Perspectives on Containment Wall Failure at ITC Deer Park, Texas

Fire at First & Second 80's Tank Farm at Intercontinental Terminals Company Event of March 17, 2019 at Deer Park, Texas

Tank Farm at the time of Containment Wall Failure, ITC First and Second 80's Tank Farm

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Prepared for
U.S. Chemical Safety and Hazard Investigation Board
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April 24, 2023

U.S. Chemical Safety and Hazards Board
1750 Pennsylvania Avenue, NW Suite 910
Washington, DC 20006

Attention: **Crystal Thomas**
Chemical Incident Investigator
U.S. Chemical Safety and Hazard Investigation Board

Subject: **Perspectives on Containment Wall Failure at ITC Deer Park, Texas**
Fire at First & Second 80's Tank Farm at
Intercontinental Terminals Company
Event of March 17, 2019 at Deer Park, Texas

Ms. Crystal Thomas,

Atlas Engineering is pleased to provide this report on the fire and subsequent containment wall failure that occurred at the first and second 80's tank farm at Intercontinental Terminals Company, Deer Park Texas on March 17, 2019. The following is our perspective on the likely mode of failure for the containment wall and the potential lessons learned from this event.

Atlas Engineering visited the site on July 7, 2021, and reviewed the documentation available from the excavation of the containment wall footing on June 9, 2022. Our work for this has been performed in accordance with CSB's request on May 27, 2021.

Atlas Engineering appreciates this opportunity to be of service. Please call on us with any questions at 919-420-7676.

Sincerely,

Atlas Engineering, Inc., by

NORTH CAROLINA PROFESSIONAL SEAL 041451 ENGINEER MATTHEW J. POISEL
4/24/2023

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Background

A fire occurred at a tank farm on Intercontinental Terminals Company (ITC) property on March 17, 2019. The fire occurred in a section of the facility known as the "first and second 80's" tank farm, hereafter referred to as the tank farm. This tank farm is located at the south-west corner of the intersection of Tidal Road and Independence Parkway in Deer Park, Texas (figure 1). The fire originated at tank 80-8 and proceeded to spread throughout the tank farm over the next serval days despite firefighting efforts. On March 22, 2019, a section of the north secondary containment wall failed, permitting product, water, and firefighting foam to flow into a drainage ditch along Tidal Road and into the Tucker Bayou waterway north of the site. The United States Chemical Safety and Hazard Investigation Board (CSB) has investigated this incident and as part of the investigation has requested that Atlas Engineering provide our opinion on the potential reasons for the containment wall failure and lessons-learned from this incident.

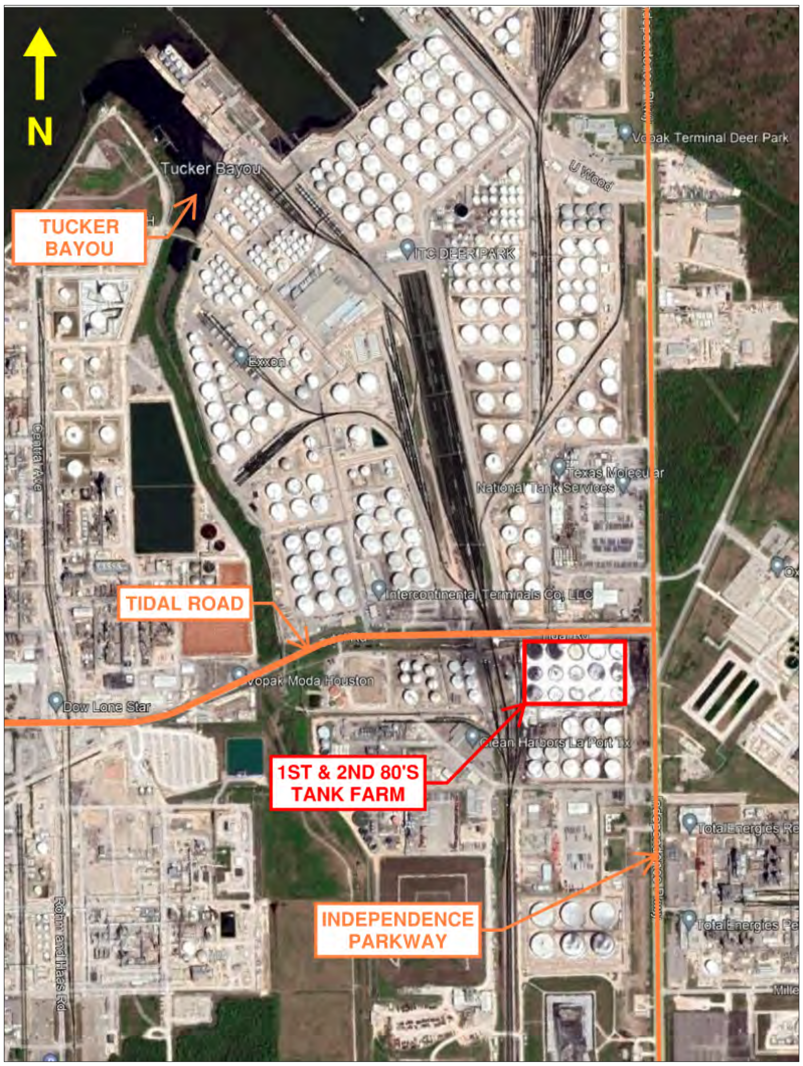

Figure 1: ITC Deer Park, Texas Facility with "First and Second 80's" Tank Farm Indicated[1]
imagery date: March 20, 2019

