CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

GHAZIPUR LANDFILL REHABILITATION REPORT

Ghazipur Landfill Rehabilitation Report

Prepared for:

East Delhi Municipal Corporation

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on behalf of

U.S. Environmental Protection Agency
and
Climate and Clean Air Coalition
Municipal Solid Waste Initiative

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1 INTRODUCTION

Located in East Delhi, the Ghazipur landfill site has been operational since 1984 (DIMTS and IDFC, 2010). The East Delhi Municipal Corporation (EDMC), responsible for landfill operations at Ghazipur, has long sought to address the capacity constraints at the landfill. Since at least 2001, municipal officials have explored a number of options to address these capacity concerns (Response to Showcause Notice, 2017).

Ghazipur landfill slope failure (EDMC)

On September 1, 2017 a portion of the Ghazipur landfill's slope failed. Waste from the landfill slid 110 meters across an area adjacent to the landfill, including a road, the Hindon Canal, and the Escape Canal. As a result of this incident, two people died and five were injured. This incident spurred a renewed immediacy to improve operations and management at the Ghazipur landfill, explore alternative waste management options, and identify future landfill sites. The EDMC and its counterparts including the other Delhi municipal corporations, the Delhi Development Authority, and National Highways Authority are required to complete a series of actions. These action call for the EDMC and partners to develop action plans for waste management, begin bio-stabilization and compaction activities, begin waste segregation activities, identify new landfill sites, revisit environmental management practices, inspect augmenting the capacity of existing waste-to-energy (WTE) plants, develop new WTE plants, and create a pilot project using waste as a component of embankment filling at a nearby national highway (NGT, 2017a,b,c).

SCS Engineers, Abt Associates, and The Energy Resources Institute (TERI) conducted a site visit of Ghazipur landfill site and met with staff of EDMC on November 1 and 2, 2017. This report is based on information gleaned from the site visit and additional information provided by EDMC. It provides a preliminary assessment of the Ghazipur landfill structure and operational practices that contributed to the September 1 slope failure. It also addresses three topics of concern to EDMC – (1) lowering the risk of future slope failure, (2) mitigating landfill fires and (3) identifying capacity at the current landfill until an alternative landfill is developed. For each of these topics, this report provides best practices for actions and identifies additional detailed analyses to inform specific actions to be undertaken by EDMC.

Report Findings

Several significant problems exist at the Ghazipur landfill site, potentially contributing to the recent slope failure. Landfill fires and additional slope failures, with associated environmental and human injuries, may occur if these problems are not addressed.

- **Site operations do not include proper placement and compaction of waste** – The waste is currently spread daily over a wide area of operation, insufficiently compacted due to lack of proper compaction equipment, and exposed to the elements. These factors increase the risk of future landfill fires and slope failures.

- **Symptoms of potential future slope failures exist** – A tension crack with a noticeable vertical drop of about 1 meter was observed in the same crest where the recent slope failure occurred. Its width is about 0.5 m and its length is almost 60 m. The waste surface is comprised of loose material and no soil cover. Due to the tension crack, the steepness of the landfill side slope, and

uncompacted and uncovered waste, future tension cracks may continue to appear. These types of tension cracks are indicators of potential slope failures.

- **Fires contribute to human health and safety concerns, and slope instability** – The waste mass is loose, uncompacted, and exposed; these conditions encourage aerobic decomposition and generate heat. Given the right conditions, such as the presence of combustible materials and elevated ambient temperatures, spontaneous fires might occur. These fires create health and safety hazards and destabilize the waste. Additionally, side slope fires can be difficult for workers or firefighting equipment to access.

- **A lack of air space reduces overall landfill capacity –** Air space is the remaining capacity of the vertical volume of the landfill. The Ghazipur site has exceeded its planned maximum elevation in many locations, and there are very few locations on the site where waste can be safely deposited. While continuing to use the Ghazipur site is not ideal, it appears to be necessary to identify options to prolong the longevity of the landfill until an alternative site is developed.

- **The landfill was originally constructed without a liner and leachate collection system –** The Ghazipur landfill has no liner system to confine the leachate from infiltrating to the ground below or a system for collection and removal of leachate from the waste mass. This is a typical situation of an open dump that may possibly lead to liquids building up in the waste mass to a level that increases risk of slope failure(s).

The rest of the report details the findings and best practices based on initial observations during the site visit and review of existing materials. Key best practices are summarized below:

- **Stop disposing waste at the top –** Waste filling at the top of the landfill should cease immediately as it could further compromise slope stability.

- **Identify a new sanitary landfill site –** EDMC should begin the process of closing the Ghazipur site and moving disposal operations to a new landfill site as quickly as possible.

- **Establish interim on-site landfilling locations –** As a temporary measure while a new landfill site is identified and constructed, waste could be placed at alternate on-site locations that do not have the height and slope concerns that may contribute to instability. One possible location is the area currently closed for landfill gas capture. A design and feasibility study will be needed to consider how additional waste disposal would affect the current gas collection system and to examine expansion of the system. A second possible location is between the south slope and the WTE plant. It should be possible to fill in certain portions of this area, without affecting the WTE plant expansion.

- **Improve practices to limit future slope failures –** Waste is currently deposited at a slope too steep to safely maintain. Due to the steepness of most of the upper portion of the side slope, future slope failures are highly probable if nothing is done to the slope configuration, especially during rainy seasons. Erecting a mechanical stabilizing embankment wall to improve slope stability should also be considered. Further studies (topography, liquid level, stability evaluation) should be undertaken in other slope sections and for the whole site.

- **Reduce the potential for fires –** Proper disposal practices, including operating in a limited area with waste compaction and daily cover will lower the risk of fires. Additional measures include limiting sources of fires and fighting fires appropriately to prevent further spread.

- **Change fire suppression practices –** Firefighters should avoid using water to squelch fires, especially near slopes. The most effective and preferable method is smothering with soil to cut off oxygen supply. Foams and suppressants are alternative methods and can be used to put out fires but it may be a more expensive option depending on how big the fire is.

- **Identify and improve use of available air space –** While waiting for a new landfill to become operational, a number of potential actions should be taken to safely capitalize on available vertical air space at the landfill site. These include separating waste to limit the volume and types of waste, properly compacting waste, increasing the capacity of the existing WTE plant, increasing the capacity of the WTE plant, and conducting landfill mining where slope stability is an issue. Together, these actions should conserve air space, and limit waste deposition in areas that are too high or too steep.

- **Reduce the amount of waste to be disposed at the landfill –** The WTE plant appears to have underutilized capacity, and the waste going to the landfill could be reduced by increasing waste diversion to this plant. Additionally, large generators of organic waste could be identified and decentralized organic waste treatment systems (composting or anaerobic digestion) could be implemented as per the new Municipal Solid Waste Rules of 2016.

Section 2 provides a brief overview of the landfill; Section 3 discusses the causes of slope failure and provides best practices to address it; Section 4 identifies types and causes of landfill fires and ways to mitigate and suppress them; Section 5 discusses ways to increase capacity for the interim period while a new landfill is developed; and Section 6 summarizes the conclusions.

2 SITE CHARACTERISTICS

East Delhi is home to approximately 3.9 million people; its population is projected to grow over the coming decades and waste generation has increased in-step with population growth. East Delhi's Ghazipur landfill is among three primary landfilling sites for all of Delhi and accepts approximately 1,800 to 2,000 tons of waste per day, including 200 to 300 tons of construction and demolition waste that is used as daily cover. [1] Common components of waste include food; packing materials; paper; spent coal, ash, and wood; metals; plastics; ceramics; cloth; glass; construction and demolition debris; drain silt; poultry, fish, meat, and dairy industry byproducts; and non-hazardous hospital materials (Central Road Research Institute, 2016).

