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EVALUATING OPEN PIT HIGHWALL DIG COMPLIANCE

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by

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Abstract

The mine planning process comprises three major stages: collection of relevant data, application of design methods and measurement of performance. Relevant information about the geology, structure, rock mass and hydrogeology are collected to create a geotechnical model. This information, collected by the geotechnical engineer, is used to design the pit slopes which are incorporated into the pit design by the mine planner based on mining regulations, safety and economics. Drilling, blasting, excavation and dewatering activities mainly constitute the implementation stage of the mine design. Mining to achieve design has proven to be difficult practically. Factors such as geology, blasting and excavation practices affect adherence to the mine plan; therefore, it is important to measure performance along the mine value chain by reconciling actual data with the mine plan. For this study, four final pit high walls were identified and analyzed to determine compliance with the mine design and to evaluate rockfall potential. Compliance was measured by the distance the mine as built deviates from the plan. A target of 80% compliance was set for distances within 3 feet of design and 100% compliance for distances within 4 feet of design. From the study, 33% of the as built were within ±3 feet and 41% within ±4 feet of the design. The as built slopes were flatter than the planned slopes. From the rock fall analysis, the east wall had the highest potential of rockfall with an average movement of 782 feet.

Keywords: Highwall, Compliance, Reconciliation, Rockfall, Mine Design

Dedication

I dedicate this work to my family for their support, love and guidance, most especially to my mum, Christine Bansah. I wish you were here to celebrate with me.

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Glossary of Terms[1]

Term	Definition
Highwall	Unexcavated face of exposed overburden
As built	A model which captures the exact physical shape of an object
Rockfall	The fall of a rock fragment or a portion of fractured rock mass under gravity without the simultaneous occurrence of a seismic event.

[1] Definition from the Dictionary of Mining, Mineral and Related Terms.

1. Introduction

The mine planning process comprises three major stages: collection of relevant data, application of design methods and measurement of performance (Potvin et al, 2015). Before a mine project commences, extensive exploration drilling is performed on the site to retrieve information about the subsurface. Relevant information about the geology, structure, rock mass and hydrogeology are collected to create a geotechnical model. Strength tests are conducted on the drill cores to determine the uniaxial compressive strengths and failure modes of the rocks present on the site. This information collected by the geotechnical engineer is used to design the pit slopes which are incorporated into the pit design by the mine planner based on the mining regulations, safety and economics. Drilling, blasting, excavation and dewatering activities mainly constitute the implementation stage of the mine design. Practically, mining to achieve design has proven to be difficult due to factors such as geology, blast designs and excavation practices affecting the mining process. It is, therefore, important to measure performance along the mine value chain by reconciling actual data with the mine design. Reconciliation between planned and actual results highlights opportunities to improve mine designs and mining techniques to minimize ore loss and avoid pit stability issues (Riske et al, 2010). Mining to design is critical for optimal and safe extraction of the mineral reserve therefore the implementation stage must be tracked frequently in order to update slope design criteria and pit layouts based on the mining cycle as the mine is developed (Bester et al, 2016). Read and Stacey (2009) suggest that the goal of mining to design can be achieved by implementing controlled blasting around the final pit walls, excavation control and scaling, dewatering and ground support.

1.1. Problem Statement

During the implementation stage of mining, pit wall stability issues can occur if the mine is not built according to the mine design. The major causes for not achieving the mine design include improper blasting or excavation practices. These issues may stem from any combination of the following:

- Blasting: deviation of presplit holes, insufficient hole depth (thus not drilling to the required reduced level), error in the blast pattern (excessive burden and spacing), using less or too much explosives and;
- Excavation and scaling: mining too much or less material and improper scaling of rocks at the final pit walls.

Pit wall instabilities can affect both profitability due to lost production and workforce safety as any rock fall incident exposes the workforce and equipment to hazards. This project focusses on quantifying the increase in rock fall hazard associated with noncompliance of pit walls. The two different scenarios of noncompliance include the failure to achieve bench widths and sacrificing highwall position.

<u>Scenario 1- Improper Bench Width</u>

In this scenario (Figure 1), though mine design is achieved, the bench width is compromised and, as a result, safety may be compromised. Bench width (serving as a catch bench) in mine slopes is necessary in areas of rock fall because the catch benches prevent rocks from rolling from upper portions of the pit slope to the working areas where personnel and equipment are located (Ryan, et al).

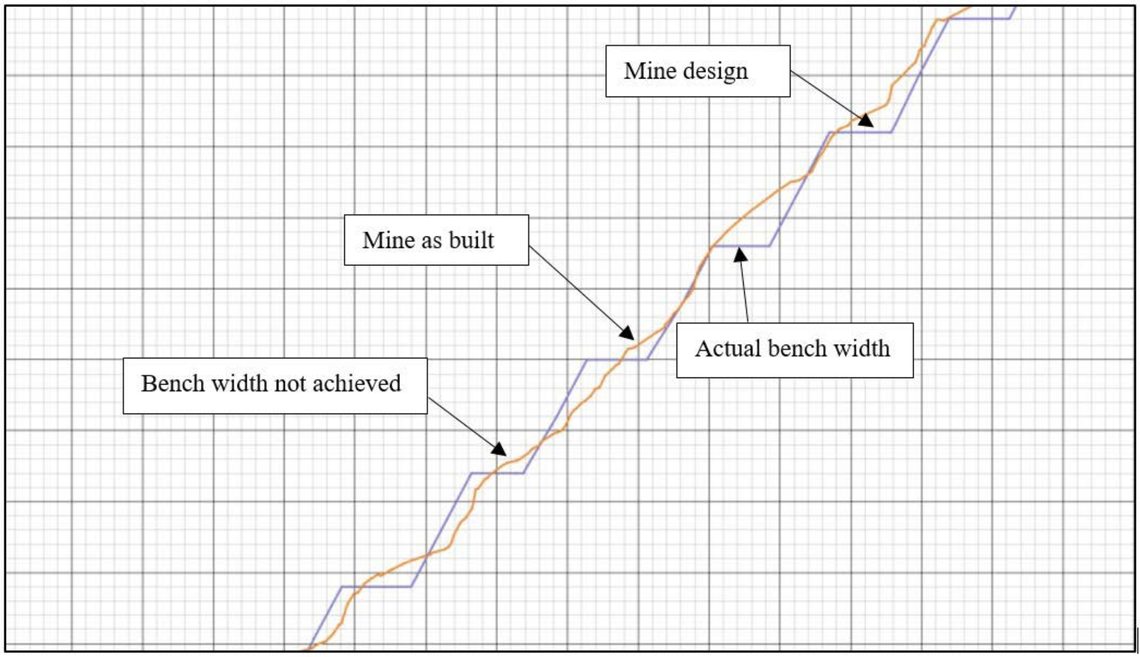

Figure 1: Mine as built versus Mine Design showing Bench Width

Scenario 2- Improper Highwall Alignment

This scenario suggests a situation where bench width is achieved but the mine design is compromised. Though personnel and equipment are safe, some amount of material is left behind or mined beyond the design. A typical example is shown in Figure 2.

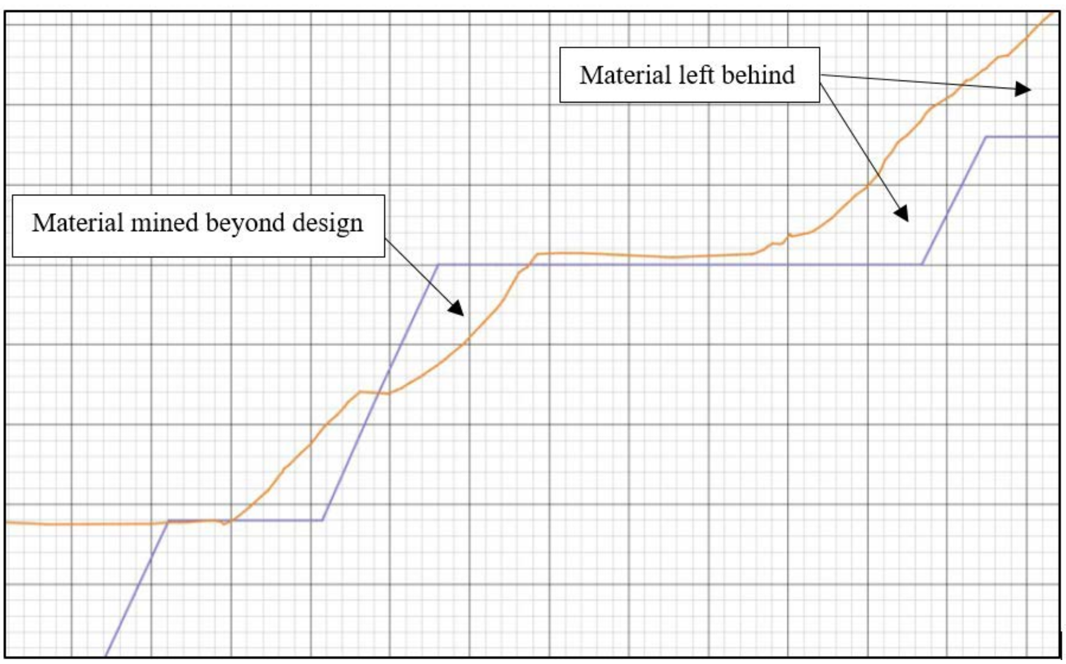

Figure 2: Mine as built versus Mine Design Showing Improper Highwall Alignment

1.2. Project Goals

The goal of this project is to reconcile the mine as built with the mine design to:

- Determine highwall compliance;
- Determine bench width compliance; and,
- Quantify the potential of rock fall around the final pit walls.

2. Literature Review

2.1. Introduction

Macfarlane (2015) defines mine reconciliation as the comparison of measures and estimates along the mine value chain, at different points in time, in order to track and optimize metal recovery. Reconciliation of mineral resource to mineral reserve, mine planning reconciliation of long-term to short-term plans, grade control reconciliation of head grade among others is conducted to measure performance. Riske, et al (2010), mention the three main types of reconciliation: spatial (three-dimensional reconciliation), temporal (time based) and physical (attributes based). Reconciliation of mine to design uses both spatial and temporal reconciliation. Chitombo and Scott (1990) state that the two important rocks in a mine are: (1) the rock that is required to be removed; and, (2) the rock that is required to be left behind to form part of the mine structure. In order to ensure continuous extraction of the mineral reserve, the geotechnical aspects of the mine structure must be incorporated into the unit operational activities of the design implementation stage of a mine project. Bester, et al (2016), suggest that mining to design is critical for optimal and safe extraction of the mineral reserve hence the implementation stage must be tracked frequently in order to update slope design criteria and pit layouts based on the mining cycle as the mine is developed. The major operational activities adopted during the development of a mine are drilling and blasting of the rock mass and excavating the blasted material. According to Read and Stacey (2009), to achieve the mine design it is required that the mine practice controlled blasting around the final pit walls, excavation control and scaling, dewatering and ground support.

2.2. Causes for not Achieving Mine Design

Drilling, blasting, excavation and dewatering activities constitutes the implementation of the mine design. To avoid ore loss and pit wall stability issues, the final pit slopes must be mined to design in terms of achieving both bench width and overall design angle. Mining to design is challenging due to factors such as geology, blasting and excavation practices affecting adherence to the mine plan. The effects of blasting, excavation and scaling to achieving mine design are discussed below.

2.2.1. Blasting

Blasting is a significant activity in mining because it provides the energy needed to fragment the ore bearing rock to subsequently extract the mineral of interest. The purpose of blasting is to consciously destroy the structural competence of the rock mass by creating fractures in intact material and by extending, opening and dislodging existing fractures and planes of weakness (Chitombo et al, 1990). When an explosive is detonated in a blasthole, there is a rapid chemical reaction which produces a shock wave that radiates from the blasthole and causes ground vibration. The shock wave crushes the rock and causes radial splitting farther out from the blasthole. When the shock wave is reflected, tensile forces are generated which causes a slab like spalling. The high-temperature and high-pressure gases produced penetrate and extend both the shock wave induced and natural fractures. This pressure displaces and fragments the rock. This energy produced during blasting causes damage to the mine structure especially when blasting near the final pit walls.

2.2.1.1. Blast Induced Damage

Scoble, et al (1996), describes damage to a rock mass to be the reduction in its integrity or quality. Rocks that form part of the mine structure are expected to maintain their strength and structural competence for the entire mine life but are subjected to shocks or vibrations and gas pressure from blasting activities. The creation of mine openings in the rock mass disturbs the initial stress distribution and subjects the rock to dynamic loading by virtue of the redistribution of stress, removal of lateral support and mining activities. These activities affects the stability of the pit wall. Little (1991) lists the different elements of blast-induced damage as:

- Back break (induced slope failure);
- New cracks (fracturing);
- Opening existing discontinuities (volume increase and loosening);
- Extension of existing discontinuities (preferential fracturing);
- Development of microcracks in intact rock blocks (intact block weakening); and,
- Loosening (dislocation of rock blocks).

Damage to the rock mass makes it less able to perform its function and may result in rockfall hazards.

2.2.2. Controlled Blasting

Read and Stacy (2009) state that the purpose of wall control blasting is to produce a well-fragmented, loose muckpile as well as an on-design and undamaged slope. As blasting activities approach the final pit wall, concerns about protection should be prioritized above production (Boucher et al, 2005). To achieve stable slopes, the site conditions such as slope design, water conditions, geology, pattern shape and available free faces must be evaluated and incorporated into the controlled blast design. Achieving stable slopes lessens the hazard and cost of rockfalls and may reduce the need to support the pit wall. Several methods of controlled blasting are adopted in the mining industry. These are (Read et al, 2009):

- Buffer blasting;

- Trim blasting;
- Pre- or mid-split blasting;
- Post-split blasting; and,
- Line drilling.

Pre-splitting is most commonly used and it involves drilling closely spaced holes along the pit design limit. These holes are lightly charged with explosives and blasted before the production blast holes. This creates a surface allowing the explosives gases to escape to avoid damage to the slope face.

2.2.3. Excavation Control and Scaling

Excavation control and scaling of the bench faces are a crucial step in the achievement of safe and optimum slopes in all open pits. The key performance index for excavation around final pit walls should be achieving the toe and crest, the design batter face angle and bench width. Prior to excavation, the production team must define the limit of digging by clearly marking out the toe and crest of the bench. Monitoring of excavation activities around the final pit walls is important to avoid overdigging in areas where there is blast damage or underdigging by removing less material than required. Overdigging and underdigging could result in ore loss by leaving behind ore bearing materials or ore dilution by mining waste together with ore. Scaling of the bench face and the crest is required to remove loose blocks that may cause rockfall hazards and to clean up the bench to preserve its catchment capacity. Scaling is usually performed by a backhoe excavator while digging the slope face or, in some cases, using a large chain attached to a dozer or the backhoe excavator.

A post excavation inspection of the slope face must be done to quantify the effects of blasting on the slope face to refine the design. Read and Stacy (2009) lists five cases of post excavation inspection:

- Case 1 Overbreak along the entire face (Figure 3);
- Case 2 Overbreak at the top bench (Figure 4);
- Case 3 Underbreak at the toe (Figure 5);
- Case 4 Overbreak at the toe (Figure 6); and,
- Case 5 Overbreak at the crest, underbreak at the toe (Figure 7).