[1] Google Earth Pro, historical aerial photo, imagery date: March 20, 2019

ITC Tank Farm Construction

The tank farm consisted of fifteen 80,000-barrel tanks arranged on a grid with five tanks in the east-west direction and three tanks in the north-south direction (figure 2). A concrete containment wall surrounded the site on four sides. The ground surface inside the tank farm was indicated by ITC as natural grade soil covered with a minimum of six inches of stabilized materials consisting of crushed limestone, crushed concrete, cement stabilized sand, or similar materials.[2] The site was sloped gradually from north to south, with a stormwater drainage system collecting water at the south edge of the tank farm and directing it through pipes and control structures to the drainage ditch near the north-west corner of the site.[3]

Figure 2: First and Second 80's Tank Farm, prior to incident; imagery date: February 23, 2019[4]

[2] Letter, "ITC Secondary Containment Systems" from Joe Thayer, dated February 22, 2006

[3] File, "ITC Response to Drainage Inquiry" & ITC drawing SW 003, rev A, "Plot Plans - Storm Drain System", dated 6/22/12

[4] Google Earth Pro, historical aerial photo, imagery date: February 23, 2019

The roads currently named as Tidal Road and Independence Parkway existed at the site prior to the construction of the tank farm in a general location that is consistent with the existing roads.[5] There did not appear to be a concrete lining to the drainage ditch on the south side of Tidal Road in this aerial photo (photo 1). The tank farm was not constructed at this point in time.

Photo 1: Site of tank farm prior to construction, aerial imagery date: 1953, source: Google Earth Pro

Limited documentation was available on the construction on the tank farm. No design or as-built drawings were made available for review. Permits indicated that construction started in 1976 or 1977.[6] Historical aerial photos obtained from Google Earth Pro show the tank farm containment wall as being completed by 1978.[7] From the 1978 aerial photo (photo 2, next page), the drainage ditch north of the tank farm did not appear to be lined with concrete at the time of construction of the tank farm. The first historical aerial photo available that appears to indicate a concrete lining of the drainage ditch south of Tidal Road and north of the tank farm was from 1989 (photo 3, next page).[8]

[5] Google Earth Pro, historical aerial photo, imagery date: 1953, indicated source: “Texas General Land Office”
[6] Texas Air Control Board Form PI-1, General Application – Tanks 80-1 through 80-12, dated May 19, 1976.
[7] Google Earth Pro, historical aerial photo, imagery date: 1978, indicated source: “Texas General Land Office”
[8] Google Earth Pro, historical aerial photo, imagery date: 1989, indicated source: “Texas General Land Office”

Photo 2: Aerial photo of first & second 80's tank farm, 1978

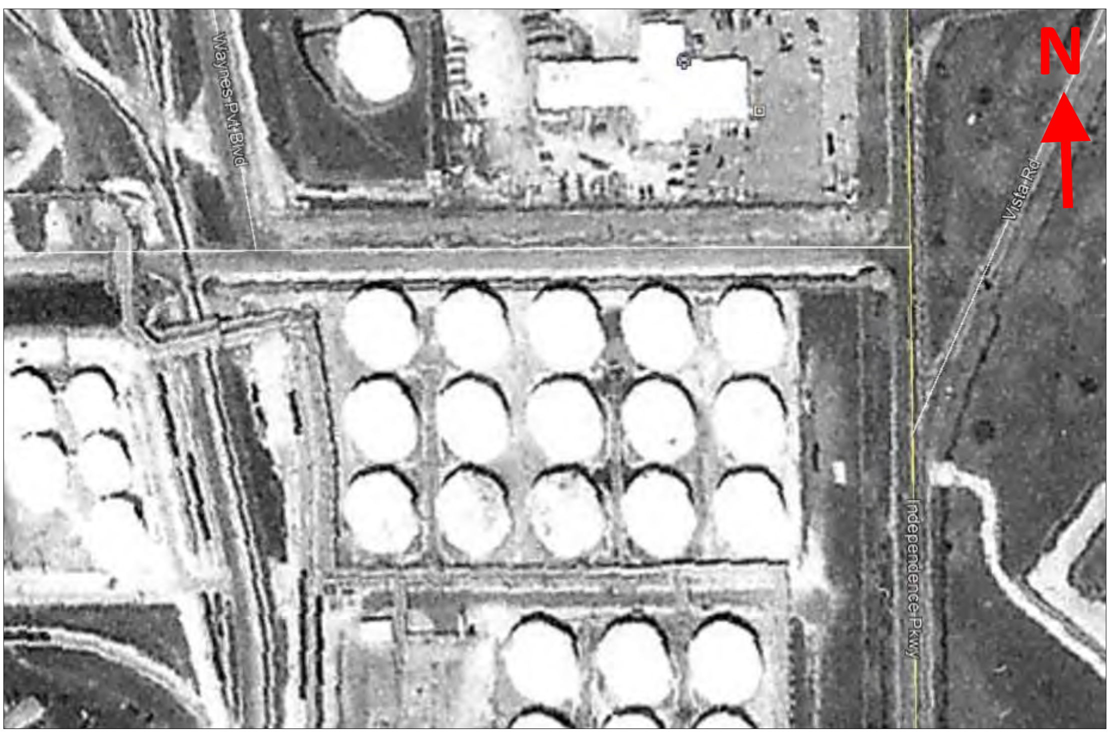

Photo 3: Aerial photo of first & second 80's tank farm, 1989

Fire Event, Response, and Containment Failure

The following is a partial summary of the fire event and response, including the events leading up to the breach of the north containment wall and the response after the breach occurred. This summary is based on a timeline compiled by the Chemical Safety Board[9] and the Summary of Current Actions produced by the Incident Command Planning Group of the response team.[10]

At approximately 10:00am on March 17, 2019, a fire broke out at the first and second 80's tank farm at ITC Deer Park Terminal. The ITC Emergency Response Team and the Channel Industries Mutual Aid organization (CIMA) fought the fire between March 17 and March 22 as the fire grew and spread to the majority of the tanks inside the tank farm. Firefighting operations consisted of the application of firefighting foam mixed with water in attempts to suppress the fire as well as the application of water to cool surrounding tanks from exposure to the fire in an effort to prevent the fire from spreading. These efforts involved the application of water on the order of magnitude of 20,000 gallons of water per minute during firefighting operations inside the secondary containment area[11]. As the fire spread and tanks were damaged, the contents of the tanks flowed into the secondary containment area as well.