The 70 acre Ghazipur landfill opened in 1984 and continues to operate in 2017, despite a planned site life of 25 years. It does not have the attributes of a modern engineered landfill, and can be classified as an open dump site due to its physical characteristics and waste disposal operations. The Ghazipur landfill is situated in a constrained area that provides limited space to expand disposal operations outside of the current footprint. The southwestern boundary of the landfill is constrained by the WTE plant. Adjacent to the site on the northwest side is a densely populated area that includes a market and dairy farm. A closed section of the landfill where a landfill gas collection system was installed in 2013 covers the north side of the site. The southeast side is bounded by a drainage ditch, a public road, and a canal.

The disposal site was developed with no bottom-liner system to prevent leachate from entering the surrounding environment (DIMTS and IDFC, 2010). Leachate, which is produced by percolation of rainfall and other liquids through the waste mass, flows into an unlined perimeter drainage ditch, which drains to a concrete open top tank with approximate dimensions of 2 m x 2 m x 3 m. When the concrete tank overflows, it discharges directly into a nearby ditch. Leachate is also collected and sprayed onto the active working face.

By 2002, the Ghazipur site reportedly had reached its planned capacity, far exceeded its permissible height, and was at risk of a slope failure due to steep slopes and poor compaction (Response to Show Cause Notice, 2017). In November 2017, the waste height was observed to average approximately 55-60m above the base of the landfill. Waste was not spread over a limited area, or compacted and covered on a daily basis. Waste disposal practices are not well controlled which has led to the formation of steep and unstable slopes. Subsurface fires, smoke emissions from the surface of the waste, animals scavenging waste, and informal sector waste recyclers were all observed during the November 2017 site visit.

The waste mass at the Ghazipur site includes steep and potentially unstable slopes in many locations. Estimates of slope ratios (vertical:horizontal) at the Ghazipur landfill were developed to examine the locations of steep slopes, and are summarized in Table 1 below. Cross-sectional profiles of selected landfill slopes also were prepared to analyze site conditions, and are provided in Appendix A. Except for the landfill plateau which is at about 5 percent slope, Table 1 indicates that landfill side slopes are as steep as 1:1 in some areas, and average approximately 1:2. Such steep waste slopes are inherently unstable and much steeper than 1:3 slopes which are considered acceptable for normal, dry conditions. Stability conditions are made worse during the rainy season, when precipitation infiltrates into the uncompacted waste and increases its moisture content.

1 Provided by Mr. Khandelwal, Chief Engineer, East Delhi Municipal Corporation on December 16, 2017.

Table 1. Landfill Slope Ratios

Location	Area (Upper/Lower)	Observed Slope Ratio (Vertical:Horizontal)
Southeast Slope	Upper slope	1:1.5 – 1:2.2
	Lower slope	1:1.6 – 1:2.7
North Slope	Upper slope	1:1.3 – 1:1.9
	Lower slope	1:2.3 – 1:3.8
Southwest Slope	--	1:1 – 1:1.6
Average of Southeast, North, and Southwest Slopes	--	1:1.5 – 1:2.3
Closed Area (North side)	Plateau area	5 percent
Northwest Slope	--	Shallow, well-benched, includes access road

In addition to physical constraints at the site, past and ongoing management practices make reducing the risk of future slope failure and human injury a challenge. Significant constraints for site remediation include waste being deposited in a manner that creates steep and unstable slopes; top elevations exceeding maximum planned levels; lack of proper compaction equipment; presence of informal sector workers, and continued disposal at the site due to a lack of other viable landfill options.

3 SLOPE FAILURES

The September 1, 2017 slope failure started from high up on the central portion of the southeast slope. EDMC reported that the slide area measured 45 m wide at the crest, extended 50 m down the slope, was approximately 3 m deep, and represented a waste volume of about 7,000 m^3. The failure occurred in an area where the slope ratio was estimated to be approximately 1:1.9 (about 28 degrees) and which is considered very steep for a landfill. The slope failure displaced a large mass of waste that moved downhill, flowed over the lower slope and into the adjacent drainage ditch, public roadway, and canal.

The slope failure occurred after a few days of continuous rain. Heavy rain events, in combination with steep slopes, poorly compacted waste, inadequate leachate management are well established as leading mechanisms to landfill slope failures. The role of wet, heavy waste in causing the slope failure was less evident two months later at the time of the November 1 site visit. As shown in the site visit photos, leachate seeps could be observed at the toe of the southeast slope below the slide area, but not on the upper or middle slopes in the vicinity of the slide.

Although seasonally high moisture conditions and a heavy rainstorm are key factors in the timing of the slide event, the fundamental causes of the slope failure are related to the steep slopes and poor waste management operations. Poor management of delivered waste and the lack of proper waste placement and compaction result in a weak and compressible waste mass that is prone to instability in areas with steep slopes. Delivered waste typically is unloaded at the high point of the waste mound and pushed by a single bulldozer into lifts (small mounds). Disposal practices at dump sites often include dumping or pushing waste off of the top deck onto the upper side slopes. These waste handling practices create steep side slopes consisting of loose, uncompacted waste with a low shear strength (measure of its cohesion), which increases the likelihood of instability.

Factor of Safety Analysis

A preliminary slope stability analysis for the slide-impacted area was performed using data and observations from the site visit, and conducting the following steps: (1) back-calculate the waste shear strength values at the location of the slope failure; (2) use the results of Step 1 to estimate a factor of safety (FS), calculated as the ratio of waste shear strength to shear stress (which is a function of slope), prior to and after the slide event; and (3) apply the shear strength estimate to calculate the maximum slope that would yield a FS value indicating a lowered risk of slope failure.[2]

Six slope profiles representing the landfill configuration were evaluated for stability, including the profile along the recent slope failure (Profile 1-1'). The stability of the six slope profiles was evaluated using a computer program (PCSTABL5M), which calculates a FS for slope failure. This program uses an automatic search routine to generate multiple slope failure surfaces, using either circular failures or block/wedge-type failures, until the surface with the lowest FS-value is found.[3] Those surfaces with low FS values are the most likely to fail. A FS of 1.0 means the slope is at the imminent point of failure; a FS of 1.5, which is normally accepted as the minimum design value for modern landfills and the value recommended by U.S. Environmental Protection Agency, means the waste has 50% more strength than

2. Using the traditional Mohr-Coulomb strength model, waste shear strength, S, is comprised to two components; cohesion, C, (also called adhesion) and friction, ϕ, or $S= C + (N-u)*\tan(\phi)$, where N is the normal stress and pore pressure is u. These components, taken together, represent the resistance to shearing stresses induced on the side slopes. For this facility, we assumed the cohesion factor to be zero and that the waste derives shear strength only from friction.

3. Only the circular failure surface was considered in this report since there is no liner system in the bottom of the dumpsite. The analytical method used for the circular or sliding block failure modes in the slope stability analysis is the Modified Bishop or Modified Janbu methods, respectively.

needed for basic static equilibrium. Detailed results of the PCSTABL5M model runs are provided in Appendix B.

The waste shear strength that results in a FS less than 1.0 (metastable condition when the slide event occurred) was back-calculated for the estimated slope ratio of 1:1.9. The estimates assume waste cohesion, C, is zero and there is no elevated liquid level within the slope area. The analysis indicated that in-place waste had a shear strength which is represented by a friction angle, ϕ, of 26.7 degrees. This value is well below the typical range of shear strength for compacted waste (32 to 35 degrees friction angle), but is typical for loose, uncompacted waste. When waste with a friction angle of 26.7 degrees is placed on a 1:1.9 slope (27.7 degrees), the probability of failure is high. In the most simple form, FS can be estimated conservatively using the "infinite slope method", where $FS=\tan(\phi)/\tan(\beta)$, where β is the slope angle.

