and the degree of damage at each building where a sample was collected are shown in Table 4. As can be seen, there is not a good correlation between soil characteristics and degree of damage. For example, buildings represented by samples AG 7A and AG 11A are both located in Agel, within 500 meters of each other. Soil samples for both buildings indicate a high swell potential. However, the building next to AG 11A has only moderate damage while the building next to AG 7A is severely damaged. A similar outcome is seen when comparing results of the field density testing with the degree of structural damage at the respective buildings, as shown in Table 4. Again, there is no apparent relationship between density test results and degree of damage.

If the crack damage were due to swelling soils, the cracks would expand during the wet season, and when the soils dry out, the walls would return to their original position and the cracks close. The engineering team visited the area just before and after the rainy season and near the end of the dry season. The crack data and photos show no such changing behavior, as noted in Table 2; rather, the cracks have shown little change. This cracking behavior is not typical of swelling soils; it is more typical of frequent ground vibration events.

VIBRATION MONITORING

Cracks in building walls can be caused by vehicle traffic, explosive blasting, construction activity, and other sources of ground vibrations. (Aimone-Martin, 2003; Dowding, 1985, 1996; Hanson, 2006.) Cracks are caused when vibrations transmit through the ground to the building, and the vibrations are strong enough to exceed the strength of materials in the building walls. Repetitive, lower intensity vibrations over a prolonged period of time also can degrade construction materials until the material fails and cracks appear.

Some typical maximum vibration standards, imposed or recommended by various government agencies, are listed in Table 5. These standards were developed in countries in which building practices are quite different from those in rural Guatemala. The values of these standards would have to be lower to protect non-reinforced concrete and adobe because these materials do not have the tensile strength of other building materials.

MEG (2003, pp. 5-115) and its consultant, J. P. Ligorría A. (2008) report vibrations in units of gravity. This unit of measure is unusual as most regulatory agencies use peak particle velocity (ppv); see Table 5 and its references. In fact, Ligorría's primary reference (Kramer, 1996, p. 68) also recommends peak particle velocity as the most applicable measure for predicting damage from vibrations.

Initial monitoring of ground vibrations performed as part of this study was conducted on 11 November 2008 for vehicle traffic and one explosive blasting event in the Marlin open pit. Tests of vehicle vibrations were repeated on 19 March 2009. The first vehicle test was in central Agel, and the second was on the west end of Agel since the road through Agel was being rebuilt. The vibration-monitoring instrument was a seismograph, Blastmate III, manufactured by Instantel. The Blastmate III calibration certificates are included in Appendix H.

Table 5. Vibration Criteria for Masonry Buildings from Various Countries

Standard	**Source**	**Frequency** (Hz)	**Peak Velocity** (mm/sec)
US Federal Transit Administration[1]	Traffic	Not specified	5.1
US Bureau of Mines and US Office of Surface Mining[2]	Blasting	< 40 > 40	19.1 50.8
Germany DIN 4150[3]	Not Specified	< 10 10 - 50 50 - 100	5 5 - 15 15 - 20
Switzerland[1,3]	Traffic	10 - 30 30 - 60	5 5 - 8
	Blasting	10 - 60 60 - 90	12 12 - 18

[1] Hanson, 2006
[2] Siskind, 1980 and Aimone-Martin, 2003
[3] Georgia Institute of Technology, 2002

Vehicle Traffic

Vehicle vibrations were monitored using an unloaded and loaded Ford three-axle dump truck model Aeromax L9000; as shown in Figure 12. The empty weight of the truck is 13600 kilograms, and the maximum capacity of the truck loaded is approximately 27300 kilograms. This truck is smaller than the largest trucks seen on the road, which were fuel tank trucks. The truck drove past the Blastmate III at various speeds up to 50 kilometers per hour.

The peak particle velocities for the tests are summarized in Table 6, and the Blastmate III detailed results are included in Appendix H. For the unloaded truck moving at a speed of 10 to 30 kilometers per hour, the peak particle velocity remains within a range from 0.238 to 0.349 millimeters per second. The peak particle velocity increases to 0.476 millimeters per second at 40 kilometers per hour, and then more than doubles to 1.16 millimeters per second at 50 kilometers per hour. For the loaded truck at 30 kilometers per hour, vibrations are a maximum peak particle velocity of 0.540 millimeters per second. The loaded truck increases the vibrations 55 percent over the unloaded truck. Road construction underway in Agel prevented additional testing of the loaded truck.

