DEPARTMENT OF THE ARMY
ROCK ISLAND DISTRICT, CORPS OF ENGINEERS
CLOCK TOWER BUILDING - P.O. BOX 2004
ROCK ISLAND, ILLINOIS 61204-2004

CEMVR-EC 10 July 2019

MEMORANDUM FOR City of Davenport, Iowa

SUBJECT: 30 April 2019 Downtown Davenport, Iowa, HESCO Temporary Flood Barrier Failure Investigation

The following memo summarizes the U.S. Army Corps of Engineers' (USACE) findings and recommendations regarding the HESCO temporary flood barrier failure in downtown Davenport, Iowa, on 30 April 2019. This investigation was completed at the request of the City of Davenport.

BOTTOM LINE UP FRONT

Engineering evaluation completed as part of the USACE investigation into the HESCO temporary flood barrier failure in downtown Davenport, Iowa, on 30 April 2019 indicates that the event was most likely initiated by a sliding failure that led to the overturning failure observed by city employees and as seen in the Roam Café, a local eatery in the vicinity of the failure, surveillance video. The failure occurred when the driving forces acting on the barrier (hydrostatic pressure from the river and potential uplift) overcame the resisting forces (the weight of the barrier and the friction against the road surface).

Based on the engineering evaluation completed, the initial calculated factors of safety for sliding and overturning were sufficient and indicated that the HESCO barrier should not fail under the load conditions experienced on 30 April 2019. HESCO's research and full-scale testing of a barrier erected on a concrete floor, filled completely with sand, and without additional sandbags placed on top of the barrier, also indicate that the barrier should withstand an overtopping without a sliding or overturning failure. The unknown variable in this engineering evaluation was the coefficient of friction between the barrier and the roadway surface and any effects the plastic sheeting placed beneath the barrier had on the coefficient of friction.

The investigation did not find that Canadian Pacific (CP) Railroad operations caused the barrier failure. The railroad swing gates at Iowa American Water were closed when the flood stage reached 21.0 feet, closing the tracks that run through downtown Davenport. The flood stage reached 21.0 feet around 11:00 am on 29 April 2019. The barrier failed around 2:30 pm on 30 April 2019. With no railroad operations for more than 24 hours leading up to the failure and an increase in the flood stage of 0.7 feet between the time railroad operations stopped and the failure occurred, it was concluded that railroad operations likely did not contribute to the failure. Wind-induced waves would have had similar impacts on the barrier as waves created by the wake of a passing train. Any effects of wave action on the HESCO temporary flood barrier were not included in the engineering evaluation performed as a part of this investigation.

BACKGROUND

The information provided in this section was provided to USACE by the City of Davenport during the HESCO temporary flood barrier failure meeting held at City Hall on 13 May 2019. This section summarizes the events leading up to the barrier failure that occurred on 30 April 2019.

The City of Davenport (City) erected its downtown HESCO barrier on 13 March 2019 for early flood stage forecasts of over 18.0 feet on the Rock Island gage located at Lock and Dam 15. Flood stage at this gage is 15.0 feet and major flood stage is 18.0 feet. Flood water reaches the barrier at a flood stage of 18.0 feet. This gage is roughly at the same river mile as the location of the failure.

The City met with CP Railroad on 21 March 2019 regarding CP's plan to raise the tracks through downtown Davenport. CP indicated at that time that this work would begin without notice. The river stage reached 18.0 feet on 24 March 2019. The large-scale track raise project by the railroad began on 28 March 2019. A letter of concern regarding the wake created by passing trains and requesting that trains reduce speeds as they pass the barrier location was sent by the City to CP on 6 April 2019. The flood stage on this date was 20.3 feet. CP complied with this request and slowed its trains through downtown Davenport. Due to the track raise, this event was the first time in history trains operated through the downtown in flood stages above 18.5 feet.

The first river crest occurred on 8 April 2019 at a flood stage of 20.68 feet, a hydrostatic loading of approximately 2.7 feet of water on the HESCO barrier. The City reported no performance issues with the barrier up to this point. From 9-24 April, the river levels fell at a slow rate, from 20.64 feet on 9 April to 18.05 feet on 24 April, at which point river levels began to rise. On 28 April 2019, the forecast for 1 May 2019 predicted a rise above 21.0 feet. On 29 April 2019, the forecast for 30 April to 2 May predicted a crest of 22.2 feet, which would overtop the HESCO barrier at 21.5 feet. City crews added sandbags to the top of the barrier on 29 April 2019 as they indicated this was the quickest measure that could be taken against the change in the forecast. Other areas of concern were also fortified with sandbags at that time. On 29 April 2019, CP notified the City that pumping operations in its independent sandbagged area were being stopped and that the area would be slowly filled. At 2100 that evening the CP sandbag wall failed during the filling process. The CP sandbag wall failure had no impact on the HESCO barrier.

The weather on 30 April 2019 brought heavy rain and thunderstorms to the Davenport area with rainfall recorded from 8 am until 3 pm. This precipitation event left 6-12 inches of water ponded behind the temporary flood barrier. To manage the interior drainage on the dry side of the temporary flood barrier, the City had installed 2 pumps on Pershing Avenue at River Drive to pump storm water from storm sewers over the barrier and into the river. The pump discharge pipes were supported by precast concrete blocks to prevent them from vibrating the barrier. The pump on the east side of Pershing Avenue was a 12-inch diesel pump with its discharge pointed in an upstream direction.