The September 1, 2017 slide event moved enough material downslope and effectively moderated the slope ratio in the impacted areas to 1:2.1. While this slight slope moderation increased the FS nominally to 1.04, the slope is still considered unstable and continues to pose a significant risk of another slide event. The estimated waste friction angle of 26.7 degrees can be used to predict the slope ratio needed to achieve a minimum FS of about 1.3. Table 2 below summarizes the preliminary calculations of the FS in the area of the slope failure before and after the slide event. The table also shows that the slope needs to be reduced to 1:2.7 or less to achieve a recommended minimum FS of about 1.3.

Table 2. Preliminary Estimates of Slope vs. Factor of Safety at the Slide Location (Upper Slopes of Southeast Side)

Status	Slope (V:H)	Waste Shear Strength* (in degrees)	FS (ratio: shear strength to shear stress)
Before slope failure	1:1.9	26.7	0.99
After slope failure	1:2.1	26.7	1.04
Recommended slope	1:2.7	26.7	1.29

*Cohesion is assumed to be zero.

Outside of the slide-affected area, there are other very steep slopes that need to be assessed. As shown in Table 1, the slope ratio at the slide location (1:1.9) is exceeded in multiple locations, and all side slopes with the exception of the lower slopes on the north side of the site have a ratio that exceeds 1:2.7. Based on the preliminary analysis of the slide-affected area, these other very steep slopes also are potentially unstable and pose a potential risk of slope failure following heavy rains, equipment loads, or other induced stresses. Detailed information should be collected and slope stability evaluations should be performed for all at-risk areas.

Surface Tension Cracks

The potential risk of another slope failure on the upper southeast slope remains high while the FS is close to 1.0. On September 11, 2017, a new tension crack was observed to have formed at the crest of the southeast slope, just above the location of the slope failure. During the site visit on November 1, the tension crack was observed to be about 50-60 m long, 1 m deep, and 0.3-0.5 m wide (see photos). The tension crack was located about 5 m from the crest of the slope. The development of tension cracks in this location is an indicator of increased potential for future slope failure.

The risk of another slope failure exists both at the existing slide location and other areas with steep unstable slopes. Excessive rains and continued disposal of waste on top of the site will increase the risk of future slope failures.

September 1, 2017 slope failure location in upper east slope
(viewing west across from the canal)

Slope failure site after canal clean-up
(viewing southeast on top of dump)

Leachate seeps on east side slope

Leachate seepage and erosion rills on east side slope

Uncompacted and uncovered waste

Waste filling on top of dumpsite

New tension crack near crest of east slope
(viewing north)

New tension crack near crest of east slope
(viewing south)

Best Practices

Since the slope failure, EDMC started forming terraces or benches along the southeast slope to moderate the slopes. Benching is a common waste industry practice to decrease the effective slope ratio and improve slope stability. In general, benches at least 5 m wide should be installed on side slopes for every 10-15 m of elevation change. Such efforts should continue at least until the slope ratio is less than 1:2.7 overall, which is needed to achieve a preliminary FS value of at least 1.3. Further studies should be performed to more accurately establish the minimum acceptable FS value and thus the maximum slope.

Besides reducing the slope angle, several other good site management practices can be implemented to improve slope stability. These include:

- Cease placing waste at the top of the landfill, which increases the instability of the steep slopes.
- Grade all flat waste surfaces to slopes of at least 5% to promote positive surface runoff and minimize water infiltration during rainy seasons.
- Apply a soil cover on side slopes of at least 0.3 m, which lowers infiltration from rainfall, enhances surface stability, and limits air intrusion that can contribute to landfill fires. Promoting vegetative growth on the soil cover will help to reduce erosion and therefore effectiveness of the soil cover.
- Improve waste compaction, which helps to stabilize the waste by increasing its shear strength and reducing its compressibility. This can be accomplished with a compactor designed for landfill applications, or other heavy equipment, provided that the waste is placed and compacted in thin lifts.

- Conduct regular monitoring of liquid levels within the waste mass to identify zones where a build-up of liquids could lead to slope instability. The lack of soil cover and the practice of applying leachate to the active disposal area will contribute to elevated liquid levels and increased slope instability, particularly during the rainy season. Leachate application should be curtailed or stopped, or moved at least 30 m away from any side slopes.

- Regularly inspect areas with steep slopes for tension cracks, deformation, or rapid settlement, which indicate an increased likelihood of slope failure.

- Conduct additional studies to conduct a detailed slope stability evaluation newly obtained monitoring data on topography and liquid levels to evaluate the relative role of pre-existing conditions (slope, waste cohesion) vs. climate (waste liquid levels) on the location and timing of slope failure events.

4 LANDFILL FIRES

Surface fires are caused by “hot loads”, equipment, people smoking onsite, and by waste recyclers. Hot loads in this context refers to waste that catches fire, smolders, or spontaneously combusts, and could include brush, leaves, construction debris, fuel, tires or chemicals that could react and cause a fire. Causes of equipment related fires include debris trapped under machines, heat from equipment (exhaust pipes), and welding. Fires are also set by recyclers to reclaim metals.

Subsurface fires result from air filtration into the waste mass. Both the waste in place and methane generated in the landfill are fuel sources; heat is generated by the microbial activity in the decomposing waste. Since the fire is below the surface, it is difficult to detect, gauge extent, and extinguish. Some of the visual indications of subsurface fires include sudden subsidence and depressions, fissures and cracks, venting holes and rills, and smoke.

Surface fire

Subsurface fire

Conditions at the Ghazipur site contribute to the occurrence of fires. Loose, uncompacted waste without soil cover accommodates the circulation of air through the waste. Spontaneous combustion may occur depending on the types of materials present and moisture and temperature conditions. Combustion is more likely to occur when reactive waste, hot loads, elevated temperatures, and/or explosive gases such as methane are present, all of which are likely conditions at the Ghazipur landfill. Fires also may occur following a slope failure. Since the Ghazipur site is not secured to prevent access from the public, arson can occur.

Landfill fires are an ongoing concern at the Ghazipur site for several reasons. First, they present a human health and safety risk for workers, firefighters, and informal sector workers. Due to steep slopes at the site, it can be difficult to access the fires, which sometimes requires the use of excavators to carve out access roads for fire engines and other equipment. Second, fires contribute to slope instability. The use of water to fight fires exacerbates this instability. Third, fires pose an environmental risk with potentially harmful emissions.

Best Practices

Strategies which may be appropriate for landfill fire mitigation at the Ghazipur site, and would work in conjunction with measures to improve slope stability and increase site capacity, include the following:

- Confine the size of the working face and apply an intermediate soil cover. A smaller working face area will help workers manage fires started by smoldering waste ("hot loads") delivered to the dump site. Also, the separation of delivered waste could help prevent fires from spreading.

- Inspect, manage, and avoid incoming loads of reactive waste, hot load sources, and combustible wastes. Perform periodic inspection of incoming trucks and ask information from the driver to screen out reactive waste, hot loads, or combustible waste materials.

- Use thermal imaging cameras to identify hot-spot zone(s). Thermal imaging of the site on a regular basis, or when there is suspicion that a hot spot exists, can identify a hot-spot zone early and increase the chances of eliminating potential fires before they fully develop.

- The most efficient method to smother burning areas is by applying a thick soil cover, which helps cut off the oxygen supply. This strategy requires having a soil stockpile nearby.

- The use of water to manage fires contributes to slope instability and should be avoided if possible. Instead of water, consider using foams and suppressants. Although this option may be expensive, it is very effective, especially for small areas. Alternatively, manufactured daily cover materials can be applied to side slopes to provide a surface that is resistant to water infiltration and that minimizes oxygen intrusion into the waste mass.

Addressing a fire at Ghazipur landfill (EDMC)

- Train landfill operators to suppress hot spots or smoldering waste. However, the landfill operator should quickly call the local fire department(s) should a fire (versus smoldering or a hot-spot) break out at the landfill. The landfill operator and fire department(s) might also consider joint training exercises to collaborate on site knowledge and fire suppression strategies.

