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MINE SAFETY AND HEALTH ADMINISTRATION

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REPORT NO. MW11-005

STRUCTURAL INVESTIGATION OF SURGE BIN TOWER COLLAPSE
HILLTOP BASIC RESOURCES
BIG BEND QUARRY
MINE I.D. NO. 15-18147
BATTLETOWN, MEADE COUNTY, KENTUCKY

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OWNERSHIP AND LOCATION

The Big Bend Quarry, Mine I.D. No. 15-18147, is operated by Hilltop Basic Resources. The facility is located in Meade County, Kentucky, approximately 30 miles southwest of Louisville, Kentucky. More precisely, the site has geographical coordinates of 38°09'09" north latitude and 86°17'43" west longitude.

INTRODUCTION

The Big Bend Quarry produces limestone from an open pit mine. The limestone is excavated by blasting and is run through a primary crusher in the pit before being transferred to the plant on the Overland Conveyor. The Overland Conveyor discharges into the 500-ton Surge Bin (photo 1) in the plant area before additional crushing and sorting is performed. The material stored in the Surge Bin is mostly 4 to 6 inches in diameter. The Big Bend Quarry employs 35 miners and operates two shifts per day, 7 days a week.

On Wednesday, November 10, 2010, at approximately 1:30 P.M., the 500-ton Surge Bin Tower collapsed. No injuries were sustained because no one was on or near the tower at the time of the collapse. An eye witness account of the collapse noted a sudden drop of the Overland Conveyor's head pulley, which was mounted on the top of the bin, followed by toppling of the bin toward the Overland Conveyor (west direction) (photo 2). The bin was at least one-half to three-quarters full and no material was being discharged into or out of the bin at the time of the collapse. On the day of the collapse, the wind speeds were low (10 MPH or less). Blasting in the pit (approximately 1/2-mile away) occurred 20 minutes before the bin collapsed. A seismograph located approximately 1/2-mile from the pit on residential property recorded a peak particle velocity below 0.0550 inches per second, which makes it is unlikely that the Surge Bin Tower vibrated at a frequency which would have damaged the structure. The level of the limestone in the bin is usually monitored by cameras and a tilt switch. The tilt switch had malfunctioned a few days before the collapse. The camera provides only a live feed to the plant operator booth, it does not record.

The collapse of the Surge Bin Tower removed the end support from the truss supporting the Overland Conveyor. As a result, a 70-foot section of truss became partially detached, and was left hanging from the adjacent vertical bent support. The mine operator then proceeded to cut the belt and truss chords in order to bring the hanging section of the truss to the ground. The collapse of the Surge Bin Tower also damaged the tail of the Transfer Conveyor which was fed from the bottom of the bin on the east side. When the tail of the Transfer Conveyor was impacted, it caused the entire length of the Transfer Conveyor truss to thrust in the east direction, permanently deflecting all of the bent supports to the east. The operator removed the truss and conveyor components of the Transfer Conveyor while we were on site and intends on repairing/replacing the bents of the Transfer Conveyor.

FIELD INVESTIGATION

On November 15 through 18, 2010, Michael Superfesky and Anthony Argirakis worked with Sonia Conway, Metal and Nonmetal Safety and Health Inspector, Lexington Field Office, by providing assistance regarding the safe removal of the damaged conveyor and bin structure. An additional 40-foot of new conveyor truss was installed at the end of the Overland Conveyor so that a stable cantilever was established until a new bin structure could be installed. Following the completion of this remedial work, the investigation of the Surge Bin Tower collapse commenced. The removal and installation of the new conveyor structure provided safe access to the area with little disturbance to the accident scene. A steady rain on November 16, 2010, did produce a light coating of rust on the new fracture surfaces of the steel.

MSHA was assisted during the investigation in collecting information and accessing the accident scene by the following Hilltop Basic Resources employees.