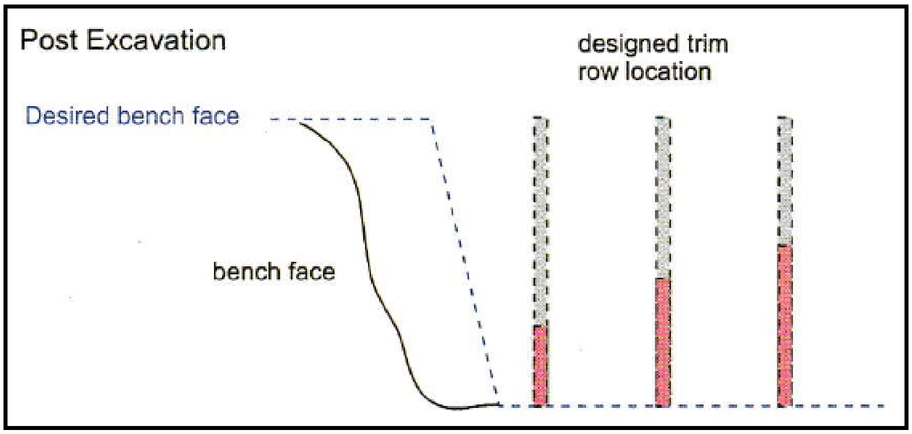

Figure 3: Overbreak along the Entire Face (Source: Read *et al*. 2009)

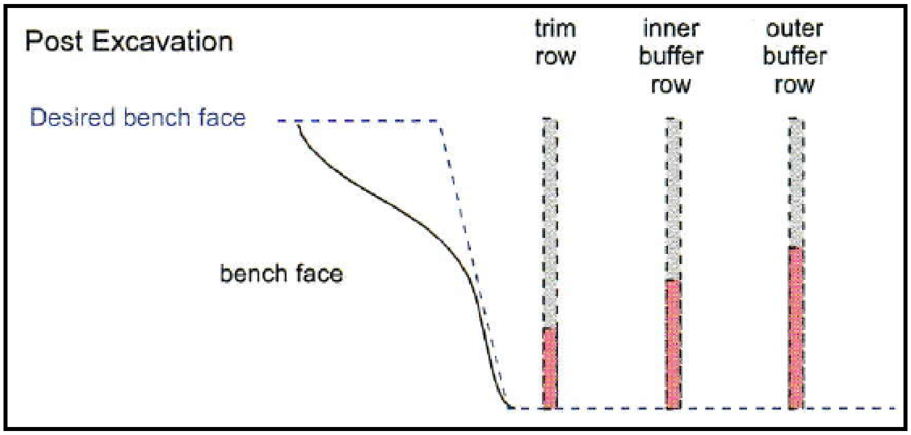

Figure 4: Overbreak at the Top Bench (Source: Read *et al*. 2009)

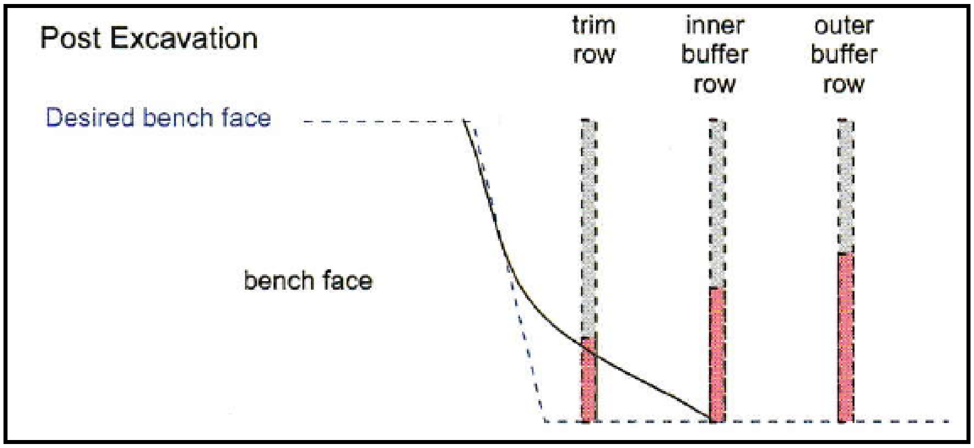

Figure 5: Underbreak at the Toe (Source: Read *et al*. 2009)

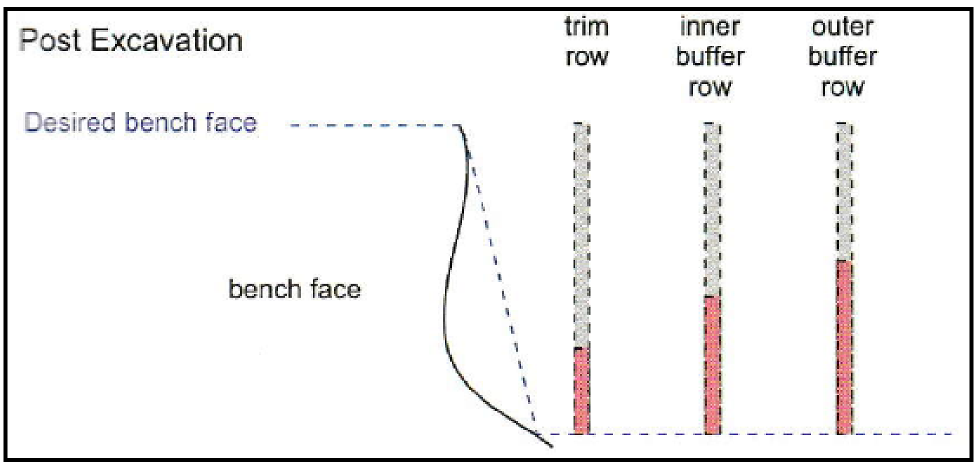

Figure 6: Overbreak at the Toe (Source: Read *et al*. 2009)

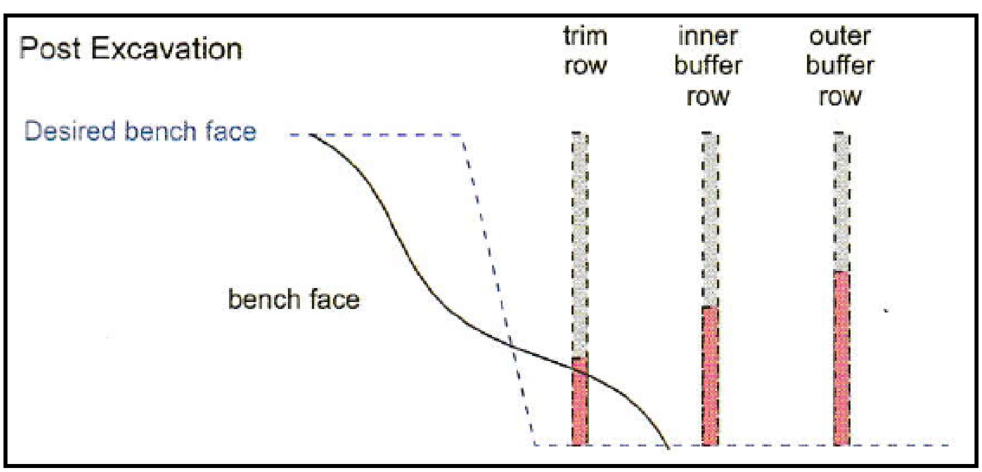

Figure 7: Overbreak at the Crest and Underbreak at the Toe (Source: Read *et al*. 2009)

3. Data Collection and Analysis

Data collection for the mine to design reconciliation requires the identification of the final pit boundaries that have been exposed over time. The scanner should be positioned such that the toe and crest of the target surface is captured for accurate analysis.

Laser scanning is the process of capturing 3-dimensional (3D) digital information about the shape of an object by a camera sensor mounted in the laser scanner which records accurate dense 3D points in space. A full 3D model is constructed by combining multiple surface models obtained from different viewing angles. In order to determine highwall compliance, the pit high walls were scanned to obtain actual field data for comparison with the mine plan.

A vehicle mounted Maptek I-Site laser scanner was used to acquire pit scans in the summer of 2015. Additional scans were collected in October 2017 using a Leica MS50, mounted on a tripod (see Figure 8, below) to obtain an updated pit scan. The Leica MS50 has a scan range of up to 1000 meters (3280.8 feet). Several scan positions were used to reduce shadows in areas not visible to the scanner at a specific position and to obtain a single composite scan of the Continental pit (Figure 9, below). The red spots in Figure 9 are the various positions of the scanner during the scanning process.