- Evaluate the performance of landfill gas collection systems to ensure that air infiltration into the waste mass is controlled. The landfill gas collection system is operating in an area that has a final cover, but could introduce air if operated aggressively, or if there are areas where waste is not adequately covered with soil or sealed with a cap system. An active gas collection system may contribute to landfill fires by introducing oxygen into the waste. Regular measurements of oxygen and carbon monoxide levels should be performed to monitor and take actions to prevent deep landfill fires near the wells.

5 AVAILABLE AIR SPACE

The Ghazipur landfill receives about 1,800 to 2,000 tons of waste per day. The site's capacity for receiving additional waste is severely constrained, but no other disposal sites are available in the region. Until a new landfill is available, site operators must improve the use of the available vertical air space to maximize capacity and extend the life of the landfill, while lowering the risk of another slope failure.

Best Practices

The following activities allow for the more efficient use of available air space and involve expanding on measures identified for improving slope stability:

- Divert more waste to the demolition and construction waste processing facility, and WTE plant, which are not running at full capacity.

- Begin compacting waste with proper methods, including thinner lifts, and utilizing equipment such as a waste compactor that drives over the waste several times. Compaction should be avoided near the edge of unstable side slopes or on very steep side slopes where maneuvering of compacting equipment is difficult.

- Consider landfill mining to address slope instability, lower the waste height, and flatten the side slopes in critical areas. These actions may create air space, reduce the risk of slope failure in the targeted area, and present an opportunity to reshape the north slope with new waste so that it will be easier to install a cap during landfill closure. However, before landfill mining is introduced, the methodologies and equipment needs should be studied and discussed with operations staff with regard to gas and leachate management, odor control, dust, erosion, stormwater, and other factors.

- Evaluate the suitability of moving waste disposal operations to two areas with potential air space. The first area is the closed north plateau, which is currently being used for landfill gas capture (see photos). The evaluation would examine the settling of the cap system, the stability of the closed side slope, and the area's safety and stability for further waste disposal. The use of this area would require an agreement with the landfill gas system operator (GAIL) before deciding whether the gas collection system could accommodate waste disposal, or whether it should be decommissioned, which would allow the removal of the final cover ("cap") and make space for additional waste. The second possible area for waste disposal is the triangle-shaped area at the south end of the site. This solution also needs further evaluation and consultation with the WTE plant operator.

- Consider a vertical retaining structure, such as a mechanically stabilized embankment (MSE) wall along the north, west and southeast slopes to gain additional air space. The MSE wall needs to be designed by qualified and experienced professionals for stability and compatibility with the landfill, and constructed carefully. MSE walls, which utilized geogrids and geotextiles as reinforcement elements, have been designed with a near vertical exterior wall and for heights of up to 10-15 m. However, walls of these heights are not common and must include detailed engineering analysis, monitoring of construction and performance, and require periodic maintenance. MSE walls can also be designed to have an aesthetic appearance.

Additional studies are needed to assess the site's ability to implement these actions and their likely effectiveness in increasing disposal capacity. It should be noted that following these practices would at best provide a temporary solution to the problem of a lack of disposal capacity. Once a new site is approved, the objective will likely shift towards closing and remediating the Ghazipur site in order to mitigate future safety and environmental hazards, which will require a proper site evaluation and closure design plan.

Closed area north of north slope (GAIL plant)

Settlement and lateral movement in north slope closed area

6 CONCLUSIONS

Site observations and a preliminary slope stability evaluation indicate that steep slopes and the lack of shear strength of poorly compacted waste material created conditions in which a slope failure was likely to occur. The occurrence of heavy rains, resulting in increased waste moisture content, increased pore pressures, and increased wet density of the waste further reduced stability and was probably the mechanism that ultimately triggered the September 1, 2017 slide. Furthermore, our analyses indicate that there continues to be a significant risk of future slope instability, both in the existing slide location and on steep side slopes elsewhere at the site. The recent development of a 60 m long tension crack near the crest of the southeast slope above the slide area is an indicator that another slope may be imminent unless stabilization measures are taken in the near future. To minimize the risk of potential future slope failure at the slide location and at other locations on site, officials should consider the following actions.

- **Identify a new sanitary landfill site –** The only long-term solution to resolving problems of slope stability, site capacity, and fires is to close the Ghazipur site and move disposal operations to a new sanitary landfill.

- **Reduce areas of steep slopes by grading and/or landfill mining, and revise waste operational practices to enhance future slope stability –** Waste filling at the top of the landfill should cease for safety reasons. However, ending waste disposal on the top-deck would not necessarily prevent future slope failures, as the existing slopes are not acceptably stable. Installing benches is among the best solutions to improve slope stability. Ideally slopes should remain no steeper than 1:3. Benches with at least 5 m width should be used for every 10-15 m of vertical distance down the side slope. Further studies of site topography, liquid levels, and a more detailed slope stability evaluation should be undertaken to evaluate areas with the greatest risk of slope failure.

- **Manage landfill fires –** Until air intrusion is limited and all waste surfaces are covered with soil, landfill fires are likely to be an ongoing occurrence and safety concern at the site. The most effective method of fire suppression is smothering it with soil to cut off oxygen supply. Firefighters should limit the use of water to put out fires, and avoid using it on steep slopes. Foams and suppressants are alternatives to applying water that are effective for small areas but are expensive.

- **Create additional air space –** A variety of potential actions have been identified to use available vertical air space at the landfill site. These include separating waste to increase diversion to on-site waste processing and combustion facilities, properly compacting waste, evaluating and potentially developing areas on the north and south side of the site to receive waste, conducting landfill mining where slope stability is an issue, and erecting a mechanical stabilizing embankment wall. Together, these actions should conserve air space, and limit waste deposition in areas that are too high or too steep.

- **Establish two interim on-site locations for waste disposal –** One potential disposal location is the area between the north slope and the closed area. A feasibility study will be needed to consider how to modify the current gas collection system in order to accommodate waste filling over the gas collection system or to decommission the gas collection system. The second potential disposal location would be the triangular area on the south side of the landfill. A study will be needed to determine how to best use this area for disposal without impacting the construction of a future WTE expansion plant.

Further studies are needed to assess and select the best strategies to address issues of slope stability, fires, and site capacity, and to allow disposal operations to continue at the Ghazipur site until a new sanitary landfill site is approved.

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NGT. 2017b. Original Application No. 199/2014; 61/2017; 281/2016; and 428/2017. Almitra H. Patel & Anr. Vs. Union of India & Ors. And Almitra H. Patel & Anr. Vs. Union of India & Ors. And Kudrat Sandhu Vs. Govt. of NCT & Ors. And Court on its own Motion Vs. Govt. of NCT Delhi. Item No. 4. September 11.

NGT. 2017c. Original Application No. 199/2014; 61/2017; 281/2016; and 428/2017. Almitra H. Patel & Anr. Vs. Union of India & Ors. And Almitra H. Patel & Anr. Vs. Union of India & Ors. And Kudrat Sandhu Vs. Govt. of NCT & Ors. And Court on its own Motion Vs. Govt. of NCT Delhi. Item No. 01-04. September 22.