The downtown HESCO barrier failed on 30 April 2019 at a flood stage of 21.7 feet. At this flood stage, the HESCO barrier was fully loaded with an additional 0.2 feet of water on the sandbags placed on top of the HESCO barrier. The original HESCO barrier, without the additional sandbags, provided temporary flood protection to a flood stage of 21.5 feet. The additional sandbags placed on top of the barrier provided additional protection to an estimated flood stage of 23.0 feet at the top of the sand bags.

BARRIER CONSTRUCTION

The information described in this section was provided to USACE by the City or was observed by USACE during their field inspection after the failure of the HESCO temporary flood barrier. USACE was not involved in the planning, coordination, or erection of the HESCO barrier and the City did not request technical assistance from USACE prior to and leading up to the HESCO barrier failure.

The temporary flood barrier in downtown Davenport, Iowa, was erected using the HESCO basket system. The HESCO basket system consists of wire basket cells, with an inside felt liner, filled with sand to provide temporary flood protection. One standard section of the HESCO system consists of 5 cells (each cell is 4 feet tall by 3 feet wide by 3 feet deep). Multiple sections are connected together using spiral wire corner connections and metal pins. This system can be configured to follow shallow curves in the desired alignment, make 45 or 90 degree turns as needed, and follow gradual elevation changes.

The City installed the HESCO barrier from Perry Street to Bechtel Park located at Iowa Street and 2nd Street, see Figure 1 for reference. The west end of the barrier tied into the brick wall behind the Radisson Hotel at Perry Street. The barrier was set against the brick wall and sandbags placed on both sides of the tie-in to reinforce the connection. The east end of the barrier tied into the south section of wall at Bechtel Park. A second row of HESCO baskets, approximately 90 feet in length, was added as a second row behind the original barrier starting at the western edge of the intersection of River Drive and Pershing Avenue, moving west due to seepage concerns. The City also added a second row of HESCO baskets, 15 feet in length, behind the original barrier at the intersection of Iowa Street and River Drive. CP Railroad installed a temporary sandbag barrier where it could pump an area between 3rd Street and Pershing Avenue in order to keep its trains running as long as possible. CP's sandbag wall tied into the City's barrier at the east end of the River Drive planter median, approximately 90 feet to the west of Iowa Street along River Drive. The HESCO barrier was heavily reinforced with sandbags on both sides between the CP tie-in and high ground at Bechtel Park.

The City installed the barrier along River Drive on the north side of the planter median. The barrier was offset from the median by approximately 1 foot. Installation on this side of the planters provides crews sufficient room to fill the baskets with sand using front loaders and skid steers and to add to the barrier if needed from the dry side. Plastic sheeting, 100 feet long by 20 feet wide, was tucked under the flood-side edge of the baskets approximately 1 foot according to the City. Consecutive sheets were overlapped by approximately 10 feet. The baskets were erected in the configuration described in the flood plan and filled with approximately 1 foot of sand. This first layer was then hand-tamped before the remaining sand was placed in the baskets. Once the baskets were filled, the plastic sheeting was pulled over the barrier and held down at the dry side toe using sandbags. This configuration was in place until 29 April 2019, when crews pulled back the plastic sheeting and placed the 4 levels of sandbags in a pyramid pattern on top of the barrier. The plastic sheeting was then pulled back over the top of the barrier and held down with sandbags. This configuration was in place at the time of the failure.

Figure 1: Davenport Downtown Temporary Flood Barrier

FIELD INSPECTION

Representatives from the US Army Corps of Engineers (USACE), HESCO, and the City met at City Hall at 0900 on 13 May 2019 to discuss the items described in the background section of this memo, review photographs and video of the barrier prior to and during failure, ask questions regarding the circumstances and observations prior to and at failure, and brainstorm all factors that may or may not have had an impact on the incident. After the meeting, the team visited the failure location at River Drive (US 67) and Pershing Avenue. At the failure location, the team met with additional City staff, took photos of the failure location, and made notes of relevant observations.

Based on video evidence, the failure initiated approximately 40 feet to the east of the west end of the River Drive median, see Figure 2. The entire length of the failed portion of the barrier stretched approximately 320 feet from Pershing Avenue to the CP Railroad tie-in.