Firefighting efforts involved attempting to maintain a continuous blanket of firefighting foam over the exposed product in damaged tanks and the secondary containment area for the duration of the event until thermal imaging indicated that the contents of the site had cooled sufficiently to prevent re-ignition. As a result of these efforts, the area inside the secondary containment walls, as well as the surrounding area of the site, was exposed to a continuous application of water, foam, and spilled hydrocarbon liquid products for six days prior to the breach. The level of liquids inside the secondary containment walls varied over time as water was applied, individual tanks failed, and as drains and pumps were utilized in an attempt to prevent the liquids from overflowing the secondary containment area.

On March 22, the fire had been successfully suppressed and the firefighters were periodically re-applying additional firefighting foam to maintain a continuous blanket of foam across the site. UAS overflights were being conducted periodically to observe the status of the tank farm. Operations planned for that day included removal of product from vessel 80-7 by utilizing a concrete pump truck to reach damaged vessels from outside the containment wall. Drains and pumps throughout the site were also being used to lower the liquid level inside the containment area. But at approximately 12:00pm on March 22, a section of the containment wall on the north side of the tank farm, between tanks 80-4 and 80-7, failed, allowing the liquid mixture inside the tank farm to flow into the drainage ditch between the tank farm and Tidal Road (photo 4).

[9] CSB document "ITC timeline – FINAL (August 27, 2020)"

[10] ICS 201-2 Summary of Current Actions, prepared by Incident Command Planning Group, updated 03/23/2019 07:54 UTC

[11] Jensen Hughes report "Perspectives on Tank Farm Fire ITC Deer Park (Texas), March 2019" rev 1, dated September 22, 2020.

Photo 4: Containment wall failure (red arrow) during fire suppression efforts[12]

The response team had to retreat from immediately impacted areas. Flare-ups of fire in the drainage ditch and tank farm required re-application of firefighting foam. The team deployed additional booms in the waterways to contain product, and took measures to mitigate the leak from the tank farm. Initially, the incident response team utilized T-rail Jersey Barriers and sandbags inside the tank farm in an attempt to build a new containment structure to stop the breach and reestablish containment. This was augmented on March 23 by bringing in off-site soils to reinforce the immediate measures and construct a dike wall inside the breach (photo 5).

[12] CSB investigation photo: ITC_CSB_00007732

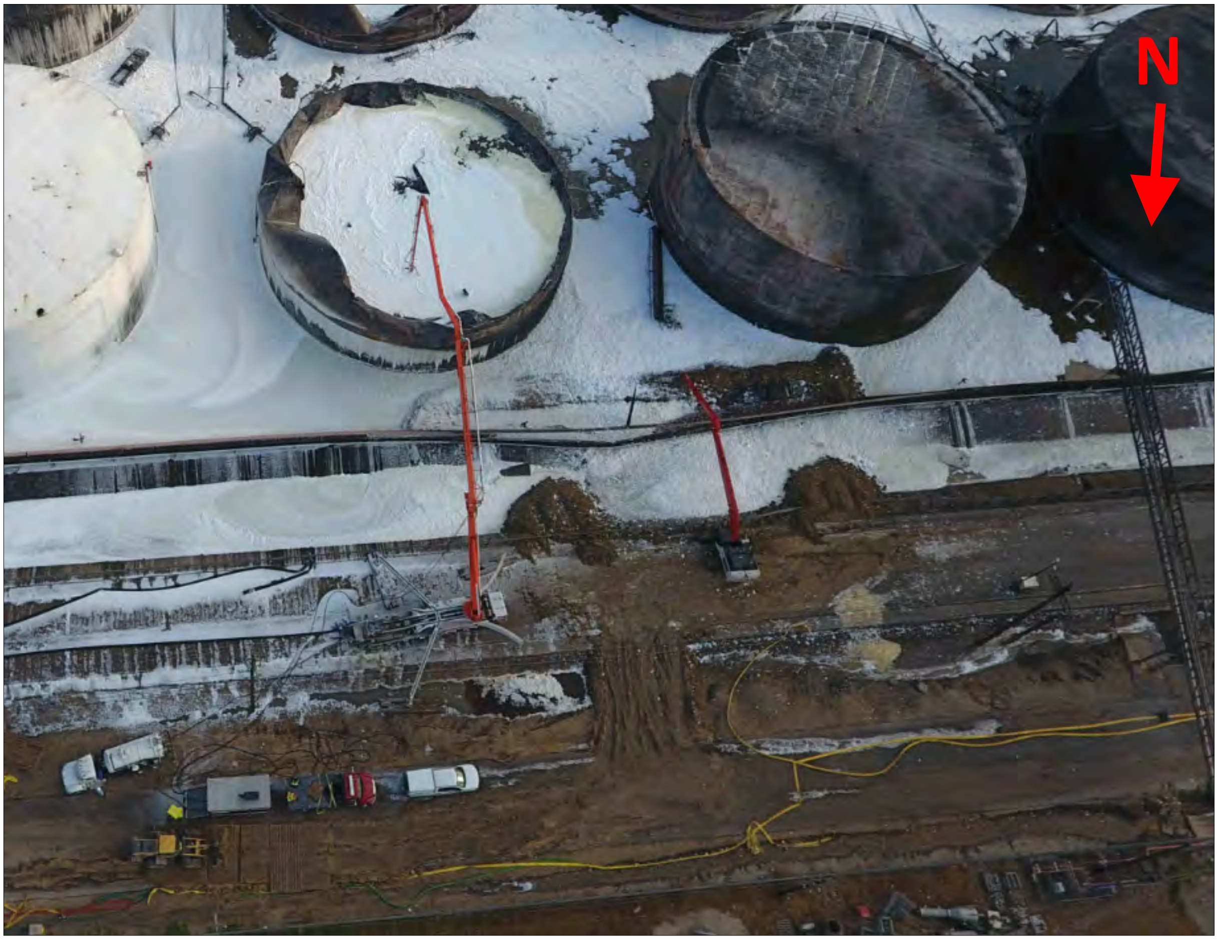

Photo 5: Responders constructing soil dike wall inside containment area to mitigate breach[13]