Figure 8: Leica MS50 Mounted on a Tripod

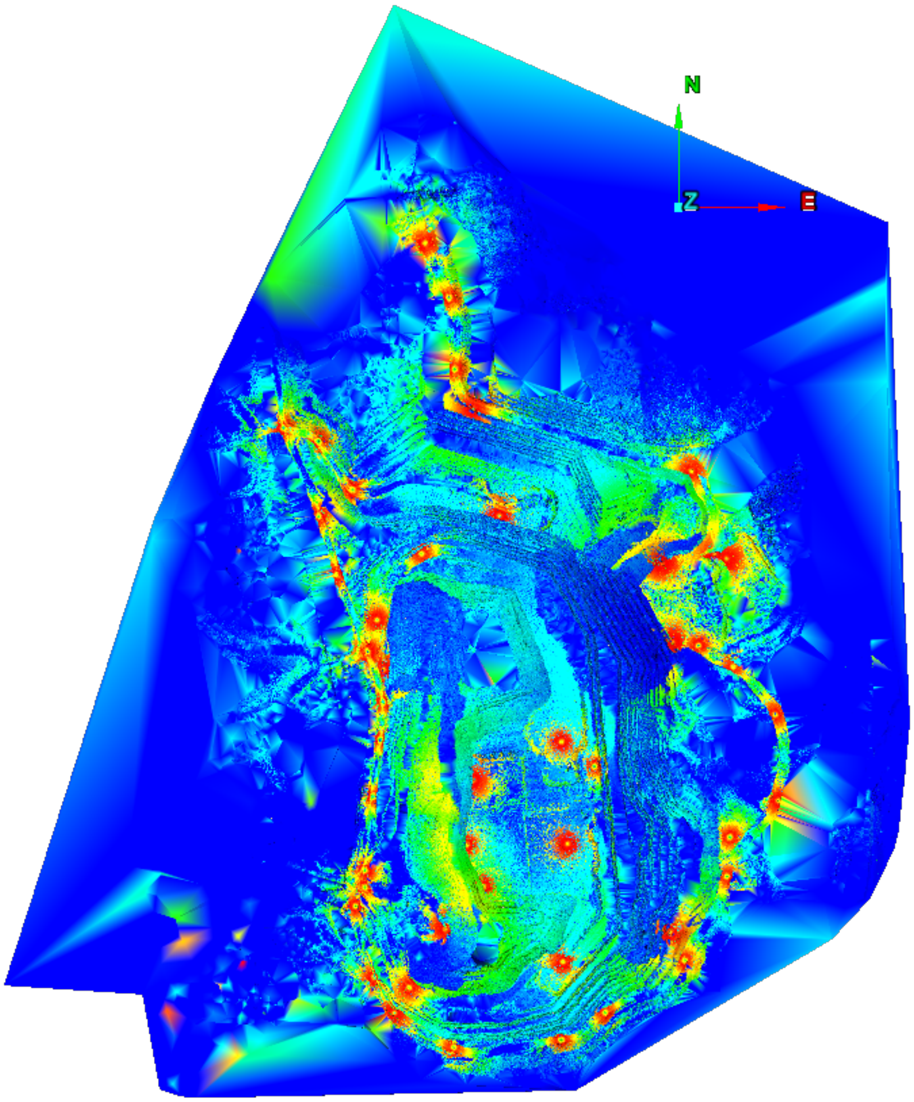

Figure 9: Pit Scan of Continental Pit

Pit design for the Continental pit (Figure 10) and parameters for rock fall analysis were obtained from Montana Resources.

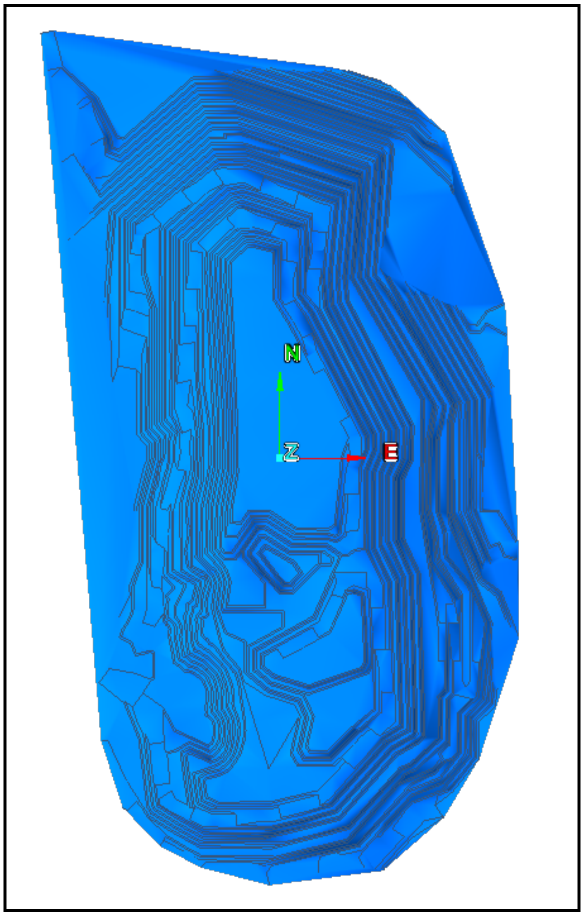

Figure 10: Pit Plan of Continental Pit

3.1. Data Analysis

A design conformance analysis was conducted to determine highwall compliance with the pit plan using tools in Maptek I-Site studio software. Distance measurement data from I-Site were exported into Microsoft Excel to compile a histogram of highwall compliance. To quantify the potential of rockfall, slopes were extracted from the pit as built as well as the pit design and imported into the RocScience RocFall software. Rockfall analysis was performed for both pit as built and pit plan for comparison.

3.2. Design Conformance

Raw laser scanning data imported into I-Site studio can be processed by the steps outlined in Figure 11, below. I-Site Studio software utilizes various filtering functions to process the raw scan data to allow for conversion into a digital terrain model (DTM). A DTM for both the mine as built and pit design were created. From the pit scan obtained, four final pit high walls were identified; north (red), south (green), east (yellow) and west (cyan) high walls as shown in Figure 12, below. Each highwall was extracted using the filter by polygon tool and a DTM was created. The pit plan was overlain on each highwall to run a design conformance report.

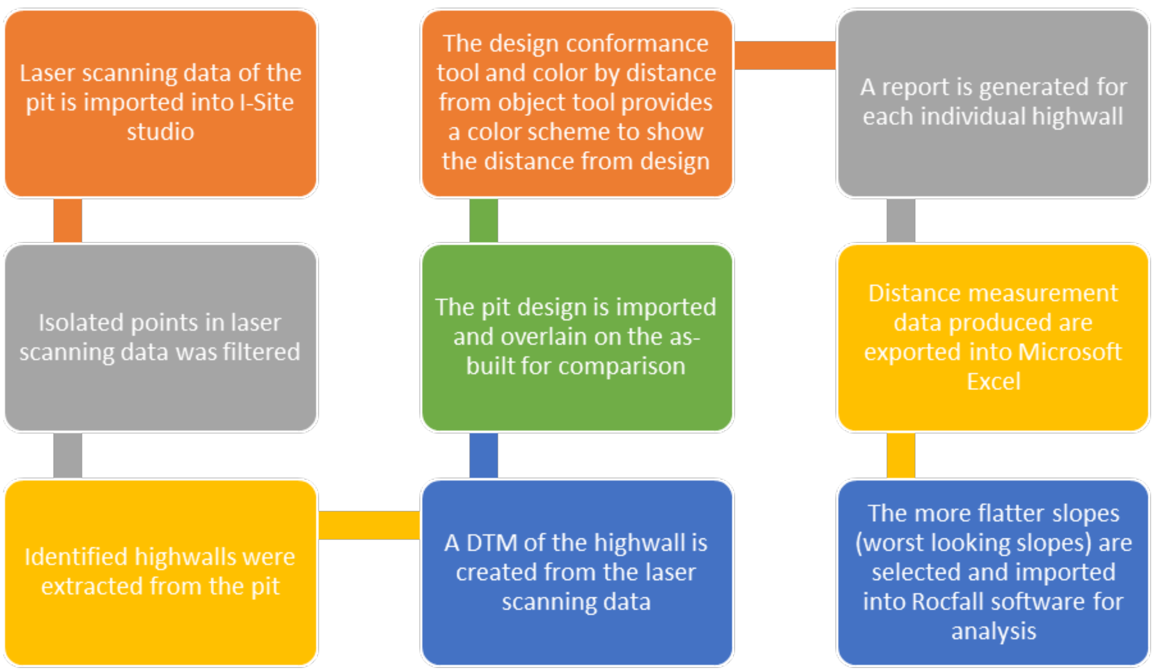

Figure 11: Data Analysis Procedure

Figure 12:Pit Highwall Sections

The design conformance report tool in I-Site accepts a design surface and object(s) representing the as built surfaces and generates a report detailing the conformance between the two (Maptek, 2018). This tool reports on the volume and percentage of underdig and overdig. In this tool, settings like the cross section spacing, tolerance (distance to design) and a threshold of underdig and overdig can be adjusted by the user. In this analysis, a cross section spacing (Figure 13, below) of 300 feet; a tolerance distance (Figure 14) ranging from -10 feet to +10 feet; and distances from 0 to 3 feet were colored in green, 3 to 4 feet were colored in yellow and above 4 feet were colored in red. The threshold percentage was set at 25%.