John Morgan,	Vice President Mining Operations
Gary Lewis,	General Manager
Richard Popham,	Quarry Manager
Kelly Carver,	Team Leader

<u>Configuration and Operation</u>

The Surge Bin Tower was configured with an overall height of 54 feet and square base of 20.5 feet per side. Photo 1 shows the Surge Bin Tower approximately 5 years prior to the collapse. The main structural members of the tower consisted of four columns with lateral bracing between the columns, a 2-level orthogonal arrangement of floor girders hung from the bin walls at the bottom, and stiffened bin walls which acted like plate girders (deep beams). The bin was square with interior dimensions of 20 feet by 20 feet and a height of 28 feet. The bin was constructed by vertically stacking three prefabricated boxed sections (20 feet by 20 feet) together and bolting the box sections at each interface. The 3/4-inch-diameter bolts used for connecting the box sections were installed through the flange plates located on the top and bottom of each box section. The walls of each box section (bin walls) consisted of 1/4-inch-thick steel plate stiffened on 2 foot centers using (non-bearing) steel angle sections with dimensions of 5 inches by 3 inches by 1/4 inch. At the corners, the walls of the bin framed together at 90 degrees and were connected using a 1/4-inch fillet weld placed on the inside. The corners of the bin were stiffened for bearing purposes by welding two vertical steel bars (plates) 6 inches by 1/4 inch at 90 degrees to each other on the outside corners for the full 28-foot height of the bin. With respect to viewing the top of the bin from overhead, each corner of the bin, with the steel bar stiffeners attached, formed a cross. The attachment of the steel bar stiffeners to the bin corners helped in transferring the overall bin load (in bearing) to the columns below. The top of the columns had 3/4-inch-thick filler plates welded between both flanges on each side of the column's web to provide a bearing surface to connect the bottom of the bin corners and the bar stiffeners to the column. The bottom of the bin corners framed on top of the columns such that they interiorly rested upon one quarter of the total area provided by the filler plates and the column's web and flanges. Framing the bottom of the bin corner within an interior quadrant of the column top allowed the steel bar stiffeners to be welded to the top of the column. The weld between the bottom corners of the bin and filler plates was the only connection between the bin and the columns, with the exception of the K-braces installed between the columns. The top of the K-braces were attached to the underneath side of the bin at midspan on all four sides of the bin. The primary purpose of the K-braces is to provide lateral support to the columns and secondarily assist with the vertical bin load.

There were three feeders located at the bottom of the bin in the center, east, and west sides. Wear or abrasion resistance plates were installed around the openings for the three feeders. There were no wear plates installed to protect and cushion the floor of the bin from impact and abrasion, instead the operator had placed a 2-foot-thick layer of sandy-silt soil at the bottom of the bin.

The bin rested above ground on four 17-foot-tall columns (W12x120) that were anchored to a reinforced concrete footing using 3/4-inch diameter J-hooks embedded in the footing. The columns were laterally braced using K-braces on the north and south sides of the bin at both the upper and lower half of the columns with a horizontal brace between the two sets of K-braces. On the north and south sides of the bin, the columns were laterally braced in the east-west direction using K-bracing in the upper half of the columns. Only the upper halves of the columns were braced so that sufficient clearance existed on these sides for haulage trucks to pass under the bin. The center and west feeders of the bin were used very little during the life of the structure. The feeder on the east side of the bottom of the bin was the most active feeder because it was located above the tail of the Transfer Conveyor.

The bottom flooring around the feeder openings consisted of 3/4-inch steel plates and two levels of orthogonally arranged W24x104 girders. The 3/4-inch steel plate flooring was welded to the bottom flange of the top level of W24x104 girders (running east to west) and was supported underneath by a second level of girders which were oriented in the north to south direction. In order to attach the 3/4-inch steel plate flooring to the bin walls, 1/4-inch fillet welds were implemented.

The Surge Bin Tower was designed and constructed in 1999 by Process Machinery, Incorporated, Shelbyville, Kentucky. Reportedly, the bin was not actively used until 2006. Full use of the bin began once the Overland Conveyor, which feeds the Surge Bin from the pit and the Transfer Conveyor was installed. Prior to 2006, earth material surrounded the north, west, and east sides of the bin to form a ramp that equipment could drive up to in order to feed the top of a crusher located just to the east of the bin. When the crusher was removed, the earth ramp was also removed and the tail of the Transfer Conveyor was installed underneath the bin on the east side. Since the tail of Transfer Conveyor was installed underneath the bin on the east side, the corresponding feeder had been used for discharging material out of the bin since 2006.

The head pulley of the Overland Conveyor was mounted on the top of the bin at the southwest corner and extended diagonally approximately 10 feet toward the center of the bin. It was reported that the discharge stream arced toward the east or Transfer Conveyor side of the bin where the east feeder was located. The height of stone on the east side was lower than the west side due to the evacuation of material through the east side. Evacuation through the east feeder formed a drawdown cone which intersected (flowed against) the east wall of the bin. The material on the three other sides of the bin was static. This type of flow discharge is referred to as asymmetric flow and is contrary to the desired condition of symmetric flow. Symmetric flow would have been occurring if the drawdown cone was symmetrically centered on the feeder located at the center of the bin. The symmetry of the position of the cone relative to the four walls of the bin causes the pressure to be uniformly applied to the walls and this helps to moderate the stresses in the bin walls. During asymmetric flow, the pressure along the bin walls is not uniform because there are flow channels and static zones against the bin walls. This causes the stresses in the walls to fluctuate which can reduce the fatigue life of the bin.