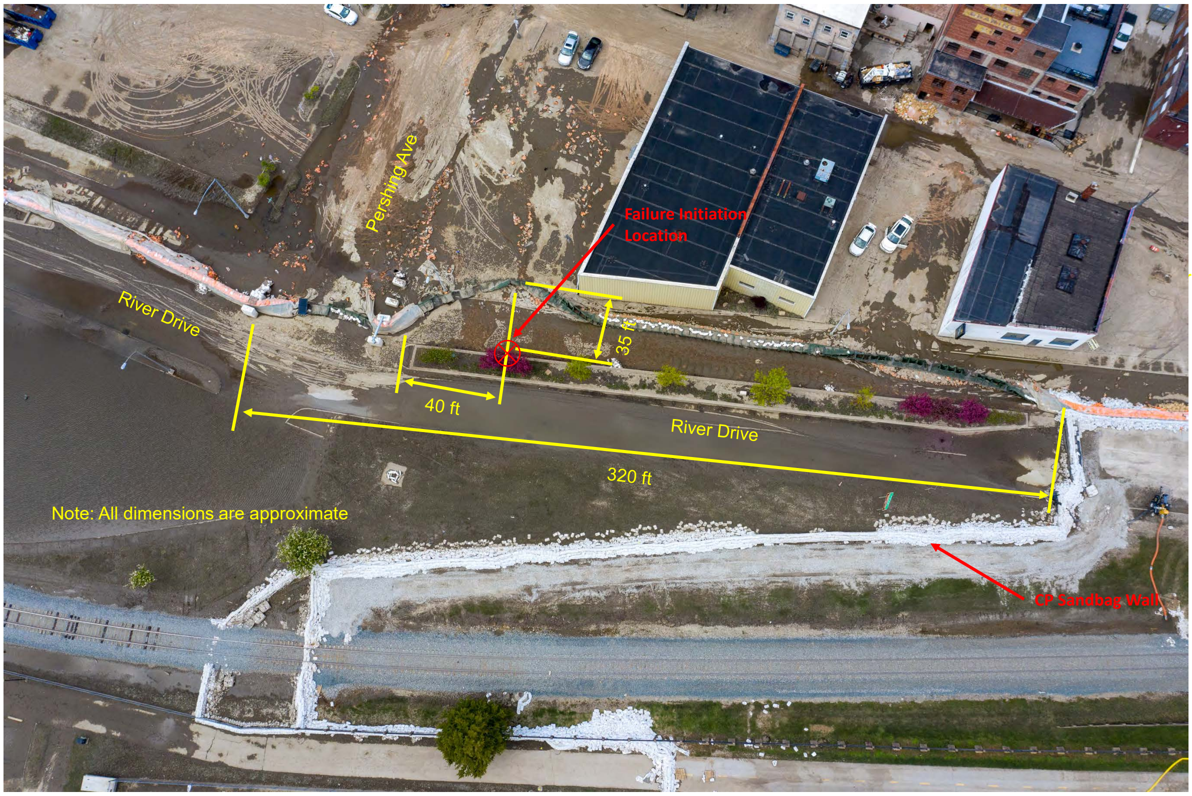


Figure 2: Overview of Failed Davenport Downtown Temporary Flood Barrier

Near the initiation location, there were several wire baskets with failed welds at the spiral wire cell-to-cell connections, see Figure 3. This indicates adjacent cells being pulled apart during the failure. There were also several locations where the spiral wire cell-to-cell connections did not fail but were stressed beyond their yield points during the failure. The coils appeared stretched near the top 12 inches of these connections, see Figure 4. This evidence indicates the basket sections being stretched near their tops during the overturning stage of the failure.

The progression of the failure to the west was stopped by the precast concrete pump discharge support blocks placed adjacent to the barrier at the locations of pumping operations, see Figure 5. These blocks provided sufficient lateral support during the failure to stop additional sections of the barrier from sliding or overturning. Similarly, the east end of the failure was stopped at the CP Railroad tie-in due to the lateral support provided by the sandbags stacked on the dry side of the barrier at that location, see Figure 6. At the initiation location, the final resting place of the barrier was approximately 35 feet north of its original location and had rotated bottom over top 270 degrees. Remnants of HESCO barrier fill sand were observed along the original alignment of the barrier, see Figure 7. The location of the sand mounds indicates where the fill sand fell out through the bottom of the baskets as they overturned. Sand mounds to the north of the original barrier alignment indicate sliding prior to overturning. The area near the failure initiation location had little sand remaining after the failure and was likely washed out during the initial stages of the failure. Inspection of the remaining intact barrier to the west showed that the bottom level of sandbags was completely below the top rim of the wire basket, see Figure 8. This would indicate that the sand experienced some settlement within the baskets as it became saturated, the cells were not filled completely to their tops, and/or that seepage under the barrier during the duration of the flood fight pulled sand particles through or under the baskets and resulted in a loss of 6 to 9 inches of fill sand from the barrier.

Figure 3: Failed wire baskets at the basket connections

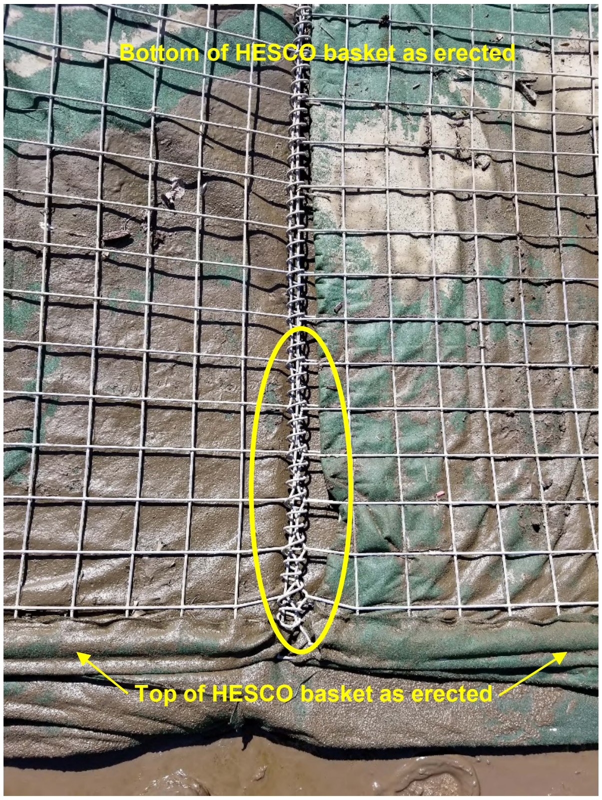


Figure 4: Spiral wire connection loaded beyond the yield point for the top 12 inches