The Summary of Current Actions document made available to us stops at 07:00am on March 23. No additional documents from the incident management team were made available for review. Eventually, the incident response team was able to stabilize the site and begin remediation measures.

[13] CSB investigation photo: ITC_CSB_00007805

Observations from Videos and Photos Provided

UAS overflight video footage was made available to Atlas by the CSB to aid in determining the condition of the wall during the event. Aerial footage showed that a section of the wall had shifted laterally to the north, tearing the waterstop at multiple construction joints and permitting fluid to flow into the drainage ditch north of the tank farm (photo 6). The wall remained straight and continuous between construction joints. A section of the soil immediately south of the containment wall shifted laterally as well, opening a crack in the ground surface that permitted large volumes of fluid to wash down into the soil. A steel pipe that was supported on top of the containment wall was separated from the wall as it displaced, but appears to have remained intact and was suspended above the area of the breach. The two pipes on the exterior of the containment wall, one black and the other white, were displaced by the wall.

Large volumes of firefighting foam flowed out of the containment area during this event, with foam traveling underneath the containment wall at the area of the breach. No foundation was visible in the photo, indicating that the wall may have separated from the foundation slab as it shifted. Much of the drainage ditch is obscured by foam, but there are indications that the sloped slabs lining the ditch, adjacent to the containment wall, have displaced.

Photo 6: Closeup from aerial view of containment wall failure[14]

[14] CSB investigation photo: ITC_CSB_00006832

Photo 7 was taken after the bulk of the liquid had ceased to flow from the breach in the containment wall, but before emergency measures to build a temporary berm were taken. In this photo, a large erosion gulley has been formed at the location of the primary breach, between 80-4 and 80-7, with smaller erosion gullies formed at adjacent construction joints in the wall where the waterstop was compromised as the wall shifted. The crack in the soil is visible parallel to the containment wall that resulted from the lateral shift of the wall and soil immediately behind the wall. The firefighting water distribution pipe running parallel to the containment wall can be seen exposed where the soil eroded away. It is not possible to determine if the foundation was displaced from its original position from this photo. The remains of a wood light pole that has been burned can be seen standing in this area. The remaining section of the light pole is still vertical. The sloped slabs on the south side of the drainage ditch have been displaced, with many buckling in the middle and some displaced entirely by the flow of liquid into the ditch. Eroded soil can be seen in the drainage ditch.

Photo 7: Aerial photo of containment wall failure after water flow stopped and before temporary dike wall was constructed[15]

[15] Photo extracted from UAS video, CSB investigation file: ITC_CSB_00007860

A photo of the breach after the response team had placed soil inside the tank farm to build a temporary berm can be seen in photo 8. The containment wall can be seen to have shifted laterally, with a slight outward rotation in this photo. The wall sections remained intact between construction joints, however the lateral displacement of the wall had resulted in gaps and torn waterstop at several construction joints. The sloped slabs on the south face of the drainage ditch can be seen buckled upward.

Photo 8: View of containment wall failure, after temporary dike wall was constructed[16]

[16] CSB investigation photo: ITC_CSB_00006855

A close-up photo of the primary breach location can been seen in Photo 9. The soil had been eroded away from both sides of the containment wall at the breach. The wall had separated at a construction joint, and no dowels were visible spanning across the construction joint. The bottom of the wall was not visible in this photo, and it cannot be determined from this photo if the wall had a footing. The soil on the lower-right corner of the photo was soil placed after the breach to form the temporary dike wall. The temporary dike wall constructed by the responders inside the containment area can be seen in the upper left corner of the photo.

Photo 9: Close-up photo of containment wall breach provided by CSB[17]

[17] CSB investigation photo: ITC_CSB_00006824

Observations from Site Visit

Atlas Engineering was contacted by the CSB on May 27, 2021 regarding this incident. The CSB requested our assistance in determining the likely failure mode of the containment wall, and in finding the lessons learned from this event. Atlas Engineering visited the site on July 7, 2021 to view the existing condition of the site as well as make observations from the containment wall construction. Our observations consisted of a UAS flight over the site, photographs of structures, field measurements on exposed sections of the containment wall, and in taking samples of the site soil.

At the time of our site visit, remediation measures had been performed. These included draining the product and water from the site as well as removal of the existing tanks and above-grade piping. The top surface of the soil inside the containment area appeared to have been significantly disturbed by these initial remediation measures. The additional soil brought in to construct the containment remained in place. New T-rail Jersey barriers were in place, likely to prevent equipment involved in the remediation of the tank farm from entering the section of the breach. The elevated pipes that were located just outside the tank farm wall had additional temporary supports added where the original supports were disturbed in the breach. Erosion ditches at the area of the breach had been backfilled. Some sections of the damaged concrete slab that had lined the drainage ditch between the tank farm containment wall and Tidal Road had been removed, as well as sections of the damaged portion of the containment wall. The immediate area of the breach was thoroughly disturbed from the remediation and stabilization operations. However, sections adjacent to the breach along the containment wall appeared to remain minimally disturbed since the incident (Photo 10).