Figure 12a Blastmate III (Sensor on Left, Data Recorder on Right)

Figure 12b Monitoring Vehicle Vibrations

Figure 12 Vibration Monitoring

Figure 12c Blast Monitoring

Figure 12 Vibration Monitoring

Table 6. Maximum Peak Particle Velocity of an Unloaded and Loaded 3-Axle Dump Truck

Truck Velocity (k/h)	**Unloaded Truck Peak Particle Velocity** (mm/sec)	**Loaded Truck Peak Particle Velocity** (mm/sec)
10	0.349	
20	0.238	
30	0.349	0.540
40	0.476	
50	1.16	

The peak particle velocities did not reach the typical vibration standard of 5 millimeters per second given in Table 5. Nevertheless, as the truck velocity and load increased, the peak particle velocity approached the standard. It is notable that the peak particle velocity with the unloaded truck increased geometrically from 30 to 50 kilometers per hour, and might have continued to increase geometrically with the loaded truck as well.

Dowding (1996, p. 249) reports that trucks of the same size as the one tested above can produce vibrations that exceed the traffic criteria given in Table 5 under the following conditions:

- Truck Size – 22000 kilograms
- Speed – 50 kilometers per hour
- Bumps – 100 millimeters

These circumstances produce peak particle velocities of 0.5 to 10 millimeters per second at distances of 10 to 100 meters from the truck. The higher end of this range exceeds the criteria of 5 millimeters per second, and the source distance is within the distances of buildings from roads in the area around the Marlin mine.

Generally roads in the affected villages are unimproved and lie directly on soil or bedrock. There is no base course nor are there road improvements to decouple traffic vibrations from the soil. The roads are poorly maintained, and have potholes and washboard. These conditions cause vehicles to impact the ground surface, which increases ground vibrations. In addition, any vehicles with poor suspension would increase the ground vibrations. Further, adobe and concrete block buildings are particularly susceptible to vibrations as these construction materials have low tensile strength compared to lumber or steel.

The road through the villages around the Marlin mine was being improved in March 2009, as noted above. If properly maintained, this improved road will probably reduce the risk of vehicle vibration damage to the adjacent buildings.

MEG monitored vibrations due to vehicle traffic in several villages around the Marlin mine prior to the construction and operation of the mine (MEG, 2003, pp. 5-115), and reported its results in units of gravity instead of the more common measure of peak particle velocity. MEG reported a maximum acceleration of approximately 0.020 gravity (2003, Figura 5.6-21). However, MEG did not report the size of vehicles monitored. Because the monitoring was prior to construction and mining operations, the vehicles were likely not the typical large trucks used in delivering large-scale construction and processing equipment and supplies to the mine. The maximum vehicle vibration registered in this current study was a peak particle velocity of 1.16 millimeters per second, which is approximately equivalent to an acceleration of 0.028 gravity given typical wave forms of the vibrations (see the 50-kilometer per hour test, Appendix H). This vibration significantly exceeds the 0.020 gravity maximum reported by MEG for vehicles that were probably smaller than those used during mine construction. In regard to MEG's monitoring and the monitoring conducted for this report, there are two possible circumstances that could give false results, as follows.

- MEG monitored vehicle traffic before mine development when the vehicle traffic was relatively light.
- The much larger trucks (six and more axles) used to supply mines were not monitored, and larger trucks cause low frequency and high amplitude vibrations that are most likely to result in structural damage.

Thus actual vibrations experienced by the buildings in the villages around the Marlin mine have almost certainly been greater than shown by any vibration monitoring conducted to date. As the monitored vibration of 1.16 millimeters per second is within an order-of-magnitude of the vibration criteria of 5 millimeters per second, it is likely that vehicle traffic could have caused structural damage.

The vibration criteria listed in Table 5 are for industrialized nations where construction is regulated with building standards. The villages surrounding the Marlin mine are built with traditional techniques, adequate for local needs but not adequate for the intrusion of a large-scale industrial activity with impacts such as increased heavy truck traffic and mine blasting.

Blasting

One blasting event in the Marlin open pit was monitored by the team on 11 November 2008. See Appendix H for the results. Maximum vibrations were low compared to the blasting standards given in Table 5, showing a peak particle velocity of 0.524 millimeters per second at a dominant frequency of 9.5 Hertz. These results are consistent with good blasting practices as claimed in the letter from MEG dated 26 July 2006 to Sr. Valentin Melecio Juárez and a blast monitoring record covering the period from January to August 2009 (Appendix B). This monitoring record shows low vibration frequencies. Although the monitoring record provides coordinates for the monitoring locations, the coordinate system is proprietary to the mine and the information provided is not adequate to determine whether the monitoring locations are relevant to damage in the villages surrounding the Marlin mine.