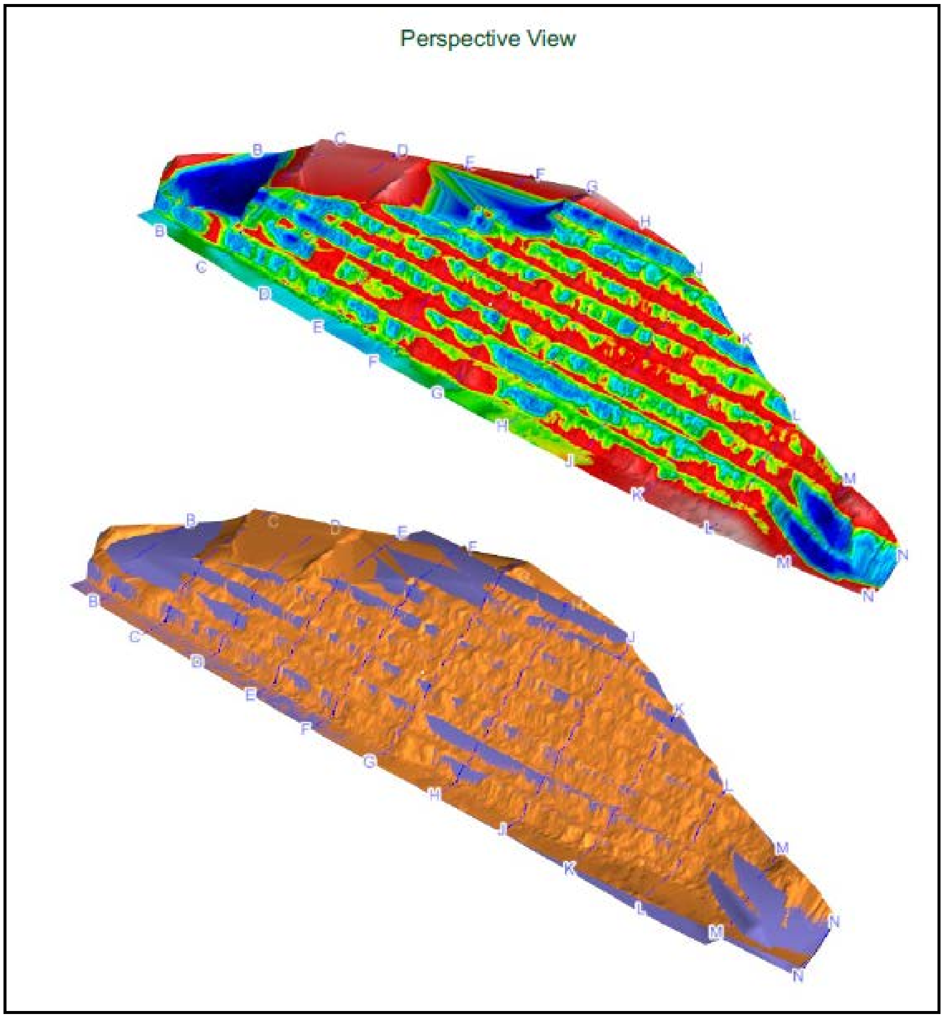

Figure 13: Cross Section Spacing

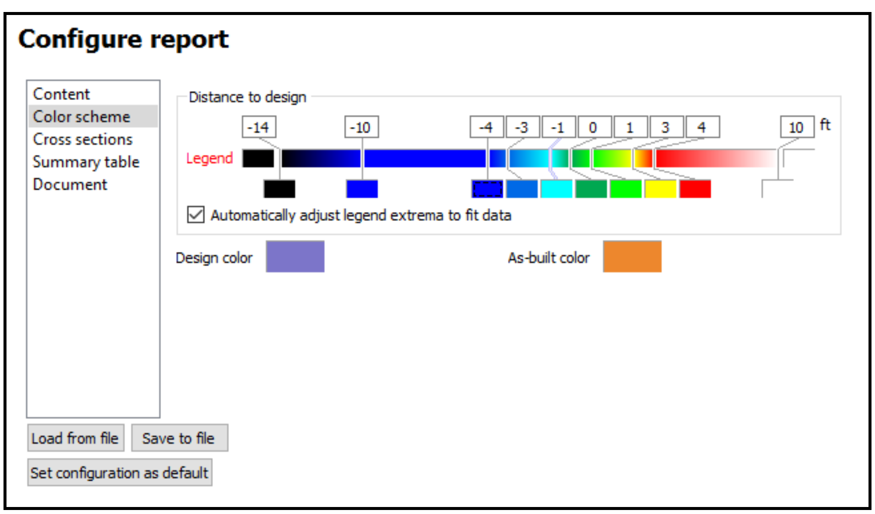

Figure 14: Tolerance Distance

A design conformance report was generated quantifying the volume and percentage of underdig and overdig. Multiple cross-sectional views between the design and as built were generated giving a closer view for further analysis. As seen in Figure 15, the cross sections give a graphic view of how the as built slopes aligns with the pit plan and shows areas of underdig and overdig. Appendix A contains the cross-sectional views generated for each highwall.

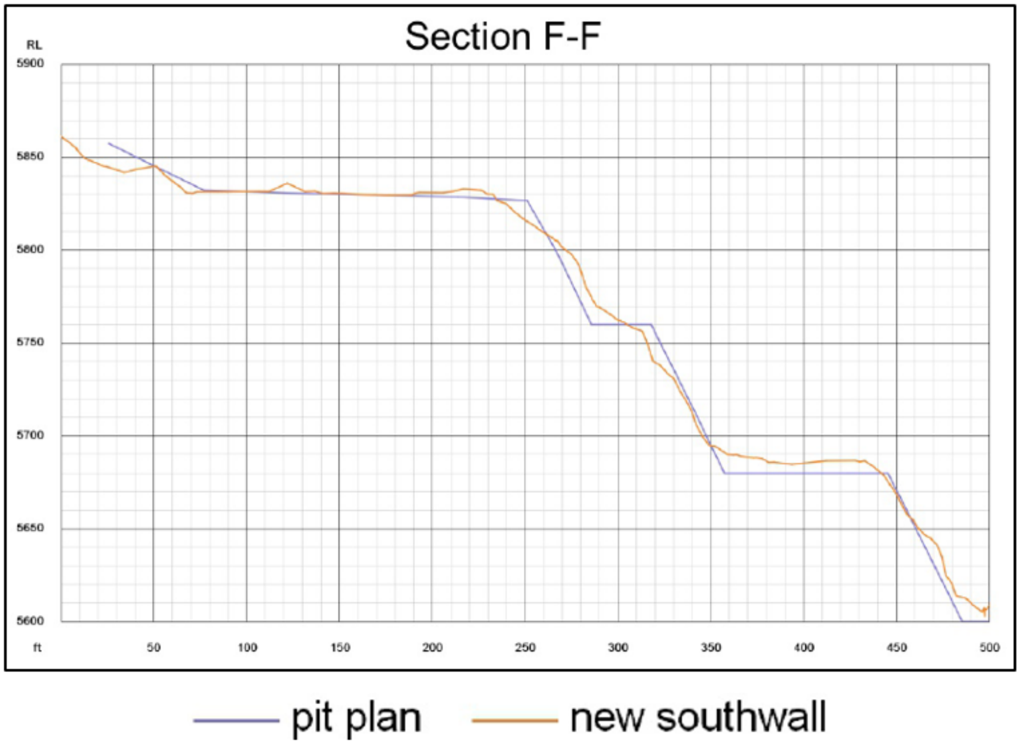

Figure 15: Example of a Cross-Sectional View of Pit Design and Pit As built

The flatter slopes (worst slopes) were selected using the arbitrary sections tool in the create menu in plan view. To ensure that the same slope is selected from the pit plan, the pit plan was overlain on the as built and using the arbitrary sections tool, the slope section was selected. Two to three slopes were selected from each highwall and imported into the Rocfall software for rock fall analysis (See Appendix B).