Figure 5: Precast Concrete Pump Discharge Supports Arresting the Breach

Figure 6: Barrier Failure Stopped by the CP Railroad Sandbag Wall Tie-in

Figure 7: Remaining fill sand along the failed barrier

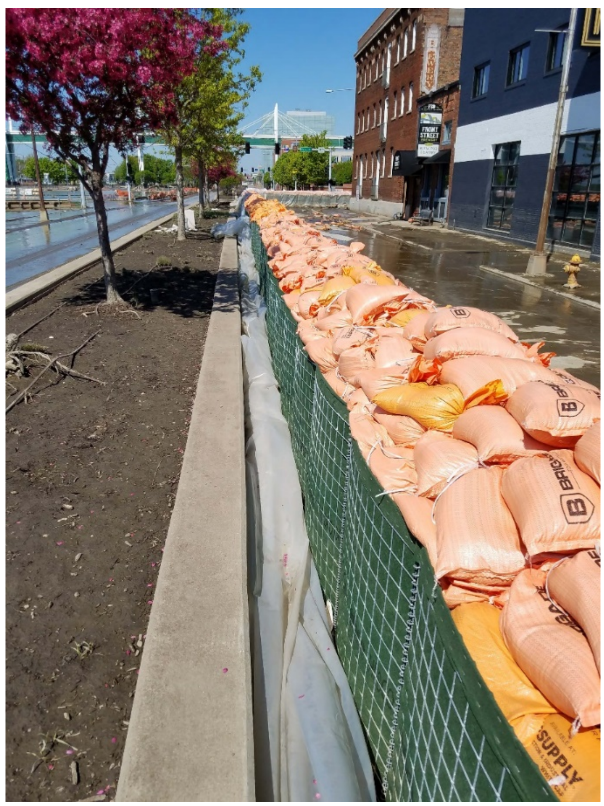


Figure 8: Typical barrier section remaining after failure

ENGINEERING EVALUATION

USACE conducted an engineering evaluation to evaluate stability with respect to sliding and overturning to determine the more likely initiator of the failure. This evaluation can be found in Attachment A of this memorandum. Assumptions were made for the weight of the wet sand, the height of the water on the barrier, and the coefficient of friction between the HESCO baskets and the wet pavement. The driving forces included the hydrostatic pressure for the corresponding flood stage elevation and any potential uplift caused by the plastic sheeting underneath the barrier. The resisting forces included the weight of the sand within the basket, weight of additional sandbags, and the frictional force between the barrier and the wet pavement. This evaluation does not account for other loading factors including those that could be induced by wave or pump discharge. The initial part of the evaluation investigated the sliding and overturning stability of the HESCO barrier while ignoring the additional sandbags placed on the barrier by the City. The sandbags were ignored during the intial evaluation as these computations were done to determine the trends in the response of the barrier to various loadings in order to show whether sliding or overturning was the more likely failure mode. Once these trends were determined, the sliding and overturning computations were recalculated for the actual barrier in place and loadings observed at the time of failure.

The equation for sliding stability is shown below in equation 1. The height of the water on the barrier, h_w, was assumed to be 4 feet based on flood stage information and video evidence. Frictional coefficients for various materials were researched in civil engineering text books and online. From www.engineeringtoolbox.com, the range for friction coefficient values for rubber on wet asphalt is 0.25 to 0.75 and 0.45 to 0.75 for rubber on wet concrete. The coefficient for wood on concrete is 0.62, for a car tire on grass is 0.35, and 0.2 for automobile brake material on wet cast iron. Based on these ranges, the assumed starting value for the coefficient of friction for sand on wet asphalt was 0.6. The value of this coefficient was adjusted for the various load cases evaluated to determine the trend in the response of the barrier to the loading at the time of failure. The weight of the sand per 1 foot of linear wall, W_{sand}, assumes sand to the full height of the HESCO basket.

$FS_{sliding} = F_{resist}/F_{driving} = F_{friction} / R_{water} = [\mu W_{sand}]/[\ ½\gamma_w h_w^2]$ (equation 1)

$FS_{sliding}$ = factor of safety against sliding

γ_w = 62.4 lb/ft^3

h_w = height of water on the HESCO barrier

μ = friction coefficient

W_{sand} = weight of the sand in a 1 ft wide section of HESCO barrier

γ_{sand} = 120 pcf (assumed)

The free body diagram of the HESCO temporary flood barrier used for the intial evaluation of sliding and overturning is shown in Figure 9. The initial load cases investigated for sliding are described below and listed in Table 1. Values for the variables were assumed or determined using equation 1. Values shown in regular, black font were assumed and values shown in **bold, red** font were calculated.