Appendix A – Slope Profiles

Exhibit 1. Section Location Plan at Ghazipur Dumpsite, East Delhi

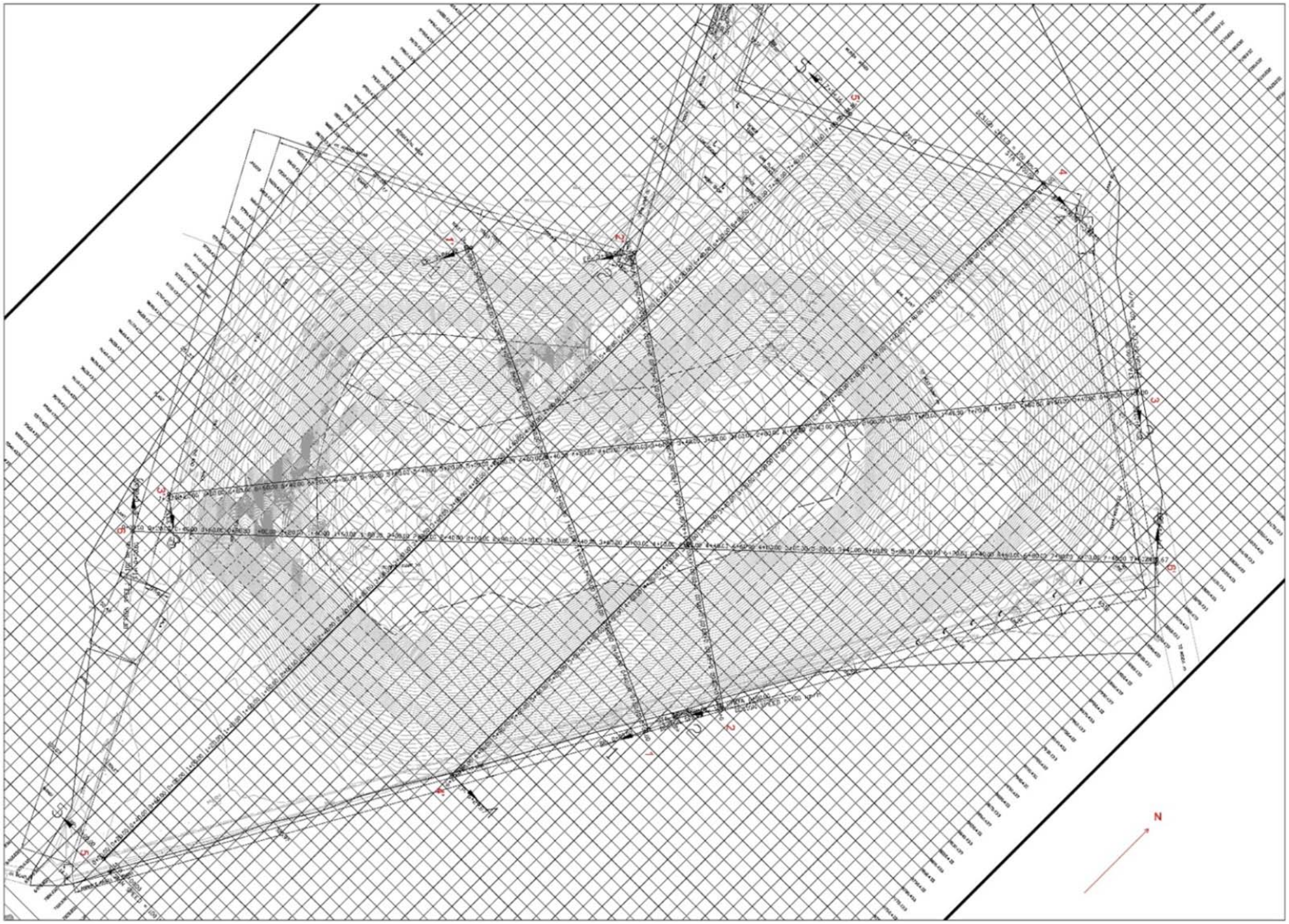
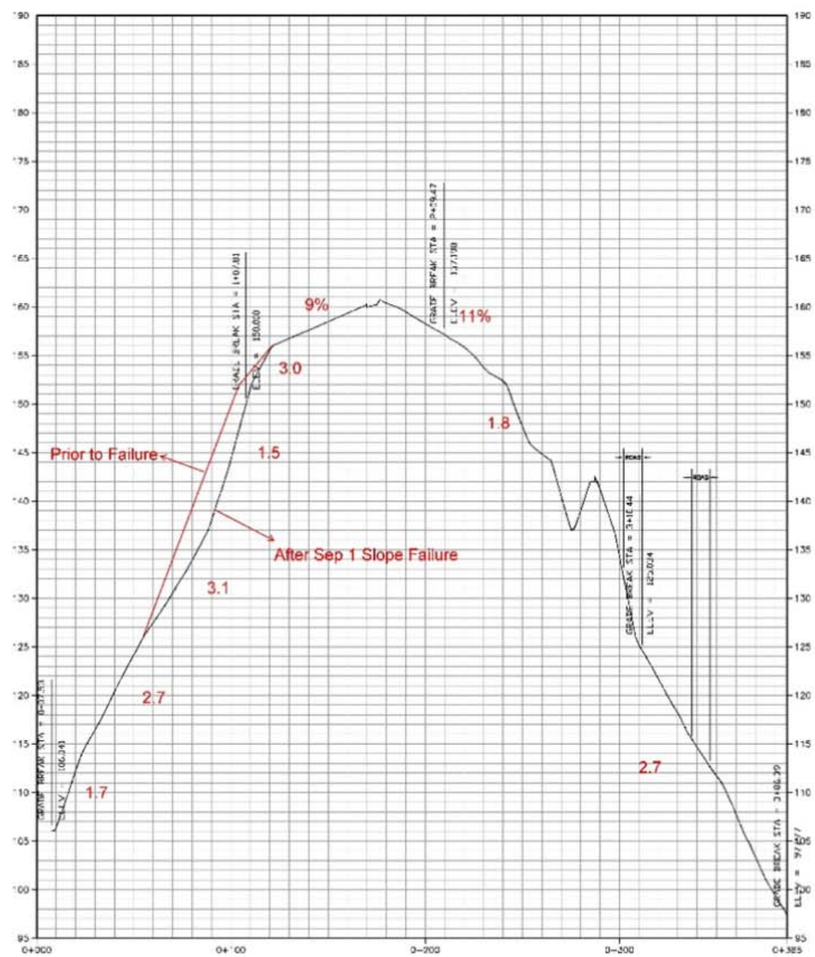
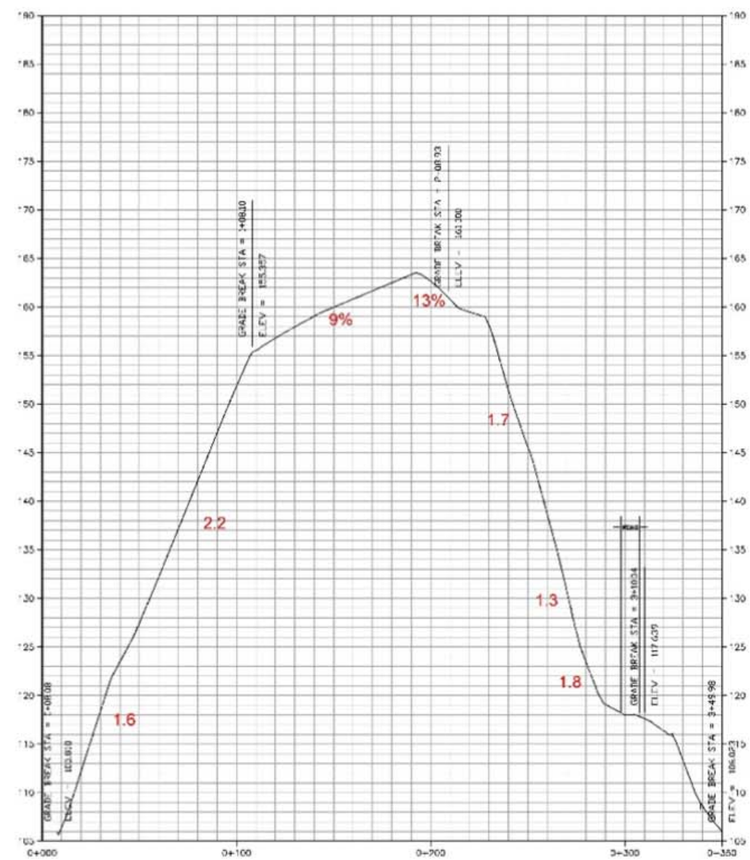


Exhibit 2. Section Profiles 1-1' and 2-2'