3.3. Distance Measurements

To obtain the distance measurement data, the ‘color distance from objects’ tool in the color menu was used. The color distance from objects tool compares objects (example the mine as built) against a base or reference object (example the mine plan) and colors the distance between the two objects according to the distance specified in the color scheme editor (Maptek, 2018). This tool allows measurement data to be exported into Microsoft Excel as CSV values for comparing triangulations of as built surfaces against design models to highlight nonconformance.

The same color scheme used for the design conformance was used. The pit design was overlain on the as built. In the color distance from objects dialog box (Figure 16), the pit plan was selected as the base object. Measurement targets was set to closest object. The data is exported as a text file with the coordinates and distance measurement from the pit plan. The data was imported into Microsoft Excel and using the data analysis tool, a histogram was plotted. Table I contains some of the measurement data for the North highwall (See Appendix E for the other high walls).

Table 1 Distance Measurement Data for North Highwall

Eastings E	Northings (N)	Reduced Level (RL)	Distance (D)
143381.8402	136068.4163	6439.596708	26.539203
143058.061	136180.4029	6445.167354	21.500876
142735.3913	136168.2512	6357.081301	2.001096
142467.894	136201.363	6319.592104	25.857219
141808.5687	136178.7769	6140.510319	16.524237
141494.3478	136178.2633	6075.763787	20.070129
142150.8017	135482.5358	5886.723238	161.880835
142674.1355	135328.208	5880.730823	153.153403
143040.1729	135228.8158	5883.192295	135.835693
143391.5311	134464.0807	5884.613169	550.566354
143521.7444	134455.2807	5948.159947	438.578907
143771.0786	135901.7517	6361.255026	122.738043
141524.9643	135759.8588	5961.155938	41.155938
141979.0325	135631.0016	5943.848886	72.315444
141641.2518	135669.9178	5922.564907	71.445911
143101.8565	136134.9929	6433.929208	3.785442
143184.0385	136115.1541	6438.752377	2.846395
143483.5668	135964.1624	6389.045615	2.683808
142539.3239	136161.7313	6322.678975	12.470051

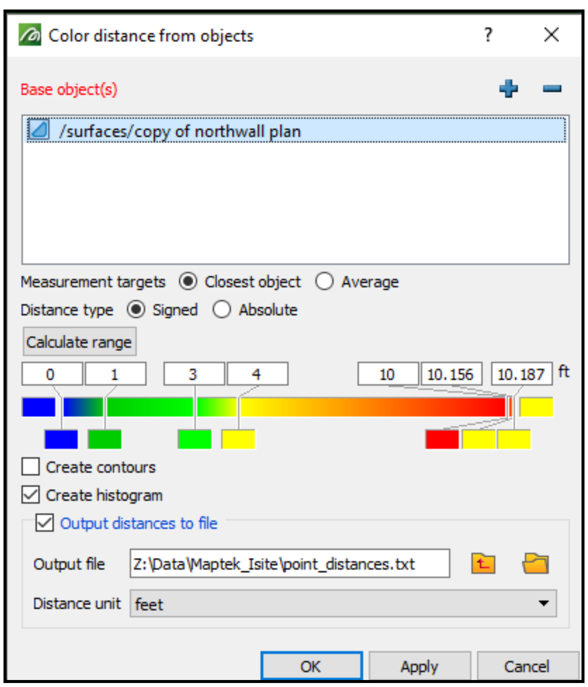

Figure 16: Color from Distance Dialog Box

3.4. Rockfall Analysis

RocFall is a statistical analysis program designed to assist with assessment of slopes at risk for rockfalls (RocScience, 2018). RocFall only accepts slopes in 2D and 3D slopes exported from I-Site Studio were converted into 2D using the UCS command tool in AutoCAD. The slopes were saved as a .DXF file since Rocfall accepts files in .DXF or .CRSP file format.

The imported slope was simplified using the simplify slope tool in the slope menu. This reduces the number of vertices on the slope boundary without distorting the original slope geometry. Slope material properties were assigned to the slope with parameters used for the various materials obtained from Montana Resources and are shown in Table I, below. Figure 17 shows a slope with rocks falling (colored in red) and finally stopping on the ramp (colored in green). The yellow and orange shaded areas are the bench face and bench surface respectively.

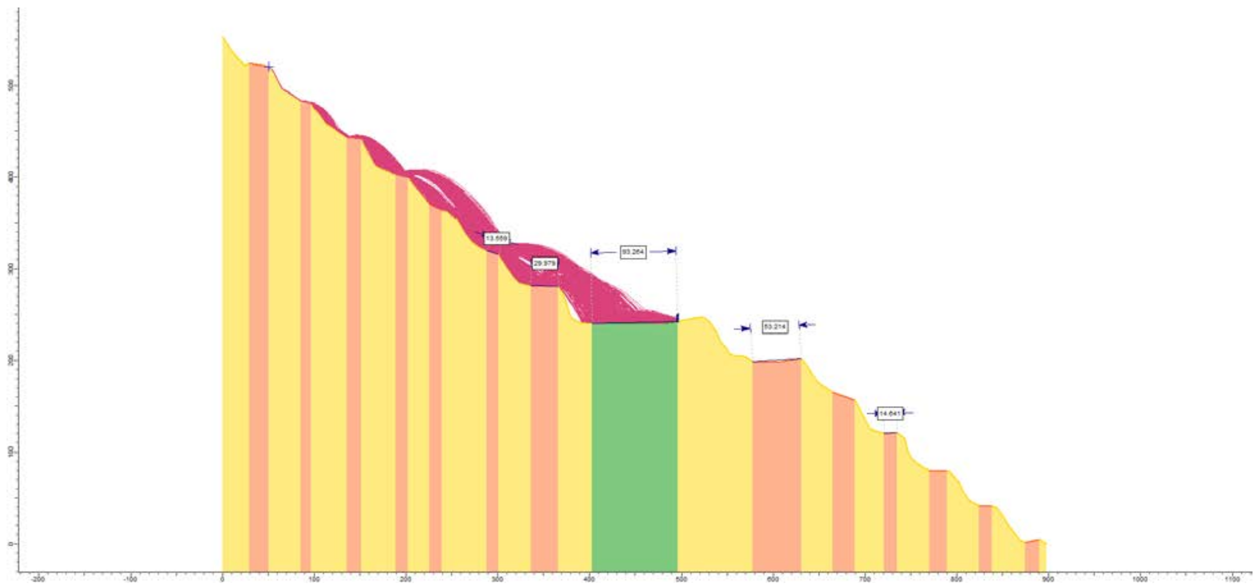

Figure 17: Rockfall in Slope View

Table II: Material Properties Used for Rockfall Analysis

BENCH FILL					
Property	**Distribution**	**Mean**	**Std. Dev.**	**Rel. Min**	**Rel. Max**
Normal Restitution	Normal	0.3	0.02	0.06	0.06
Tangential Restitution	Normal	0.8	0.02	0.06	0.06
Fricton Angle	Normal	38	1	3	3
Slope Roughness	Normal	0	2	6	6
BENCH SURFACE					
Property	**Distribution**	**Mean**	**Std. Dev.**	**Rel. Min**	**Rel. Max**
Normal Restitution	Normal	0.5	0.02	0.06	0.06
Tangential Restitution	Normal	0.9	0.02	0.06	0.06
Fricton Angle	Normal	30	2	6	6
Slope Roughness	Normal	0	2	6	6
ROAD SURFACE					
Property	**Distribution**	**Mean**	**Std. Dev.**	**Rel. Min**	**Rel. Max**
Normal Restitution	Normal	0.35	0.02	0.06	0.06
Tangential Restitution	Normal	0.8	0.02	0.06	0.06
Fricton Angle	Normal	30	2	6	6
Slope Roughness	Normal	0	2	6	6
BENCH FACE					
Property	**Distribution**	**Mean**	**Std. Dev.**	**Rel. Min**	**Rel. Max**
Normal Restitution	Normal	0.35	0.02	0.06	0.06
Tangential Restitution	Normal	0.85	0.02	0.06	0.06
Fricton Angle	Normal	30	2	6	6
Slope Roughness	Normal	0	2	6	6
CONTINENTAL					
Property	**Distribution**	**Mean**	**Std. Dev.**	**Rel. Min**	**Rel. Max**
Normal Restitution	Normal	0.4	0.025	0.075	0.075
Tangential Restitution	Normal	0.85	0.02	0.06	0.06
Fricton Angle	Normal	30	2	6	6
Slope Roughness	None	0	0	0	0

*Std. Dev – Standard Deviation
*Rel. Min – Relative Minimum Value
*Rel. Max – Relative Maximum Value

Barriers were added to the slopes with ramps to help impede the falling rock. The height of the barrier was set at the height of the windrow on the field. The parameters used for defining the barrier is shown in Figure 18.