Findings/Observations

- The two top sections of the bin separated from the bottom section as they toppled (rotated 90 degrees relative to the bottom section) toward the west in the direction of the Overland Conveyor. The movement of the bottom section of the bin was also to the west. The west side of the bottom section of the bin came to rest in a lower position than that of the east side (photo 2). This indicates that the underneath of the west side of the bin "fell out from underneath" or "gave-way" prior to the east side. It is believed that the loss of support on the west side of the bin was caused by the failure of the columns (excessive bending or buckling).

- Photo 3, which is the interior portion of the Transfer Conveyor (east) side of the bin, shows abrasive markings on the wall that the material discharging from the bin would flow against. These markings were only present on the east side of the bin and this indicates that the drawdown cone of the discharge flow was offset from the central interior of the bin (asymmetric flow).

- The columns on the Overland Conveyor side (west side) of the bin were significantly bent or buckled. This is an indication that the load carrying capacities of the columns were exceeded. Since the bin was not overloaded at the time of the collapse, and the columns were not deficient from weathering/corrosion, a shift or a deviation in the manner in which the columns were loaded would have had to occur to cause them to buckle. When the load applied to a column is not concentric to its long axis, the loading becomes eccentric (applied from a distance), and this creates a bending moment (force with a lever arm) on top of the column which makes it easier for the column to buckle. Fatigue cracks or corrosion at the bin corners would have reduced the structural rigidity at the bin corners and caused the load from the bin to be applied at some distance away from the geometric center of the column. Also, it is possible that the bin walls or connections at the corners themselves locally failed (fractured or compressed) causing the bin to detach from the column connection. Once the bin detached from one of the columns at a corner, the bin would have then sat down on that column and loaded it eccentrically causing the column to buckle.

- Vertical fractures along the west side corners of the bottom section of the bin (photo 3) were resulting damage from the collapse. The fracturing occurred through the thickness of the bin walls and not in the vertical welds which fastened the corners of the bin walls. Measurements taken along these vertical tears indicated that the loss of wall thickness from corrosion at these fracture surfaces was less than 5 percent. These fractures are not believed to be the cause of the failure, but are a secondary effect of the failure. In order for the two top box sections of the bin to topple over, they had to break free from the bottom section, and they did this by tearing the west side corners of the bottom section.

- Fracturing/detachment of the bottom of the bin occurred at the top of all four columns. It appears that most of the fracturing of the bin attachment to the top of the east side columns was caused after the tower became unstable. For example, photos 4 and 5 shows the top of the east side columns where portions of the bin wall and corner stiffening plates/bars fractured. The majority of the deformation and the fracturing observed in photos 4 and 5 are believed to be the result of the pulling away of the bin walls from the columns when the bin shifted and fell to the west. The bin also disconnected from the west side columns. Photo 6 shows the portion of the bin wall remaining on the top of the southwest column and how the portion of the bin wall remaining on the top of the column was bent and pulled down below the top of the column. Photo 7 shows the portion of the bin wall remaining on top of the northwest column and the crimping of the bin wall above the column. The crimping could have occurred because of a compressive failure in the bin wall itself or because of lateral deflection which would have accompanied the buckling of the column. The fracture surfaces of the remnants of the bin wall attached to the top of the columns did not appear depleted or damaged from corrosion. With respect to the columns on the west side, the small amount of bin wall that was remaining attached to the top of the columns shows the load transfer between the columns and bin was occurring over a small area. Smaller areas of load transfer will create greater stresses in that area. Higher stresses led to a greater chance that a fracture will occur.

- Upward bending or prying was found at the corners of the bin floor at the west side columns (photo 8). This deformation is indicative of excessive bending or rotational loading being transferred between the west columns and the corner of the flooring. There are two behaviors that may have produced this deformation. The first would result from the bending or buckling of the west side columns themselves. As the columns excessively bent/buckled, the bending load at the top of the column would have increased causing such deformation. The second mode of behavior is that if there was a loss of stiffness or rigidity where the bin attached to the east side columns, the west side columns would be required to carry more of the bin load. This would result in the structure momentarily behaving as a cantilever beam with the east end free or not supported, and all of the load would be forced to go to the west side, producing the deformation observed at the west corners.