1-1



2-2

Exhibit 3. Section Profile 3-3'

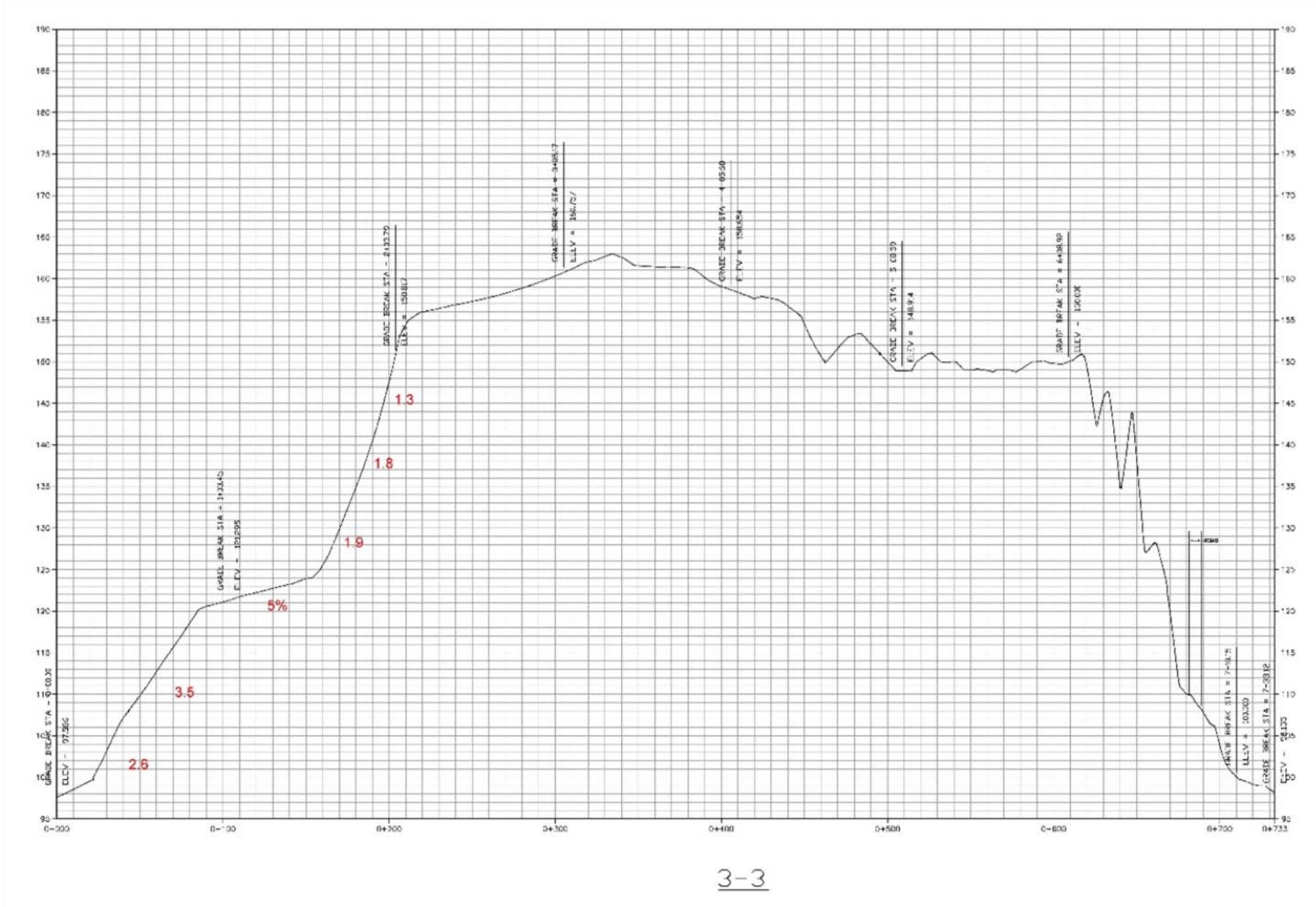


Exhibit 4. Section Profile 4-4'