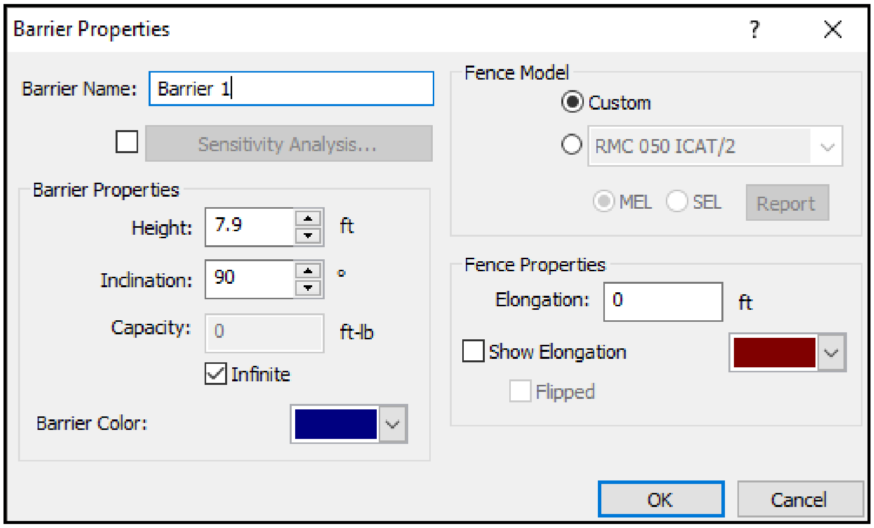

Figure 18: Barrier Parameters

Next, a seeder was added to the slope to simulate a rockfall event. Seeders are the means by which the initial conditions of falling rocks are specified (RocScience, 2018). The number of seeders or seeder locations are unlimited. In this analysis, point seeders were used which specify that all rocks fall from a single starting location at the top of the slope. A total of 1000 rock paths with a rock density of 168.5555 lb. /ft^3 was used. The seeder properties are outlined in Table II.

Table III: Seeder Parameters

SEEDER					
Property	**Distribution**	**Mean**	**Std. Dev.**	**Rel. Min**	**Rel. Max**
Horizontal Velocity	Normal	-0.1	0.1	0.3	0.3
Vertical Velocity	Normal	-0.1	0.1	0.3	0.3
Rotational Velocity	None	0	0	0	0
Initial Rotation	Uniform	0	0	0	360

4. Results and Discussions

The results of the design conformance gave a cross sectional view of how the highwall aligns with the mine plan discussed in section 4.1. The measurement data obtained was used to create a histogram to determine highwall compliance discussed in section 4.2. Rockfall analysis for both pit plan and as-built are presented and discussed in section 4.3.

4.1. Design Conformance

In this section, a cross section of the mine as built highwall and mine design are compared to show areas of alignment, underdig and overdig.

4.1.1. North wall

Figure 19, below, shows the cross section along E-E and M-M. The reduced level (RL) is plotted on the Y-axis with distance (in feet) on the X-axis. Section E-E depicts a slope that aligns closely to the pit plan. At 6120 RL, it is observed that the as-built ramp was achieved as well as some parts of the slope face. Areas of underdig were observed around the bench toe which could be as a result of underbreak at the toe or the bench was not cleaned up after excavation or accumulation of falling rocks.

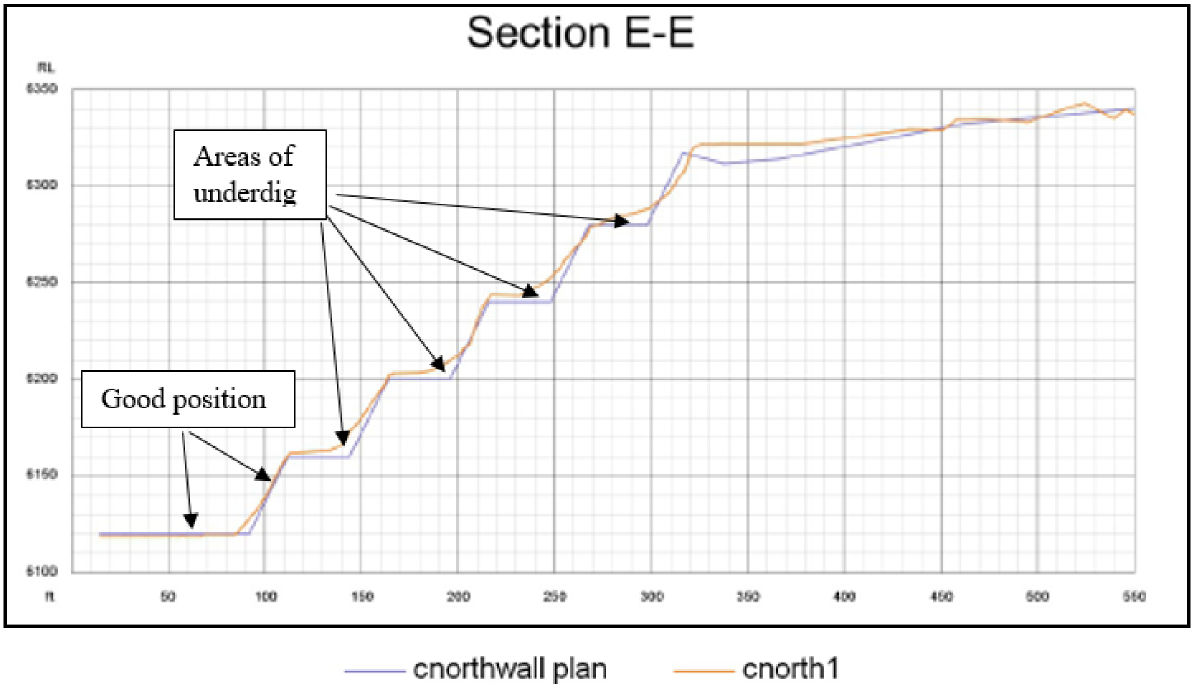

Figure 19: Slope Section of North Wall Showing Close Conformance

The slope section M-M, Figure 20, shows areas of overdig on the 6240 to 6175 RL. Due to this, the bench on 6200 RL was not achieved.