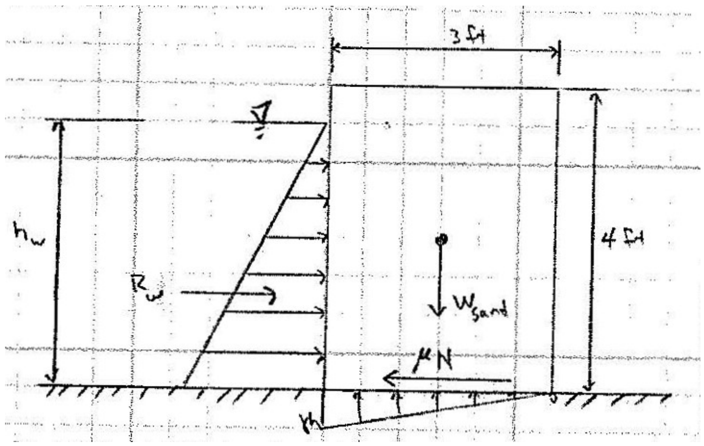


Figure 9: Free body diagram of the loaded HESCO barrier

Load case 1: determine the factor of safety (FS) under assumed conditions prior to failure
Load case 2: include uplift to determine FS, assuming the entire basket is sitting on the plastic sheeting (subtract $\frac{1}{2}\gamma_w h_w$*3ft*1ft from the numerator in equation 1)
Load case 3: solve for W_{sand} to determine the height of sand lost needed to achieve a FS = 1
Load case 4: determine h_w for FS = 1
Load case 5: determine FS assuming μ = 0.5
Load case 6: assume μ = 0.5 and determine loss of sand required for FS = 1
Load case 7: determine FS assuming μ = 0.4
Load case 8: assume μ = 0.4 and determine loss of sand required for FS = 1

Table 1: Summary of sliding load case assumptions and results

Sliding Load Case	h_w	μ	W_{sand}	FS
1	4 ft	0.6	1440 lb	**1.73**
2	4 ft	0.6	1440 lb	**0.98**
3	4 ft	0.6	**1.7 ft lost**	1.0
4	**5.26 ft**	0.6	1440 lb	1.0
5	4 ft	0.5	1440 lb	**1.44**
6	4 ft	0.5	**1.25 ft lost**	1.0
7	4 ft	0.4	1440 lb	**1.15**
8	4 ft	0.4	**0.57 ft lost**	1.0

The equation for overturning is shown below in equation 2. The height of the water on the barrier, h_w, was assumed to be 4 feet based on flood stage information and video evidence. The weight of the sand per 1 foot of linear wall, W_{sand}, assumes sand to the full height of the HESCO basket. Moment arms in this evaluation were measured as the distances from the resultant forces to the landside toe of the barrier and moments were summed about the landside toe. The purpose of the overturning evaluation was to determine factors of safety under the observed conditions at failure and to calculate required water levels and fill loss to result in an overturning failure.

$FS_{overturn} = M_{resist}/M_{driving} = [W_{sand}*d_{basket}/2]/ R_{water}*h_w/3 = [W_{sand}*3ft/2]/[\frac{1}{2}\gamma_w h_w^2 h_w/3]$ (equation 2)
$FS_{overturn}$ = factor of safety against overturning
$\gamma_w = 62.4$ lb/ft^3
h_w = height of water on the HESCO barrier

W_{sand} = weight of the sand in a 1 ft wide section of HESCO barrier
γ_{sand} = 120 pcf (assumed)

The initial load cases investigated for overturning are described below and listed in Table 2. Values for the variables were assumed or determined using equation 2. Values shown in regular, black font were assumed and values shown in **bold, red** font were calculated.

Load case 1: determine FS under assumed conditions prior to failure
Load case 2: include uplift to determine FS, assuming the entire basket is sitting on the plastic sheeting (add [$\frac{1}{2}\gamma_w h_w d_{basket}$*1ft*$d_{basket}$/3] to [$\frac{1}{2}\gamma_w h_w^2 h_w$/3] in the denominator of equation 2)
Load case 3: solve for W_{sand} to determine the height of sand lost needed to achieve a FS = 1
Load case 4: determine h_w for FS = 1

Table 2: Summary of overturning load case assumptions and results

Overturning Load Case	h_w	W_{sand}	FS
1	4 ft	1440 lb	**3.24**
2	4 ft	1440 lb	**1.53**
3	4 ft	**2.78 ft lost**	1.0
4	**5.92 ft**	1440 lb	1.0

After performing the initial evaluation, reviewing the surveillance video, reviewing flood stage data, and meeting with City officials, there is a high level of confidence in the water level acting on the barrier and the amount of sand remaining in the baskets prior to failure. Inspection of the remaining intact barrier to the west of the failure provided a high level of confidence in the number and configuration of the sandbags stacked on top of the barrier. The stability evaluation was then recalculated using h_w = 4.2 ft, W_{sand} = 1440 lb, and W_{bags} calculated to be 600 lb per linear foot of barrier assuming a 4-3-2-1 pyramid pattern placement on top of the barrier. Using these values and setting the FS = 1 at the time of failure, the new sliding evaluation revealed that the coefficient of friction, μ, was determined to be 0.27. The factor of safety against overturning was then recalculated using the values described above for the as-built configuration of the barrier and was determined to be 4.0.