- A final major deformational characteristic, which is not believed to be direct cause of the collapse, was that the base of all four columns had pulled free (uprooted) from the concrete foundation that they were anchored upon (photo 9). It appears that the base of the east side columns pulled free after the initial trigger of the failure. After the bin detached from the top of the east side columns, the bottom section of the bin slid down against the columns, and this applied a lever action to the top of the columns which uprooted the columns. It is believed that both west side columns were pried free from the foundation during the action of the columns buckling. The extreme deformations of a column during buckling are conducive for allowing the column to act like a lever and pry itself free from the foundation.

Failure Discussion

The collapse of the Surge Bin Tower occurred because the columns on the Overland Conveyor side of the tower buckled. Since the columns were in good condition and the bin was not overloaded, there had to be a change in the manner that the bin was loading the columns for them to fail as they did. It is thought that the change to the way the columns were being loaded resulted from loss of rigidity at the bin-to-column connection or at the bottom of the bin corners because of corrosion and/or fatigue. There was corrosion at the bottom of the bin wall corners where the columns were loaded. Additionally, the stresses and/or fluctuation of the stresses at the corner of the bin could have been larger than the design anticipated because asymmetric flow of material was occurring in the bin. Generally, when any type of bin (circular or rectangular) is operated under asymmetric flow there are areas in the bin wall where the stresses will increase and/or fluctuate because the material within the bin is not pressing against the bin walls equally at all locations. Corrosion and fluctuation of stresses would make the corners of the bin susceptible to fatigue cracking. Cracking from fatigue (loading and unloading of the bin) would have lessened the structural rigidity at the corners of the tower where the bin loads the columns. A weakened bin corner or bin-to-column connection could have deflected, fractured, or wrinkled and this would have changed the load path between the bin corners and the columns below. It would only take loss of structural rigidity at one of the bin-to-column connections to initiate the collapse, because the bin would shift off from the center of the columns and eccentrically load them. Eccentric loading is loading that is not concentric with the columns longitudinal axis and thus puts additional stresses in the column which can cause buckling. Once column buckling occurred, the bin was no longer vertically supported in a stable manner and additional shifting of the bin and its load caused damage to other columns and structural members resulting in the complete collapse of the tower.

Incidental Inspection/Repair Item

It was observed that the base of the legs of the A-frame bent closest to the Surge Bin Tower of the Overland Conveyor has been impacted by equipment (photo 10). The base of the column should be repaired. The repair can be accomplished by installing/fitting a channel or angle steel sections within the interior of the columns so that they rest against the web and flanges of the existing column sections. This repair should be done for both legs of the bent.

CONCLUSIONS AND RECOMMENDATIONS

The Surge Bin Tower collapsed because the columns on the side of the Overland Conveyor became eccentrically loaded which caused the columns to buckle. The column failure was most likely initiated by the bin load not being properly transferred to the top of columns because the bottom of the bin corners or the bin-to-column connection experienced a reduction in structural rigidity caused by corrosion and/or fatigue damage. Corrosion of the bin walls above the columns and large and/or fluctuating stresses at the bin corner from asymmetric flow made the bin corners and their connection to the columns vulnerability to fatigue cracking. Fatigue and/or corrosion damage caused a loss in structural rigidity at the bin corners and their connection to the columns which most likely initiated an unstable or eccentric loading on the bin columns on the Overland Conveyor side of the tower which led to sudden buckling of the columns and collapse of the structure.

Another finding of this investigation was that the bin structure was marginally adequate at the four corners to transfer the bin load to the columns. Additional stiffening of the bin walls, corners, and the bin-to-column weld connection would have enhanced the structural rigidity and prevented load concentration and vulnerability to fatigue via corrosion, shock, and vibration. If additional stiffening members had been installed at the bottom of the bin corners where they connected to the columns, it is thought that this would have strengthened this area and spread the load transfer path out so that more of the bin wall was required to carry the load, and this would have reduced the stresses and vulnerability to failure.