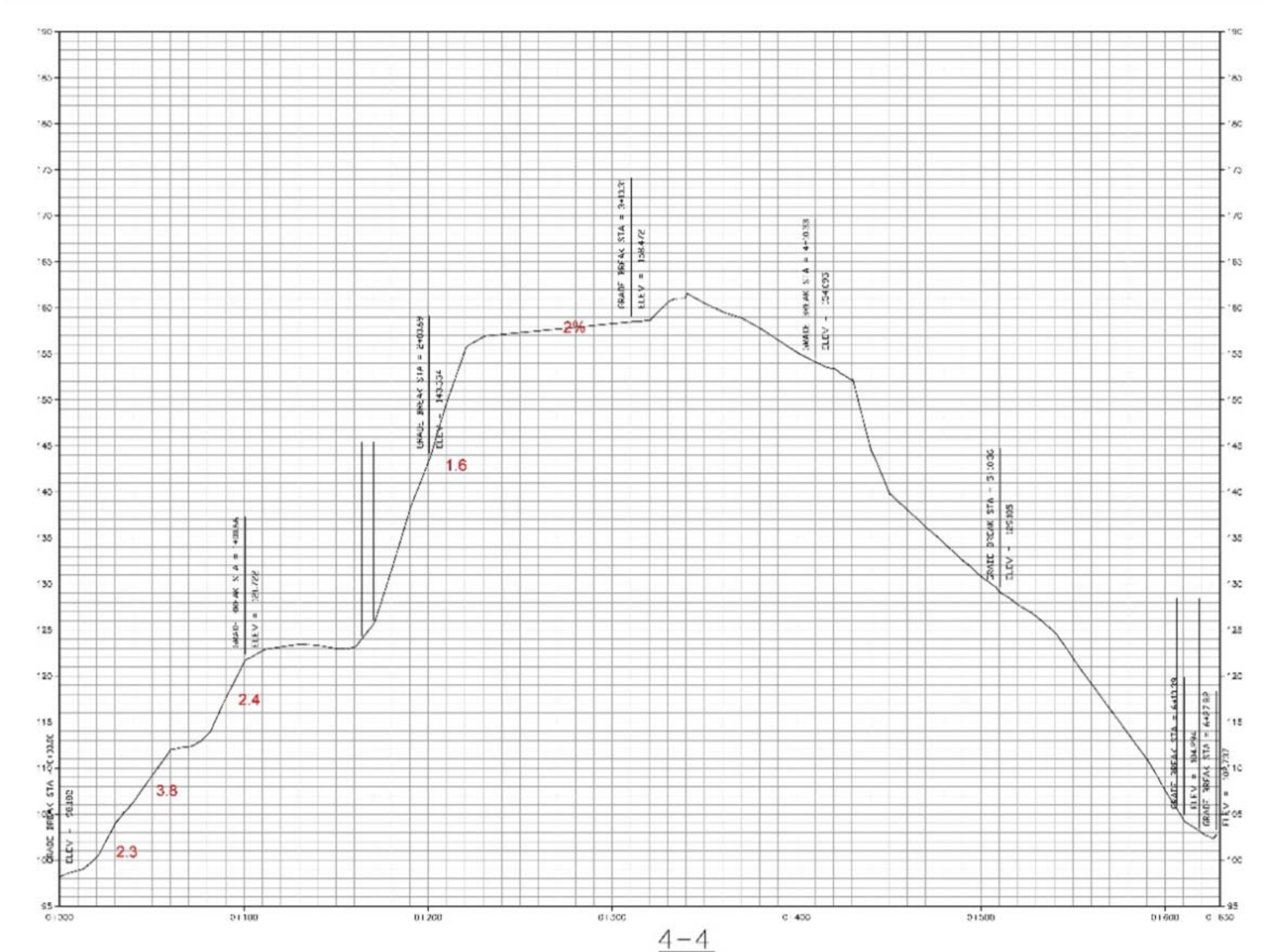
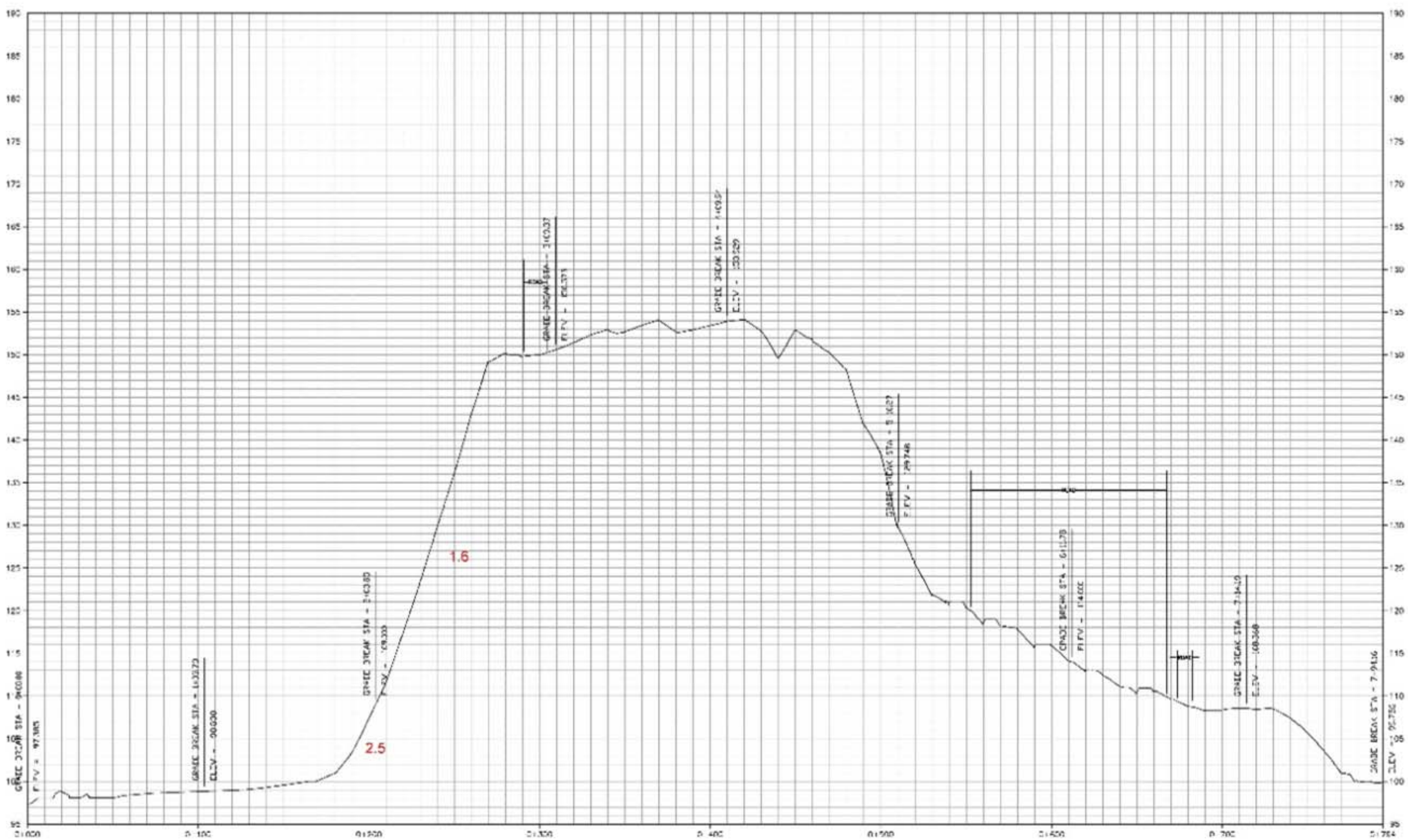
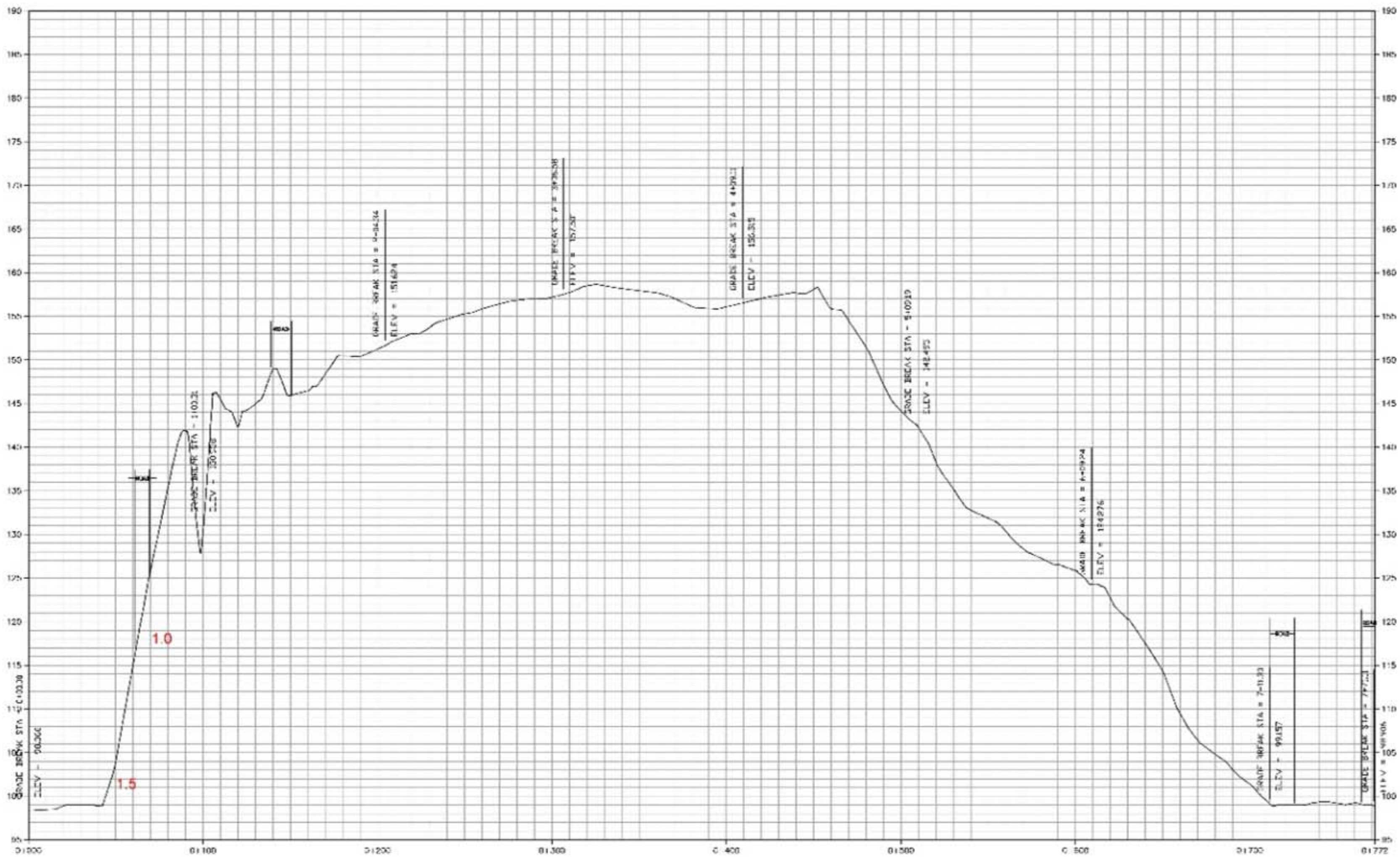


Exhibit 5. Section Profile 5-5'



5-5

Exhibit 6. Section Profile 6-6'