The engineering team was at the unused Catholic Church in San José Nueva Esperanza on 20 March 2009 when two mine blasts were detonated at approximately 12:45 pm. In spite of the above-mentioned letter and blasting record from MEG, these blasts shook the church with an intensity value of V on the Modified Mercalli Intensity Scale. An intensity value of VI is enough to cause structural damage, so the mine blasts on that day were near what would be sufficient to damage buildings.

On behalf of MEG, Ligorría (2008) conducted extensive monitoring of blasting at the mine. (See Appendix B.) He monitored vibrations from 64 blasts in the open pit and 28 blasts in the underground mine. The monitoring locations varied in distance and direction from the blasting, and included monitoring locations in Agel and San José de Nueva Esperanza. The monitoring results generally show low vibrations compared to blasting vibration criteria given in Table 5. However, when Ligorría performs a spatial analysis of the seismic data, two high-risk areas show up; the first in San Jose Nueva Esperanza (Ligorría, Figure 10 a.) and the second in Agel (Ligorría, Figure 11 b.) Ligorría dismisses the high risk in these areas in the last paragraph of his conclusions, as follows:

- With regard to San Jose Nueva Esperanza, Ligorría states that the high risk may be due to the refraction of seismic waves in the large vein of quartz-calcite. This vein strikes northerly through the mine and past the village.

  Response: The quartz-calcite vein is not going away so the risk remains. The strong vibrations at the Catholic Church, noted above, were in the high-risk area.

- In the case of Agel, Ligorría dismisses the spatial analysis by saying that its results are due to the arrangement of data and the process of normalization, and not an indicator of vibrations from the nearby blasting.

  Response: Presumably, Ligorría used state-of-the-art technology for the analysis (no reference is given for the analytical method), so it is inappropriate to discount the results. If the methodology is not reliable, the analysis should be modified.

In the last paragraph of Ligorría's conclusions and elsewhere, he makes a number of disclaimers in addition to the preceding two specific disclaimers. These disclaimers include questions about the normalization process, the interpretation's being a simplification of a complex system, numerous variables, dispersion in the results, and poor statistical correlation. The disclaimers leave the impression that Ligorría has little confidence in the results of his work.

The MEG letter to Señor Juárez, noted above, contains an inaccuracy regarding transmission of ground vibrations. It states that areas higher in elevation than a blast are less subject to ground vibrations. In fact, just the opposite is the case, as in such areas there is less damping from surface reflected vibrations, and particularly so if the higher ground is a ridge location. As ground vibrations rise towards a ridge crest, the total energy is conserved in the narrowing ground mass resulting in amplification of particle acceleration (Kramer, 1996, p. 319). Many of the villages surrounding the Marlin mine fit this circumstance. Ground vibrations traveling toward the crest of a ridge can more than double their peak acceleration from their base acceleration (Kramer, 1996, p. 320).

The results reported by Ligorría (Appendix B) are based on averages of a number of events, and recent blasting practices. However, it only takes a single mistake or omission during the blasting process to cause ground vibrations orders-of-magnitude greater than intended. Local inhabitants state that blast vibrations and blast noise were much stronger in the past, which implies that past blasting practices were not the same as the present ones. It is likely that there were larger and higher impact blasts in the past. Typically, the initial mining in open pits is primarily overburden or waste rock removal, which requires less selective blasting than ore blasting, and the volume of rock blasted at any one time may have been much larger than in current blasting. In addition, MEG may not have always used the blasting practices described in their letter, and inefficient or inappropriate blasting techniques may have been used. For example, millisecond delays may not have been used to stage energy release, or there may have been errors initiating the delays or malfunctions in the delays. Other errors that can occur in blasting include: incorrect amounts of explosives placed in blast holes, incorrect blast hole stemming, and incorrect spacing of blast holes. Inefficient blasting results in less energy used in breaking rock, and more energy goes into ground vibrations, noise, and fly rock.

Thus, there are circumstances under which blasting at the Marlin mine may have caused ground vibrations exceeding those monitored. These circumstances include early large scale blasting in the open pit and inefficient or inappropriate blasting practices. Making matters worse, the ground vibrations are amplified in the ridges around the mine where the structural damage has been documented.

A new concern is that MEG recently started mining in a new open pit that is closer to Agel. This new open pit approximately halves the blasting distance to Agel.

CONCLUSIONS

The anomalous differences between buildings in the villages around the Marlin mine and those in the control villages are compelling evidence that the mine is damaging those buildings near the mine. Every building entered by the engineering team in the villages around the mine had some structural damage. In contrast, very few buildings in the control villages had damage except in the area of mass land movements in Chininguitz.