Photo 10: Aerial view of side during July 7, 2021 site visit

Measurements of the existing wall and drainage ditch were taken to construct a cross section sketch of the area (Figure 3). Measurements of reinforcement in the containment wall were made at locations where the containment wall had been broken by equipment during remediation efforts (Photo 11).

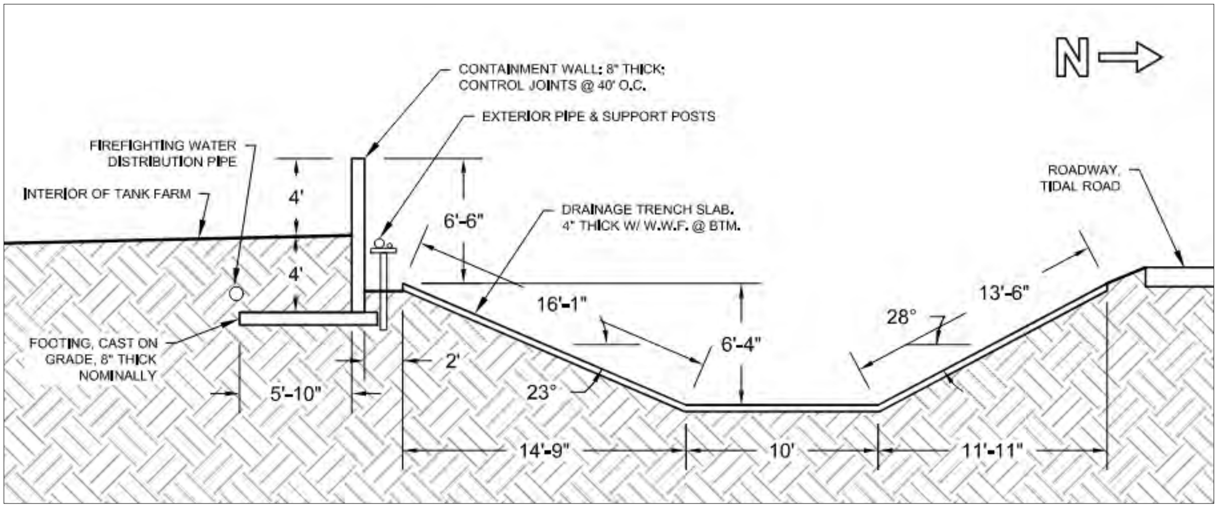

Figure 3: Cross section sketch of the containment wall

Photo 11: Exposed reinforcement at a section of the east containment wall where the wall was removed during remediation efforts

The containment wall was a cast-in-place concrete wall 8-inches thick and extending above the interior grade of the tank farm approximately 4 feet. The depth of the containment wall into the soil was not able to be determined at this visit. The wall had impressions from a panelized formwork system and through-wall break-off form ties, or snap-ties, spaced regularly in the horizontal and vertical direction, indicating it was constructed free-standing with a panelized formwork system on each face (photo 12). The wall was reinforced with two layers of deformed mild-steel reinforcing bars. The wall was cast in sections, with a construction joint every 40 feet. The joints were formed with a shear-key at the joint and a ribbed-wing centerbulb PVC waterstop incorporated into the construction joints to prevent liquids from leaking through the wall at the joints (photo 13 & 14).

Photo 12: Norh concrete retaining wall, outside face. Form tie marks on wall

Photo 13: Construction joint with cast-in concrete shear key and centerbulb waterstop

Photo 14: Torn waterstop and displaced wall. Upper section of wall that was dispaced has been partially demolished during remediation efforts.

The drainage ditch between the containment wall and Tidal Road was a concrete-lined structure with a flat bottom and sloped side walls (photos 15 & 16). The concrete slab was approximately 4-inches thick, with welded-wire-reinforcement observed at broken sections of the concrete, typically located near the bottom of the slab. The concrete slabs were cast in sections, with construction joints between the slabs (photo 17). The welded-wire reinforcement did not span across the construction joints. Holes through the slab were observed along the bottom edge of the sloped side-wall slabs, appearing to have the purpose of providing drainage of groundwater from behind the side slab into the drainage ditch. In the areas adjacent to the breach that appeared un-disturbed, sections of the sloped sidewall concrete slab had buckled upward in the middle of the slab.

Photo 15: Drainage Ditch, undamaged section at north-east corner, looking west

Photo 16: Damaged Section of Drainage Ditch, looking east

Photo 17: Displaced section of concrete slab that formed sloped sidewall of ditch

Atlas Engineering was not able to take destructive samples of the containment wall concrete during our fieldwork. We were not able to perform excavation of the wall base during this visit. Atlas requested that additional excavation be performed to identify the depth of the containment wall and if any footings existed for the containment wall. Atlas Engineering coordinated with ITC and the CSB to arrange for an excavation on the interior face of the containment wall down to expose the base of the wall at a later date.

During this visit, three isolated soil samples were taken with a hand trowel at a shallow depth from areas assumed to be soils existing at the time of the breach with locations shown in photo 18. Sample 1 was taken on the north side of the containment wall just west of the breach, at a location beneath a buckled slab of the drainage ditch (photo 19). Sample 2 was taken on the north side of the containment wall, further west of the breach, at a location beneath a buckled slab of the drainage ditch (photo 20). Sample 3 was taken on the north side of the containment wall, east of the breach, in an area that was not disturbed by the shifting wall of the breach (photo 21). No samples were taken inside the containment area since it appeared that the soil surface had be significantly disturbed during remediation efforts at the site and would therefore not be representative.