6-6

Appendix B – Preliminary Factor of Safety Analysis: Model Results

Exhibit 7. Factor of Safety at Failure at 1:1.9 Slope

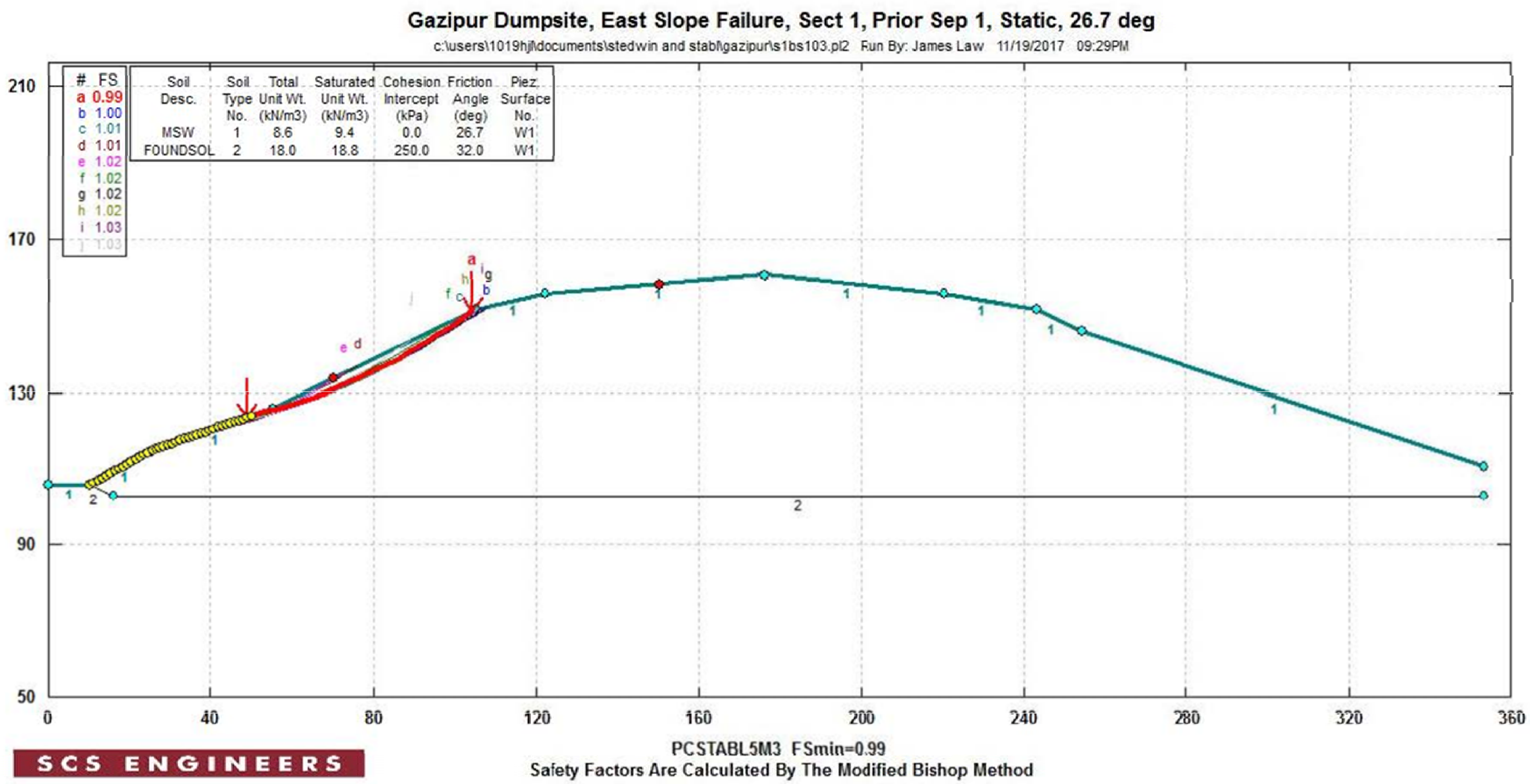


Exhibit 8. Factor of Safety after Failure at 1:2.1 Slope (Present)

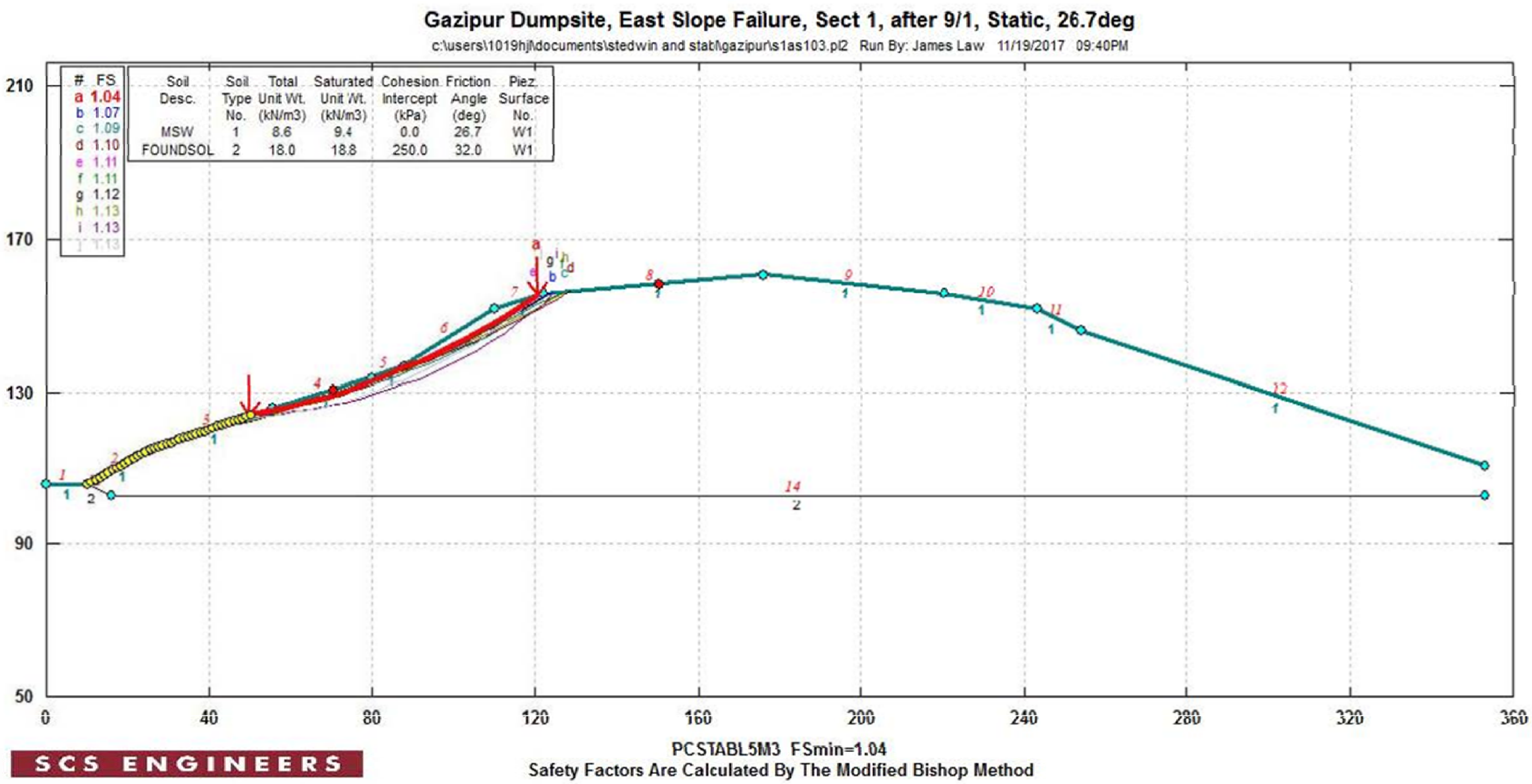


Exhibit 9. Factor of Safety after Slope Modification to 1:2.7 Slope