A surcharge load on the wire basket walls was also investigated to determine if the outward acting load resulting from the sandbags on top of the barrier was significant enough to cause a buckling of the basket. The surcharge pressure was calculated to be 126.5 lb per square foot with a resultant force of 330 lb. Technical specifications for the HESCO baskets were not provided for comparison. These loads are relatively small in magnitude and there was no evidence of any buckled wire panels observed during the site visit.

ENGINEERING EVALUATION SUMMARY

The engineering evaluation performed as part of this investigation points to a stability sliding failure as the most likely failure mode. The surveillance video and witness testimony show evidence of an overturning failure. The most likely scenario, based on all evidence discussed in this investigation, is that the failure was initiated by sliding. The barrier section at the failure location began to slide, possibly only inches or fractions of an inch, until the slack in the spiral wire connections was gone. At this point, the sliding in the barrier was stopped by the stationary adjacent sections, but the kinetic energy and momentum created by the initial slide coupled with its high center of gravity, worsened by the placement of sand bags on top of the baskets, caused the barrier to rotate and overturn resulting in the failure observed on the surveillance video and in witness testimony. The combination of the flood stage at the time of failure, underseepage throughout the duration of the flood fight, and precipitation the day of the failure leaving the barrier foundation pavement wet were all factors that played into the failure scenario.

RECOMMENDATIONS FOR FUTURE TEMPORARY FLOOD BARRIER INSTALLATIONS

The following recommendations for future temporary flood barrier installations are made on the basis of past experience with HESCO barriers and previous flood fights along the Mississippi River.

1. The initial barrier erection should include a means to fortify or add additional height as necessary for constantly changing river forecasts. As with the re-build of the downtown barrier, a second row of HESCO baskets should be installed with the first row. The second row may not require filling at the time of the initial installation, but provides the capacity to add to the barrier at a later date.

2. Limit the hydrostatic loading on a single layer HESCO barrier to 2/3 the height of the barrier. When river forecasts project river levels that will load the barrier in excess of 2/3 of the height, install another line of HESCO baskets on top of the original barrier, and another line of baskets behind the original barrier, per HESCO recommendations. The use of sandbags or other alternate means to extend the height of the HESCO barrier is not recommended.

3. When installing a single layer HESCO temporary flood barrier on pavement, provide additional lateral support on the dry side of the barrier as needed using precast concrete blocks, sandbags, or other acceptable means.

4. Do not cover the dry side of the barrier with plastic sheeting. The sheeting prevents the inspection and monitoring of the barrier during the flood fight. Seepage and loss of some sand fill is expected and should be monitored.

5. Populations and businesses behind the HESCO temporary flood barriers need to be made aware of the risks of residing and/or working within the protected area. HESCO barriers are temporary flood fighting measures and are not designed to be as resilient and robust as permanent levees or flood walls. Flood risk communication and emergency planning are essential to reduce impacts in the event of a failure of the temporary flood protection system.

6. HESCO will provide technical assistance and advisory services during the initial barrier installation upon request. It is recommended that HESCO be consulted during the planning and/or installation of future flood barriers.

The following recommendations are made to place an emphasis on the installation and monitoring of HESCO temporary flood barriers during a flood event. The City states that it currently follows both recommendations, but the importance of these topics becomes evident as there is turnover within the City staff performing these activities or long periods of time between the need for temporary flood barrier installations.

7. The HESCO temporary flood barrier should be periodically monitored when river levels load the barrier. Monitoring should focus on seepage beneath the barrier, sand loss, barrier movement, and other signs of system distress. The frequency of patrols should increase with increased hydrostatic loading on the barrier. Materials, such as sand, filled sandbags, and/or precast concrete blocks are recommended to be staged near the barrier for quick placement when needed.

8. HESCO barriers as temporary flood barriers are engineered systems that must be installed correctly and without damage to ensure they function properly. Crews should be trained on the proper installation techniques to understand the importance of details such as the plastic sheeting, the flaps at the bottom, the tamping of the sand as the baskets are filled, proper and full-length connections, and options for lateral support. The more the installation crews understand how these behave and work, the more they will pay attention to the finer details during installation.

POC is Allen Marshall, (309) 794-5204 or Allen.A.Marshall@usace.army.mil.

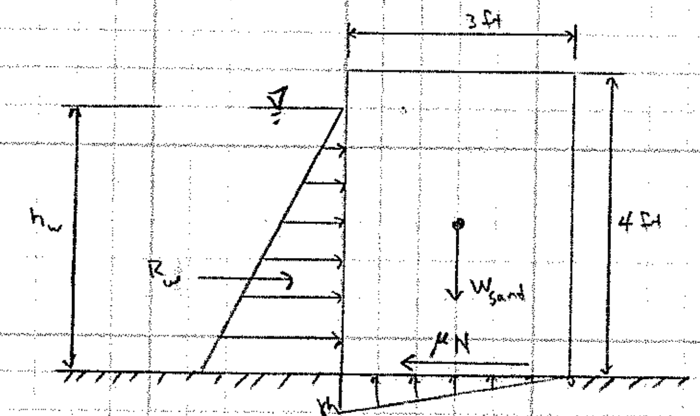
Roger A. Perk, P.E.