If this same exact bin tower configuration is installed at the subject site as a replacement, it is recommended that the bin corner/column load transfer system of this structure be analyzed in more detail by the engineer providing the design to ensure that the potential vulnerability of fatigue or overstress has been properly addressed. As a temporary and minimum safety measure, it is recommended that a structural steel section such as an equal leg angle be welded and fitted against the four bin corners for the full height of the bottom section of the bin. A second part of this stiffening measure is to install an equal leg angle at an inclination between 45 and 70 degrees from the bottom of the bin on each side of the corners of the bin walls between the corners and the vertical wall stiffener nearest the corner. Also, considering that this type of bin structure may exist at other mining operations, operators with this exact bin tower configuration should be informed of this situation/condition, and based upon the recommendation of their engineer, appropriate stiffening to the bin corners should be made.

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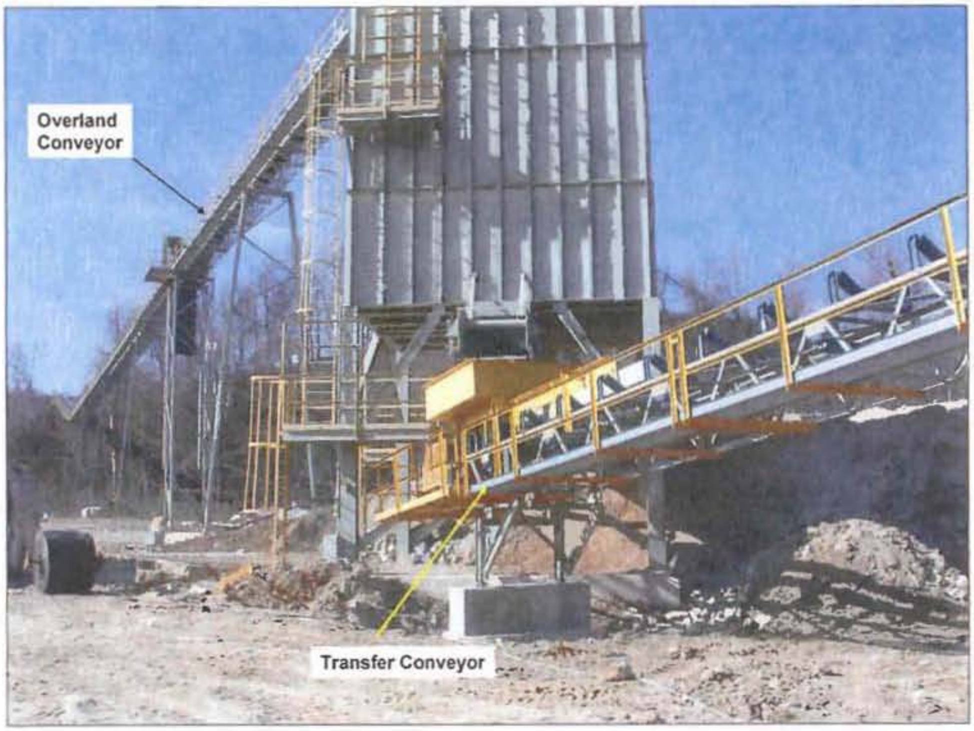

Photo 1 – East side of Surge Bin Tower during the year 2006.