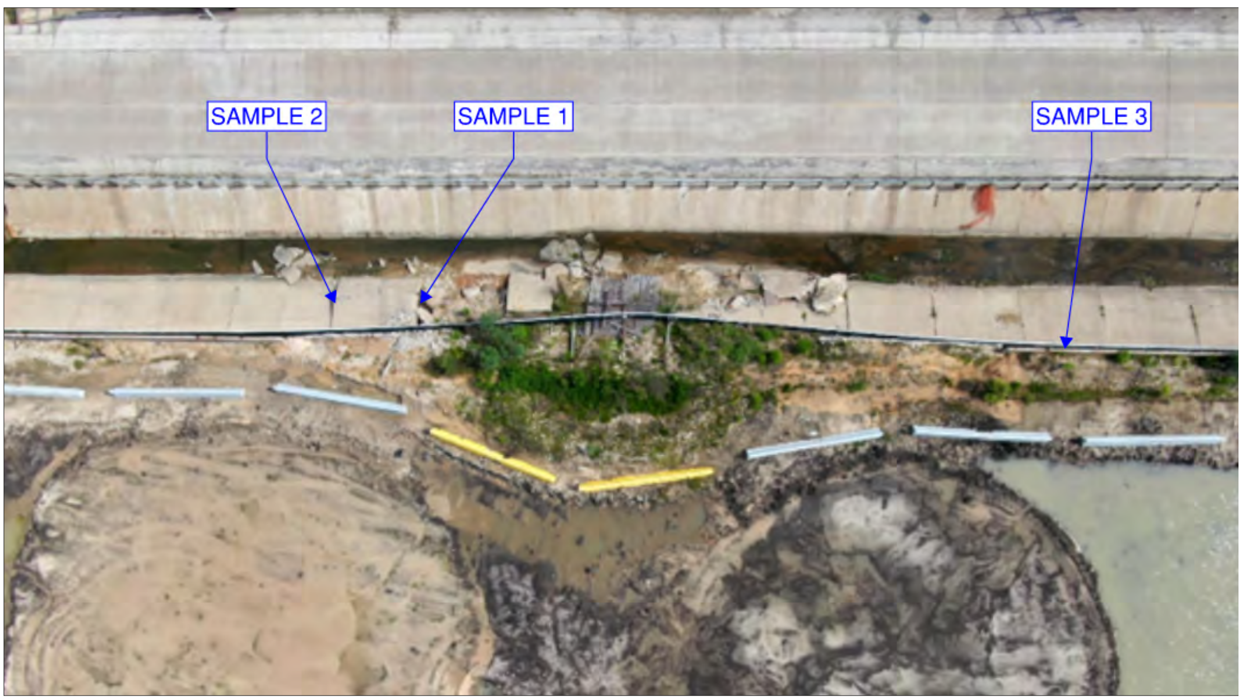

Photo 18: Soil Sample Locations relative to breach in containment wall


Photo 19: Location of Sample 1


Photo 20: Location of Sample 2


Photo 21: Location of Sample 3

Sample 1 appears to be a stiff mottled tan and gray silty deltaic clay. Its classification would be most likely "CH" when classified in accordance with the Unified Classification system. Sample 2 appears to be a dark gray deltaic clay, also likely to be classified as a CH. Sample 3 appears to be a moist soft gray marine clay CH. Both Samples 1 and 2 appear to have been disturbed and are poorly consolidated, whereas Sample 3 is fine grained and well consolidated. Samples 1 and 2 are assumed to be typical of the soils located underneath the sloped side slab of the drainage ditch. Sample 3 is assumed to be similar to the soils inside the containment area at the containment wall. The soil in Samples 1 and 2 appears to be moderately sensitive. Soil sensitivity is a characteristic describing the loss of soil strength when changing from an undisturbed natural condition to a disturbed condition through excavation and re-compaction. Soils with higher sensitivity lose a greater proportion of their strength when disturbed. Sample 3 appears to have a high shrink-swell potential, or a potential to change volume as water content in the soil changes. Soil swelling can increase the pressure on retaining walls considerably higher than normal pressures.

Observations from Excavation

ITC excavated a section of the interior face of the containment wall on June 9, 2022. Atlas Engineering was unable to visit the site during the excavation, however CSB personnel were able to observe the condition of the wall after the excavation and take measurements (Photos 22 & 23). Measurements taken in the excavation area were used to refine the cross-section sketch through the containment wall shown above in Figure 3. The excavation revealed the containment wall extends down 4 feet below the grade level of the interior of the tank farm. There was a horizontal slab extending approximately 5 feet south from the interior face of the containment wall. This slab had a highly irregular edge and bottom surface, indicating it was cast against grade. No standing water was seen in the footing, indicating the natural groundwater level was below the base of the footing. The excavation also revealed the location of an underground firefighting water distribution pipe that supplied the fixed firefighting monitors located along the north wall inside the tank farm.

Photo 22: Containment wall footing excavation, south face of north wall, inside containment area

Photo 23: Containment wall footing and underside of footing

A contractor was utilized to perform a ground penetrating radar (GPR) scan of the foundation in an attempt to determine if reinforcement was present in the foundation and its general configuration. Due to the irregular surface of both the top and bottom of the concrete footing, the GPR instrument was limited in the information it could provide. The depth of the concrete could not be definitively identified due to the irregularities of the bottom surface of the concrete, a result of being cast against grade. GPR did indicate the presence of reinforcement in the concrete foundation, running both longitudinally and across the slab.[18] GPR was not able to identify if any dowels existed between the horizontal concrete slab serving as the footing and the vertical concrete wall forming the containment wall. Longitudinal reinforcement was detected approximately 12-inches on center, while transverse reinforcement was detected with spacings varying from 6 to 8-inches on center (Figure 4). The size of the reinforcement could not be determined from the GPR results. Excavation on the exterior side of the containment wall was not possible due to the presence of active pipelines in the area.