ROGER A. PERK, P.E.
Chief, Engineering & Construction Division

Attachment A

Engineering Evaluation Stability Computations

US Army Corps of Engineers® Rock Island District	PROJECT TITLE: DAVENPORT, IA HESCO FAILURE ANALYSIS	COMPUTED BY: JWC	DATE: 5/7/2019	CONTRACT NO:
	SUBJECT TITLE:	CHECKED BY:	DATE:	SHEET: 1 OF



$\gamma_w = 62.4\ lb/ft^3$

$\gamma_{sand}\ (WET) = 120\ lb/ft^3$

ASSUMPTIONS

1) 1 FT WIDE SECTION OF HESCO BARRIER
2) HESCOS ARE 4 FT TALL BY 3 FT WIDE BY 3 FT DEEP
3) $\mu = 0.72$ CAR TIRE ON ASPHALT
   $\mu = 0.45$-0.75 RUBBER ON WET CONCRETE
   $\mu = 1.0$ DRY TIRE ON WET ROAD
   $\mu = 0.62$ WOOD ON CONCRETE
   } www.engineeringtoolbox.com
   USE $\mu = 0.6$ FOR SAND ON ASPHALT
4) IGNORE ADDITIONAL SANDBAGS ON TOP

ANALYSIS

$R_w = \frac{1}{2}(\gamma_w h)h\,(1ft) = \frac{1}{2}(62.4\ lb/ft^3)h^2(1ft) = \underline{31.2\,h^2\ lb}$

$W_{sand} = 120\ lb/ft^3(3\ ft)(4\ ft)(1\ ft) = \underline{1440\ lb}$

A. SLIDING

$FS = \frac{F_{RESIST}}{F_{DRIVE}} = \mu N / R_w$

① FOR FS = 1 : $\frac{\mu(1440\ lb)}{31.2\,(4ft)^2\ lb} \Rightarrow \underline{\mu = 0.35}$ (JUST PRIOR TO FAILURE)

$FS = \frac{0.6(1440)}{(31.2)(4)^2} = \underline{1.73}$ (ALL MAT'L HOLDS & $\mu = 0.6$)

② INCLUDE UPLIFT IN SLIDING

$FS = \frac{\mu N - UPLIFT}{R_w} = \frac{0.6(1440) - \frac{1}{2}(62.4\ lb/ft^3)(4ft)(3ft)(1ft)}{(31.2)(4)^2} = \frac{864 - 374.4}{499.2} = \underline{\underline{0.98}}$

③ HOW MUCH MAT'L LOSS TO GET TO FS = 0.99

$FS = \frac{\mu N}{R_w} = 0.99 = \frac{0.6(120)(3)(1)h}{(31.2)(4)^2} = \frac{216h}{499.2} = 2.3\ FT \Rightarrow$ MAT'L LOST = 4 - 2.3 = $\underline{1.7\ FT}$

UNANSWERED QUESTIONS

1. AT BREACH LOCATION HOW HIGH WAS WATER ON HESCOS? VIDEO INDICATES FULL HEIGHT POSSIBLY MORE
2. WHAT DID OBSERVER SEE JUST PRIOR TO FAILURE?
3. HOW EXACTLY WAS BARRIER CONSTRUCTED? WERE BASKETS SITTING COMPLETELY ON PLASTIC? HOW HIGH DID EXTRA SANDBAGS GO?
4. WHAT WAS SEEPAGE LIKE PRIOR TO FAILURE? WAS SAND BEING MOVED UNDER BARRIER?

ENGINEERING COMPUTATION PAPER

US Army Corps of Engineers® Rock Island District	PROJECT TITLE: DAVENPORT, IA HESCO FAILURE ANALYSIS	COMPUTED BY: JWC	DATE: 5/8/2019	CONTRACT NO:
	SUBJECT TITLE:	CHECKED BY:	DATE:	SHEET: 2 OF

ANALYSIS (CONT)

④ UNDER ASSUMED CONDITIONS WHAT h_w RESULTS IN A FS = 1

$FS = 1 = \frac{\mu N}{R_w} = \frac{0.6(1440)}{(31.2)h^2} \Rightarrow h = \sqrt{\frac{0.6(1440)}{31.2}} = 5.26 \text{ ft}$

⑤ ASSUME $\mu = 0.5$

$FS = \frac{0.5(1440)}{(31.2)(4^2)} = 1.44$

⑥ $\mu = 0.5$, HOW MUCH LOSS OF FILL TO FAIL

$FS = 0.99 = \frac{0.5(120)(3)(1)h}{(31.2)(4^2)} = \frac{180h}{499.2} \Rightarrow h = 2.75 \text{ ft} \Rightarrow$ MAT'L LOST $= 4 - 2.75 = 1.25$ ft

⑦ ASSUME $\mu = 0.4$

$FS = \frac{0.4(1440)}{(31.2)(4^2)} = 1.15$

⑧ $\mu = 0.4$ HOW MUCH LOSS OF FILL TO FAIL

$FS = 0.99 = \frac{0.4(120)(3)(1)h}{(31.2)(4^2)} = \frac{144h}{499.2} \Rightarrow h = 3.43 \Rightarrow$ MAT'L LOST $= 4 - 3.43 = 0.57$ ft