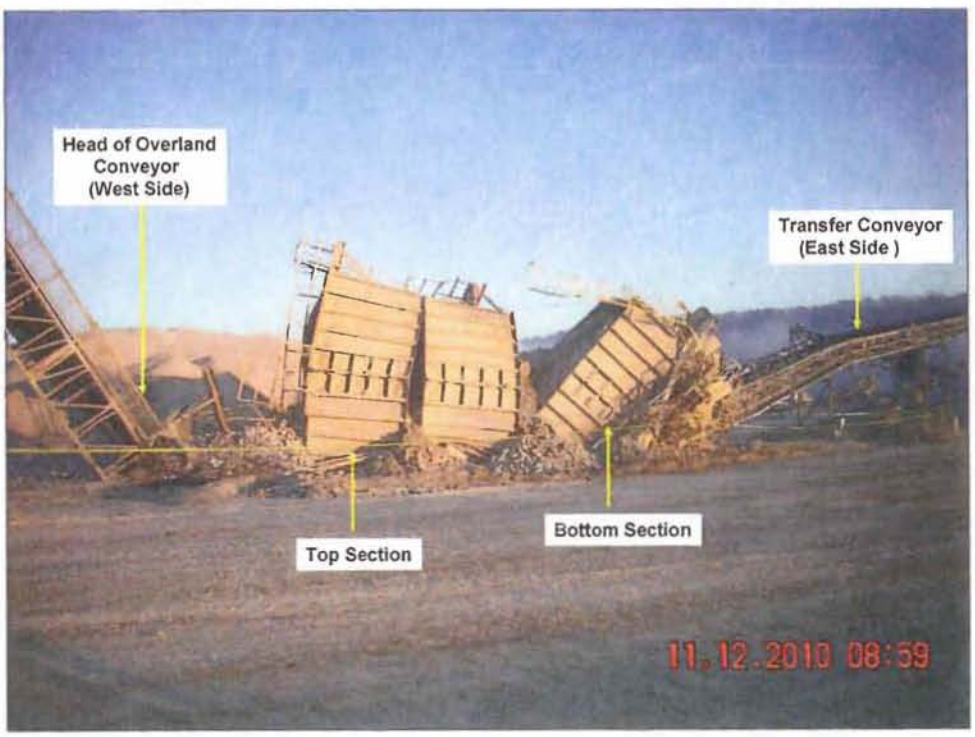

Photo 2 – South side of Surge Bin Tower with respect to looking north.

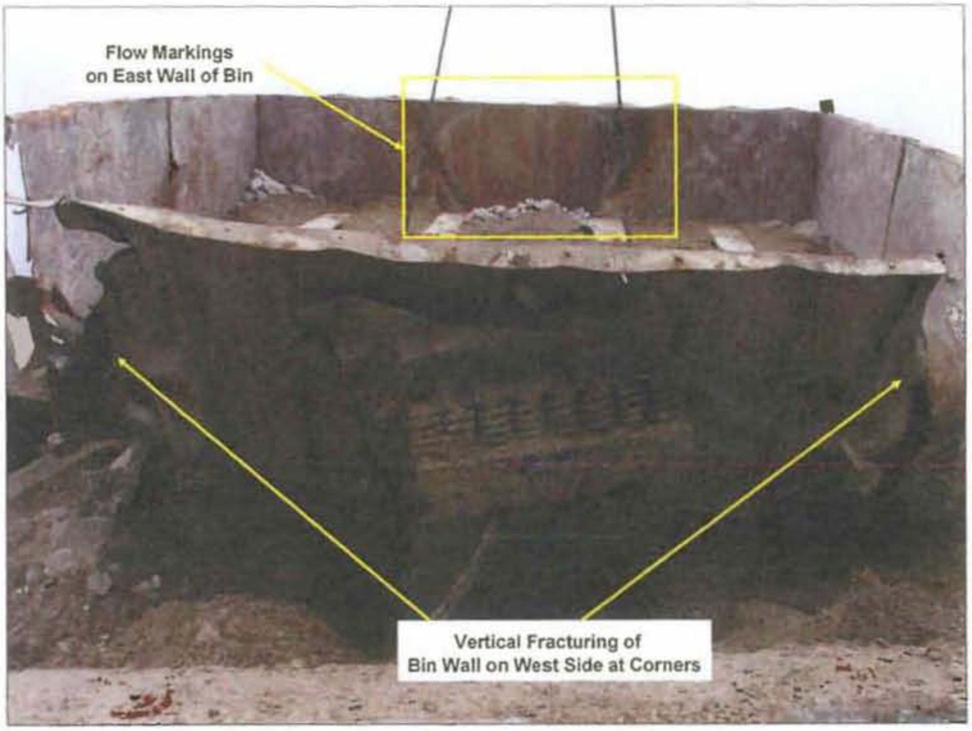

Photo 3 – Bottom section of the bin showing wall markings and fractures.