[18] Holes Technology LP Report, "Ground Penetrating Radar of Concrete Slab" June 16, 2022

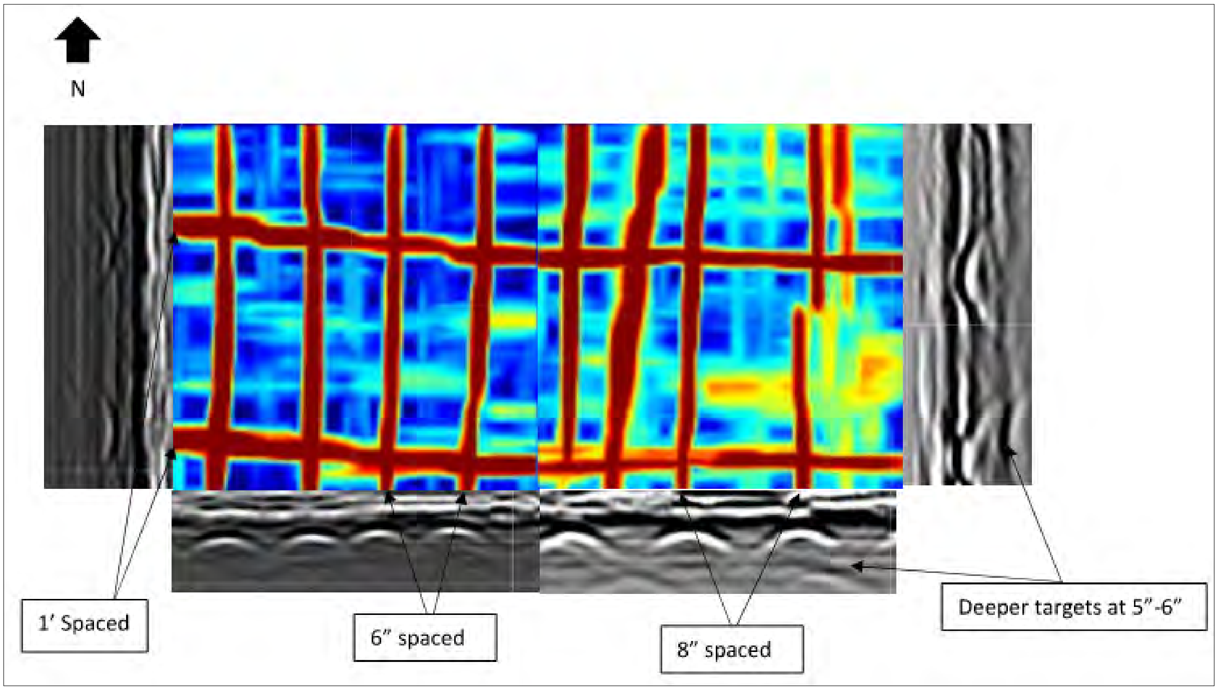

Figure 4: GPR scan results of retaining wall foundation slab from Holes Technology LP Report

Conclusions

Our conclusions are based on the photos, videos, and documentation provided by the CSB to Atlas Engineering and the limited information that could be gathered from the site after the event, after remediation efforts had been performed. The conclusions of this report are based on the timeline of the failure, the displacement seen in photos and videos from the event, general knowledge of the soil materials, and an understanding of the construction methods involved.

The Jensen Hughes report, "Perspectives on Tank Farm Fire – ITC Deer Park (Texas) Facility", has a thorough discussion on the applicable codes to the design of facilities for the storage of flammable liquids. They mention that NFPA 30, "Flammable and Combustible Liquids Code" from 1969, is the most applicable standard the containment area should have been designed to. In that edition of NFPA 30, containment structures are required to meet a number of conditions, including: designed to contain the maximum volume of the largest container in the area, designed to a liquid-tight condition, to withstand full hydrostatic head of the walls, have an average wall height of 6 feet or less above interior grade, and maintaining separation between containers by either drainage or curbs. The Jensen Hughes report also covers the issue of drainage and separation between vessels. Our observations at the site established that the wall was of adequate height to meet NFPA requirements for capacity and total height, and contained waterstop detailing in an effort to maintain a water-tight wall.

The containment wall displaced as a solid unit, with the photos provided from the incident showing the wall remained straight and continuous between construction joints. The vertical construction joints at the wall contain waterstops and a basic shear-key cast into the concrete joint, which would likely be adequate if the base of the wall did not shift laterally. It is unknown if there were construction joints in the footing at the same location as the wall, nor is it known if the reinforcement indicated by GPR in the footing was continuous across any joints. Doweling or tension reinforcement across the construction joints of the wall might have improved the global integrity of the wall, but likely would not have prevented the observed failure.

During the breach in the containment wall, the sloped slabs of the drainage ditch buckled upward, indicating either a large upward force from soil and hydrostatic water pressures or a large lateral force from lateral sliding of the containment wall. The sloped sidewalls of the ditch were not directly connected to the containment wall, with a gap between the top of the slab and the containment wall of at least 2-feet. Nor were the sloped slabs sized or reinforced in any way that indicates they were intended to brace the containment wall. Their construction appears to be designed to prevent erosion of the soil forming the drainage ditch only.

As standing water is not evident in the drainage ditch, it can be assumed that the groundwater's phreatic surface is below the ditch, therefore the soils natural moisture content is unsaturated at elevations above the bottom of the drainage ditch. Fire suppression efforts resulted in water and chemicals flooding the containment area and were left in place filling the area with liquid for several days prior to failure of the containment wall. Liquid levels inside the containment area could have potentially been as high as 4 feet above grade at the time of the containment wall failure.