B. OVERTURNING (ROTATE AROUND LANDSIDE TOE)

$FS = \frac{M_{RESIST}}{M_{OVERTURN}}$

① $M_{RESIST} = W_{sand}\left(\frac{d}{2}\right) = 1440 \text{ lb}\left(\frac{3 \text{ ft}}{2}\right) = 2160 \text{ lb-ft}$

$M_{OVERTURN} = R_w\left(h/3\right) = (31.2 \text{ lb/ft}^3)(4 \text{ ft})^2\left(4 \text{ ft}/3\right) = 665.6 \text{ lb-ft}$

$FS = \frac{2160}{665.6} = 3.24$

② INCLUDE UPLIFT

$M_{uplift} = \frac{1}{2}(\gamma h)\left(2d/3\right) = \frac{1}{2}\left[(62.4 \text{ lb/ft}^3)(4 \text{ ft})\right]\left[3 \text{ ft}\right]\left[1 \text{ ft}\right]\left[\frac{2(3 \text{ ft})}{3}\right] = 748.8 \text{ lb ft}$

$FS = \frac{2160}{665.6 + 748.8} = 1.53$

③ HOW MUCH MAT'L LOSS TO GET TO FS = 0.99 (IGNORE UPLIFT)

$FS = 0.99 = \left[(120 \text{ lb/ft}^3)(3 \text{ ft})(1 \text{ ft})h_{sand}\left(3 \text{ ft}/2\right)\right] / 665.6 \text{ lb-ft}$

$658.94 = 540 h_{sand}$

$h_{sand} = 1.22$ ft $\Rightarrow$ MAT'L LOST $= 4 \text{ ft} - 1.22 = 2.78$ ft LOST

④ FIND h_w = FS = 1

$FS = 1 = [2160 \text{ lb ft}] / [31.2 h_w^2] h/3$

$10.4 h_w^3 = 2160$

$h_w^3 = 207.69$

$h_w = 5.92$ ft

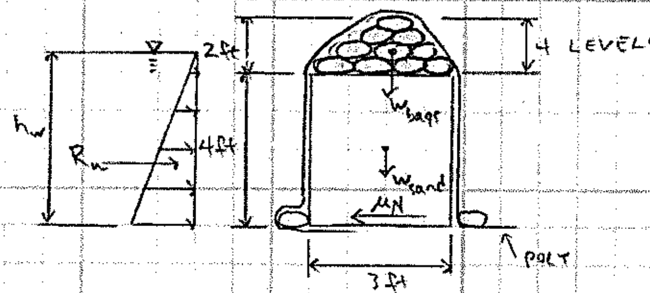
ENGINEERING COMPUTATION PAPER

US Army Corps of Engineers® Rock Island District	PROJECT TITLE: DAVENPORT, IA HESCO FAILURE ANALYSIS	COMPUTED BY: JWC	DATE: 5/27/2019	CONTRACT NO:
	SUBJECT TITLE:	CHECKED BY:	DATE:	SHEET: 3 OF

ANALYSIS (CONT)

C. SANDBAGS INCLUDED

ASSUMPTIONS:



$W_{sandbags}$: 60 lb each

No bags: 10 (per linear ft)

$W_{T sand}$: 10 (60) : 600 lb/ft

$R_w = \frac{1}{2}(62.4\ lb/ft^3)(h_w)(h_w)(1\ ft) = \underline{31.2\ h_w^2\ lb}$

$W_{sand} = 120\ lb/ft^3 (4\ ft)(3\ ft)(1\ ft) = \underline{1440\ lb}$

$W_{bags} = \underline{600\ lb}$

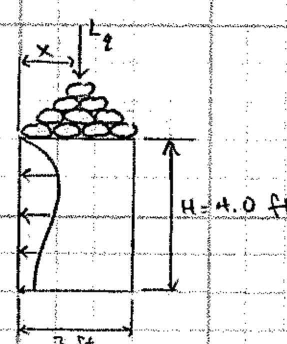
SLIDING AT FAILURE

$FS = 0.99 = \frac{\mu[(1440)+(600)]}{(31.2)(4.2\ ft)(4.2\ ft)} \Rightarrow \underline{\mu = 0.27}$

OVERTURNING

$FS = \frac{(1440+600)(1.5\ ft)}{(31.2)(4.2)(4.2)(4.2/3)} = \frac{3060}{770.5} = \underline{4.0 = FS}$

D. SURCHARGE LOAD FROM SANDBAGS



$L_q = 600\ lb/ft$

$m = \frac{X}{H} = \frac{1.5}{4} = 0.375$

$n = \frac{Y}{H} = \frac{1.5}{4} = 0.375$

$P_q = \frac{0.203 L_q n}{H(0.16+n^2)^2} = \frac{0.203(600)(0.375)}{(4\ ft)(0.16+0.375^2)^2} = \frac{45.675}{0.361} = \underline{126.5\ lb/ft^2}$

$R_q = 0.55 L_q = 0.55(600) = \underline{330\ lb}$