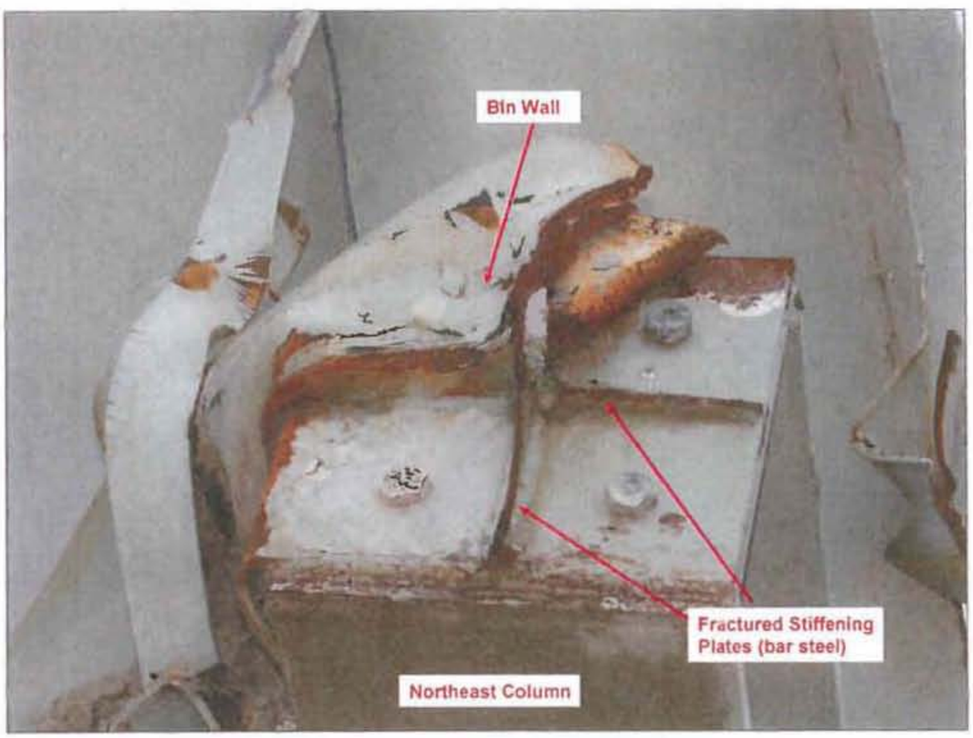

Photo 4 – Top of northeast column following the collapse.

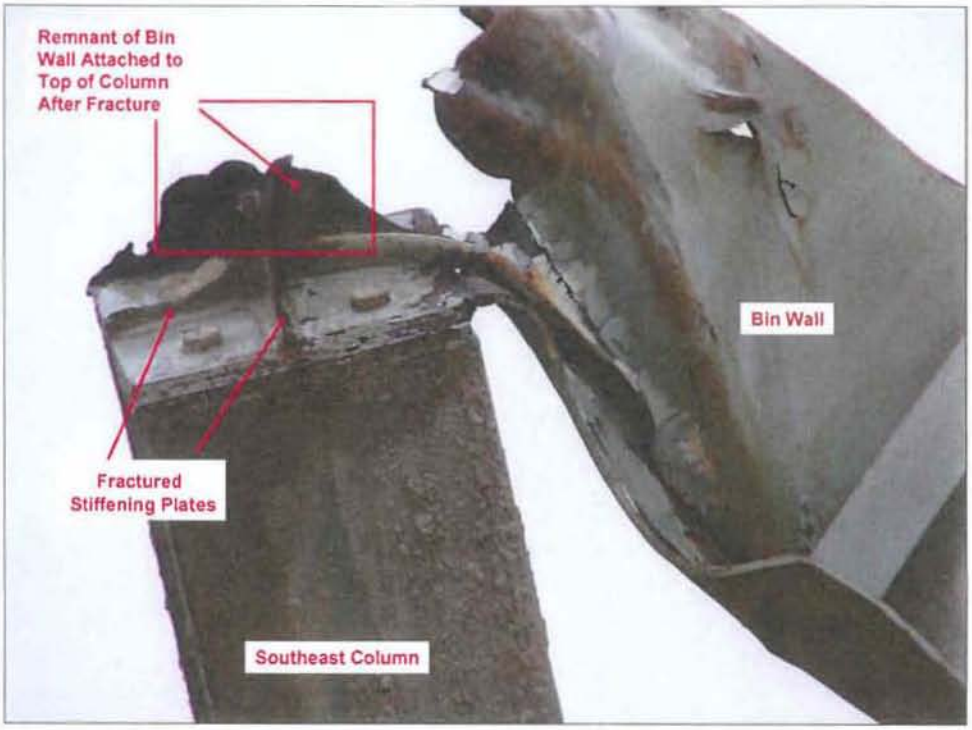

Photo 5 - Top of Southeast column following the collapse.

Photo 6 – Buckled shape of southwest column of the bin following collapse.

Photo 7 - Buckled shape of southwest column of the bin following collapse.