Our observations determined that to construct the wall, the likely sequence required: excavation to cast the footing, installing wall formwork, setting reinforcing steel, and placing concrete in the forms for the containment wall. After the concrete was sufficiently cured, the forms would have been removed, backfill would have been placed to fill the excavation on both sides of the wall, and fill would be placed to construct the tank pad. If the native soils were of sufficient quality, they were often used as backfill material requiring compaction of the fill to specified degrees of compaction within a moisture-compaction range. Where native soils were not of sufficient quality, borrow soils would have been brought in for backfill. Achieving an adequate degree of compaction adjacent to a relatively thin retaining wall is difficult, as the energy required for compaction, if applied too close to the wall, may damage the concrete wall. In addition, compacting backfill in a narrow trench, such as the one likely excavated for the firefighting water line, would also have been difficult. Compaction of soil around a pole set in the ground, such as the light pole in the area of the wall failure, is especially difficult. Inadequate compaction would result in excessive void space in the soils and not adequately seal the interface between the structures and the soils.

It is unknown what the intended soil elevation and slope for the side of the concrete wall outside of the containment area was for the original design. Proper retaining wall design must include the geometry and condition of the soil on both sides of the retaining wall. With no design documents available, it is unknown if the current geometry of the soil outside the wall matches the original design geometry for the containment wall. If the concrete lining to the drainage ditch was added after the construction of the containment wall, as aerial imagery suggests, it is possible that the soil geometry outside the wall was changed, perhaps significantly. It is reasonable to assume that the drainage ditch may have been enlarged to handle increased stormwater flows as the general area continued to develop. This could have resulted in less soil being present outside the containment area against the wall. The soils that are on the outside of the wall contribute greatly to ability of the wall to resist lateral pressures. The concrete slabs formed to line the drainage ditch primarily served to prevent erosion of soil as stormwater flowed through the ditch. The slabs do not appear to have been designed to buttress the containment wall.

If water is introduced to poorly compacted backfill, it will more readily absorb into the soils. As the soils become more saturated, they weaken. That loss of strength combined with the increased wet unit weight of the soils, ever increases the lateral earth pressure against the wall and the sloped slabs of the drainage ditch. This additional pressure can be greater than twice the design pressure, possibly overloading the wall or causing the drainage ditch concrete slabs to buckle upward. In addition, as the wall or slab deflects or displaces and the soils continue to fail, tension cracks can form in the soils allowing even more water into the backfill, further weakening the soil and further increasing the lateral pressure against the wall.

As mentioned above, the interface between the soils and the concrete is typically the most problematic for soil erosion due to the difficulty in achieving adequate compaction immediately adjacent to the wall. Not only will the poorly compacted zone settle over time, creating pockets for the water to collect and infiltrate, but the high volume of pore space will provide conduits for water to infiltrate. This water will collect then move through the soils, picking up fine particles along the way creating tubes, referred to as "piping". These tubes act as open conduits for freely flowing water and can eventually erode the subsurface sufficiently to undermine the wall structure and bring hydrostatic pressures to bear.

The failure of the containment wall appears to be related to the soil conditions supporting the wall. The containment wall primarily displaced laterally, with the lateral movement due to excessive lateral soil and hydrostatic pressures and inadequate soil resistance on the outside of the containment wall and inadequate sliding resistance of the footing. Based on on-site observations and examination of the soil samples, the following opinion is offered as the most probable scenario under which the initial failure of the containment wall may have occurred.

It is most likely that less than optimum on-site soils were used as backfill. CH soils are difficult to manage within a suitable moisture compaction range and, as they are highly plastic in nature, they often fail and deflect excessively under standard compaction effort. It appears that it was difficult to achieve an adequate degree of backfill compaction at soil/structure interfaces, such as along the containment wall, water line, and light pole. With potential for as much as 4-feet of fire suppression water retained in the containment wall for days, this possibly led to saturation of the soils and increased lateral earth pressures against the containment wall.

As the wall deflected due to the excessive lateral earth and hydrostatic pressures, the construction joints began to open, tearing the waterstop material and increasing the velocity of the escaping water. As the water velocity increased, the erosion of the soils at the joint and beneath the sloping slab subgrade accelerated and piping increased, increasing the hydrostatic pressure, eventually lifting and damaging the thin drainage ditch slab that lined the slope. In addition, as the wall shifted outward, it further damaged the sloped slab. Eventually, it appears that pieces of the slab were washed out of place by the final torrent of escaping liquid.

Lessons Learned

From the information reviewed for this report and the conclusions inferred, the following lessons learned were developed..

1. Classify containment structures and drainage structures as systems critical to fire safety and emergency response.
2. Preserve design and as-built documentation for containment structures, including site grading plans. Make this documentation accessible for future review. Include containment structures as a system to be reviewed when conditions change at the site.
3. Assess the impacts of adjacent construction, both inside and outside the containment area, to the strength and stability of containment structures. When containment structures are close to a property line, review how changes to adjacent property may affect support conditions of the containment structure.
4. Design containment walls for fully saturated soils on both sides of the wall. Design for maximum hydrostatic head on the interior of the containment wall assuming all soils are saturated.
5. Incorporate water stop features to develop full continuity of systems. Pay special attention to terminations or transitions between systems, such as where footing-to-wall joints meet wall construction joints.
6. Provide robust structural continuity across construction joints, particularly shear and tension continuity.
7. Ensure adequate compaction of suitable backfill to the structures edge with careful construction technique. Verify acceptable compaction by inspection of compaction results. Ensure adequate compaction of excavations for ancillary items located in proximity to containment structures. If achieving adequate compaction is not practical, other methods such as placement of flowable fill for backfill, pressure grouting along the soil/structure interface, or installation of HDPE membranes lapped below the backfill then up along the soil/structure interface should be considered to reduce the potential for subsurface erosion.

END OF PERSPECTIVE