The engineering team was not present prior to development of the mine and cannot determine the cause of the structural damage with absolute certainty. Unfortunately, the MEG EIA&S is inadequate in establishing pre-mine baseline conditions, as it should have done. Therefore, the process of determining the likely cause of the damage to buildings is one of eliminating those factors that are obviously not the cause, and then narrowing the remaining possible causes to the most likely cause, using any post-damage evidence and data that can be discovered.

Building damage can result from natural causes such as climate, earthquakes, poor soils, and mass land movements such as landslides. Human causes of building damage include ground vibrations from vehicle traffic or blasting, and inadequate construction practices. The likelihood of these various causes being responsible for the damage in the villages surrounding the Marlin mine is summarized below, based on the preceding sections of this report.

Given the temperate climate and seismic history of the area, it can be concluded with confidence that the building cracks are not due to freeze-thaw and/or seismic events. If so, there would be much other evidence of these causes in the damaged buildings. The control villages support this conclusion as they have experienced similar climate and seismic events but have not incurred the type of damage found in the villages around the Marlin mine.

Soil heaving under the houses due to moisture and swelling soil is not likely, as most of the buildings do not lie on swelling soils, water drainage is sufficient around building perimeters, and floor slabs are often not cracked themselves. In addition, monitoring of crack widths shows that the widths do not change with the rainy and dry seasons, which would be the case if soils were swelling during the rainy season and contracting during the dry season. Once again, the control villages support this conclusion as they have very similar building construction and soils, but do not show the type of damage found in the villages around the mine.

The type of structural damage in the villages around the Marlin mine is inconsistent with mass land movements, and there was no evidence in these villages of mass land movements. In fact, many of the buildings in these villages are built near the top of a ridge on thin soil or bedrock, so there are no massive thicknesses of soil to slump downward. Chininguitz demonstrates the difference between damage from mass land movements and other causes. One small valley of this village has mass land movement that has damaged many buildings. The mass land movement includes very long ground fractures, hummocky soil, scarps, and landslides, which are not seen in the villages adjacent to the mine.

Structural damage in the villages around the Marlin mine is not due to construction practices as the same building practices are used in these villages and the control villages. Base compaction under the buildings is not the problem, as field tests of base compaction did not correlate with the damage.

Most of the damage presents itself as cracks in the grout of concrete blocks walls and in adobe walls, of the type typical of damage from ground vibrations. That is - cracks in walls where there are none in the floor, cracks in mid-wall, and cracks most frequently found in walls oriented towards vibration fronts from vehicle traffic and/or mine blasting. Given the data collected, the most heavily supported cause of the structural damage in the villages around the Marlin mine is the Marlin mine blasting and increased vehicle traffic of heavy mine supply trucks.

In comparison with the control villages, the villages immediately surrounding the Marlin mine show obvious structural damage that is beyond normal aging and occasional construction problems. Using standard engineering methods, monitoring, and testing, the engineering team eliminated all of the realistically possible causes of the building damage except one. The causes eliminated include mass land movements, seismic activity, poor soils, and construction practices. The team concluded that the most likely cause is ground vibrations from mine blasting and increased heavy vehicle traffic. The local construction materials of concrete block and adobe are susceptible to vibration damage as these materials have low tensile strength compared to, for example, lumber and steel-reinforced concrete. Prior to the construction of the mine, concrete block and adobe served the local communities well; there was no need to incur the added expense of more substantial construction and no knowledge that it might be necessary.

RECOMMENDATIONS

Further monitoring of building damage and ground vibrations is needed to provide information on the impacts of mining activities at the Marlin mine and to provide information for decision-making. A monitoring plan should be developed through a collaborative effort among the impacted villages, the mining company, and the government agencies. The various parties should agree upon the goals and scope of the monitoring. The monitoring plan should include a thorough baseline inspection of existing conditions in all buildings within an agreed-upon geographic area surrounding the mine. (As noted above, a pre-mining baseline survey would have been preferable, but was not performed.)

The monitoring plan should include regular, periodic visits to each building or to a representative sample of buildings to document any changes in conditions. Results of these inspections should be made available to the building owner and village representatives in a timely manner. The inhabitants of any buildings that exhibit extensive damage should be notified and should be provided with safe alternate housing until a resolution to the situation can be agreed upon.

For monitoring of ground vibrations, permanent seismograph recording stations should be set up throughout the villages surrounding the mine at locations agreed upon between all parties. The stations should provide full time monitoring, with results made available to the public in a timely manner. Any events that show high levels of ground vibrations should be thoroughly analyzed for possible damage to buildings.

These monitoring recommendations are even more important now that MEG has started mining in a new open pit that is much closer to portions of the impacted villages.

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