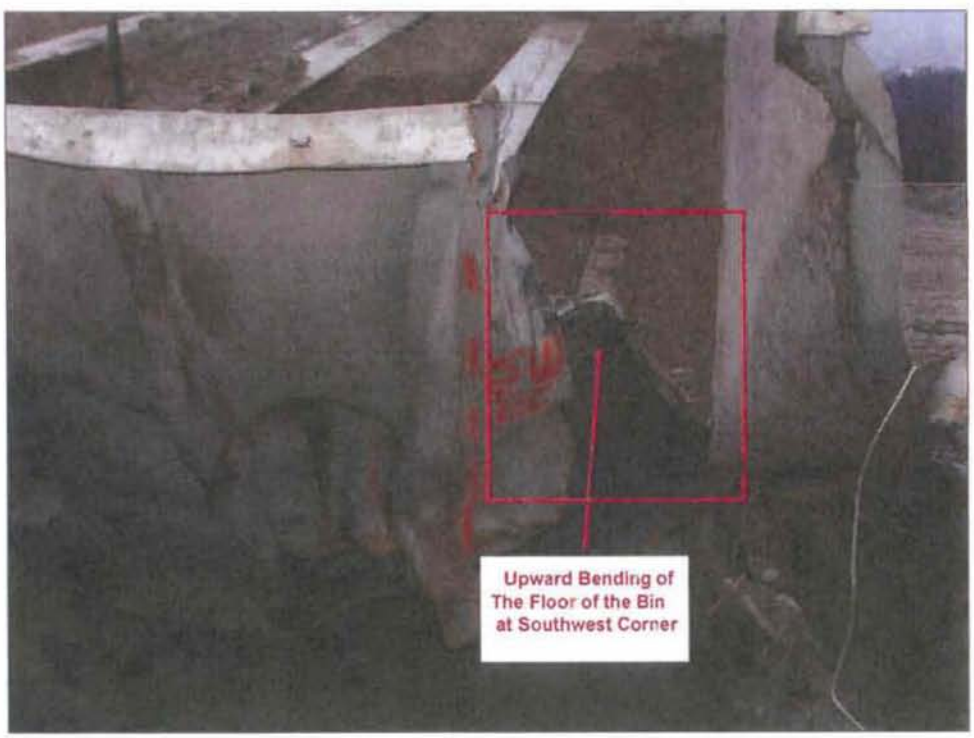

Photo 8 – Southwest corner of the bottom of the bin.

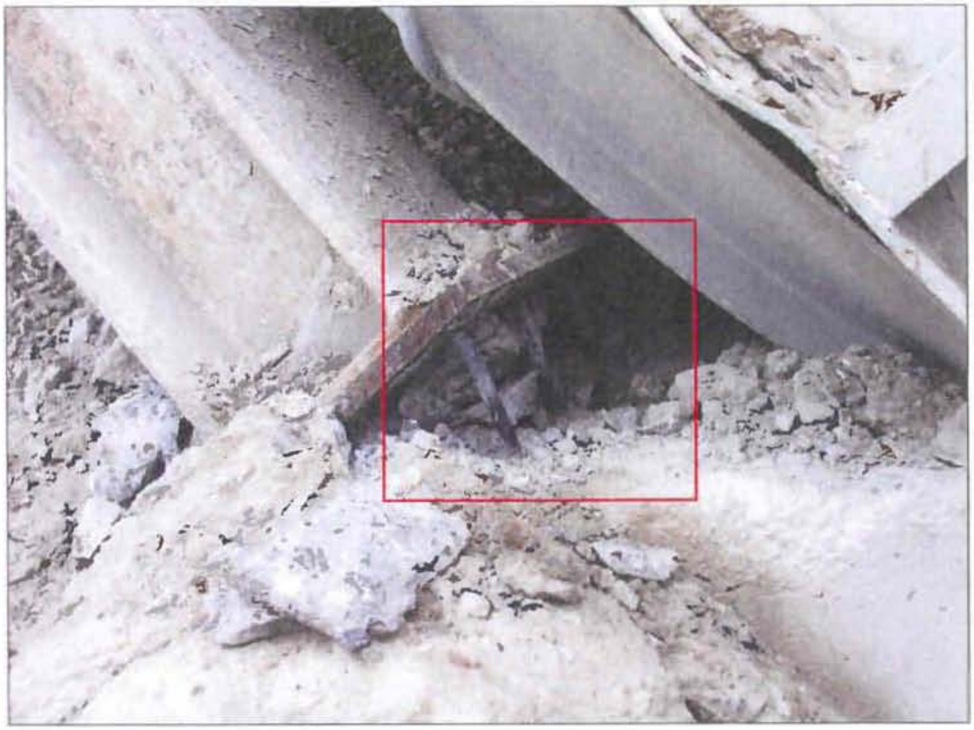

Photo 9 – Base of northeast column uprooted from the footing.

Photo 10 – Base of north leg of A-frame bent closest to Surge Bin Tower.