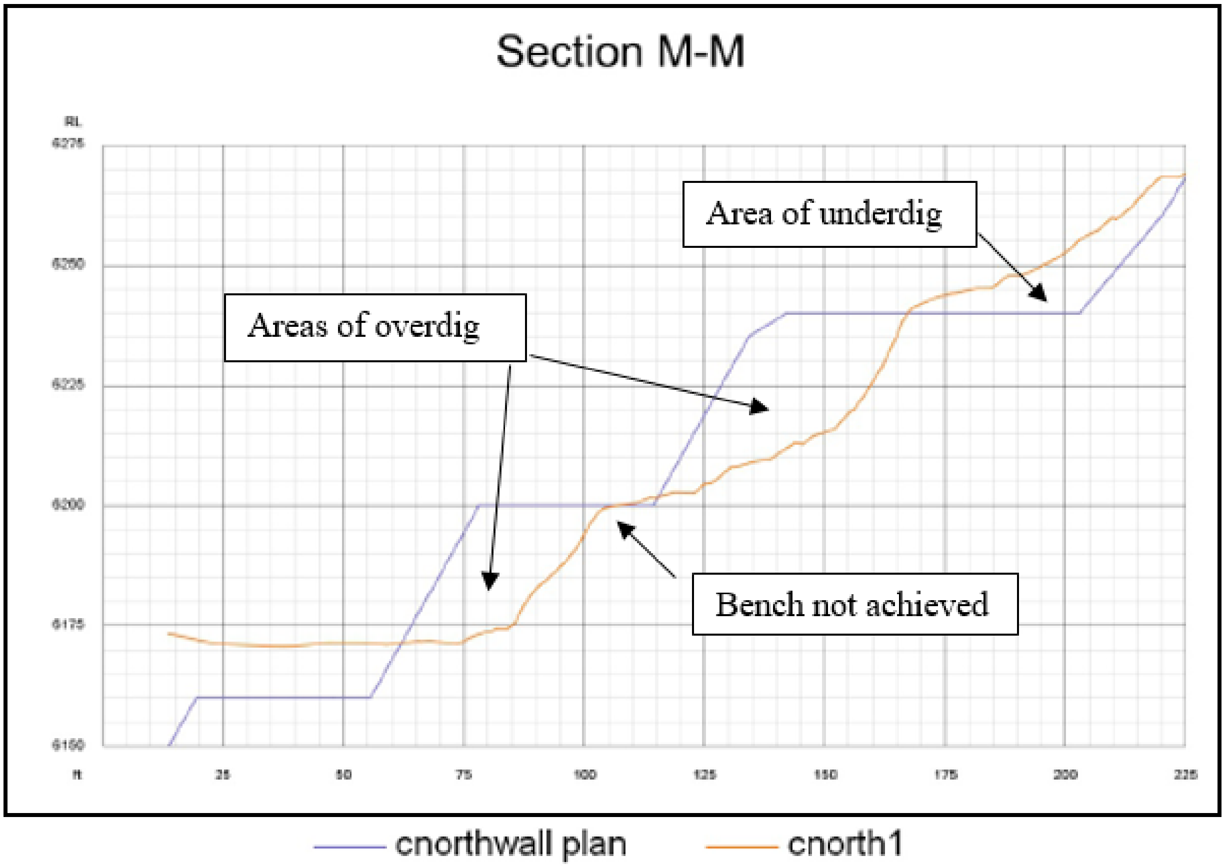

Figure 20: Worst Slope Section of North wall

4.1.2. East wall

In section D-D (Figure 21), it is observed that the slope is in alignment at the 6330, 6155, and 6090 RL. A few underdig areas are observed at 6350, 6200 and 6100 RL and overdig areas at 5845 and 5750 RL. In section G-G (Figure 22), the benches intended to be built on 6080, 6040 and 6000 RL were not achieved creating a flat slope not capable of catching rocks falling from the upper levels.

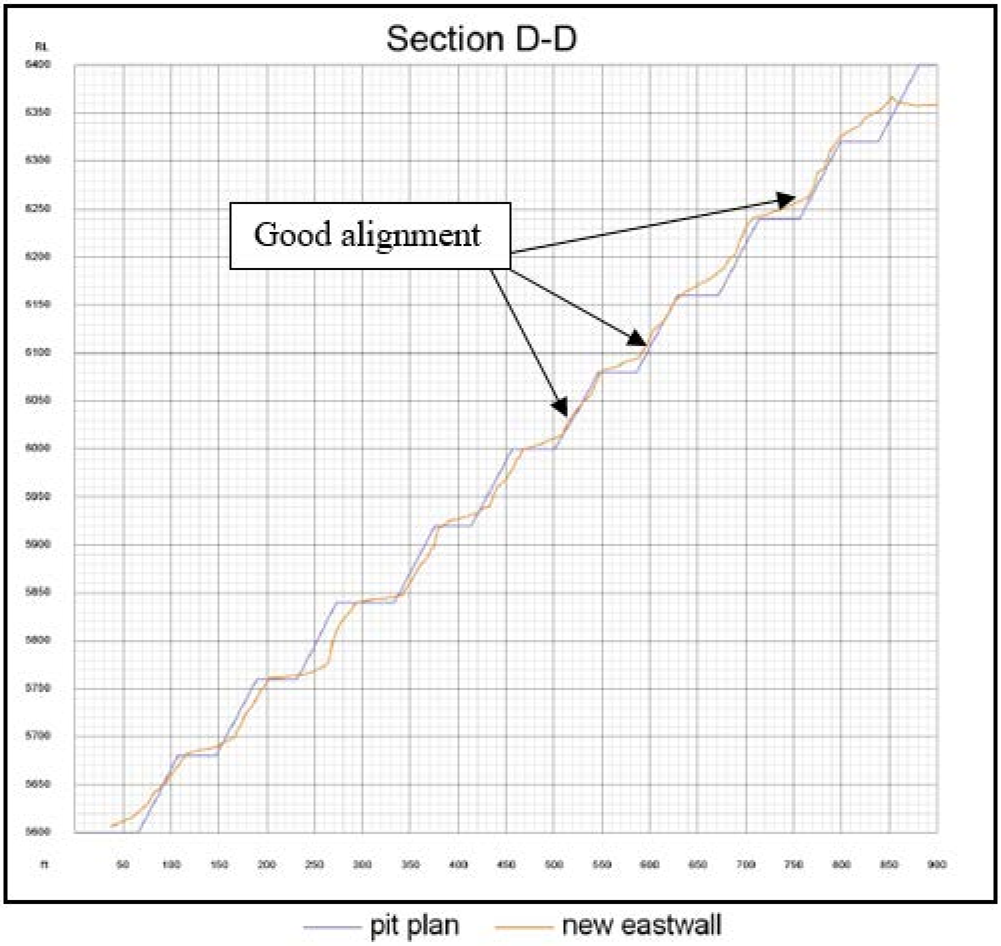

Figure 21: Good Slope Section of East wall

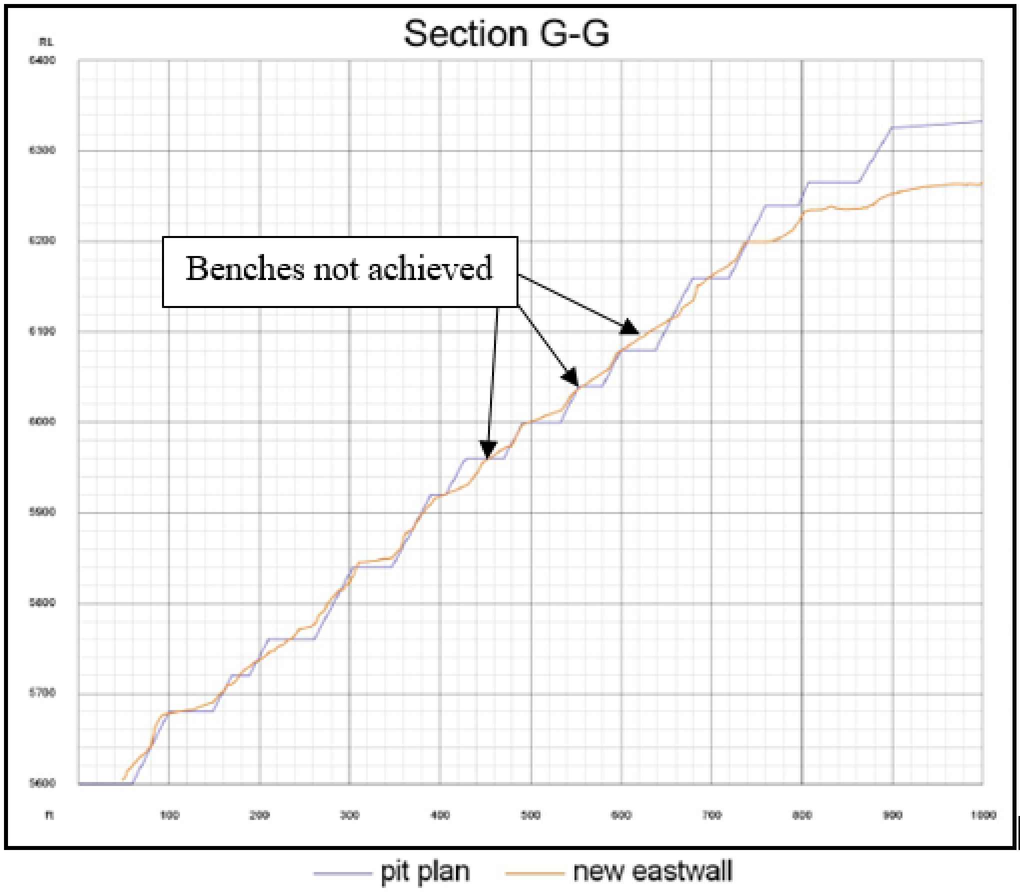

Figure 22: Worst Slope Section of East wall

4.1.3. South wall

Section J-J (Figure 23) generally shows good alignment of the as built with the pit plan. The planned benches were achieved. On the other hand, section M-M (Figure 24) shows four consecutive benches that were not achieved and few areas of underdig and overdig.

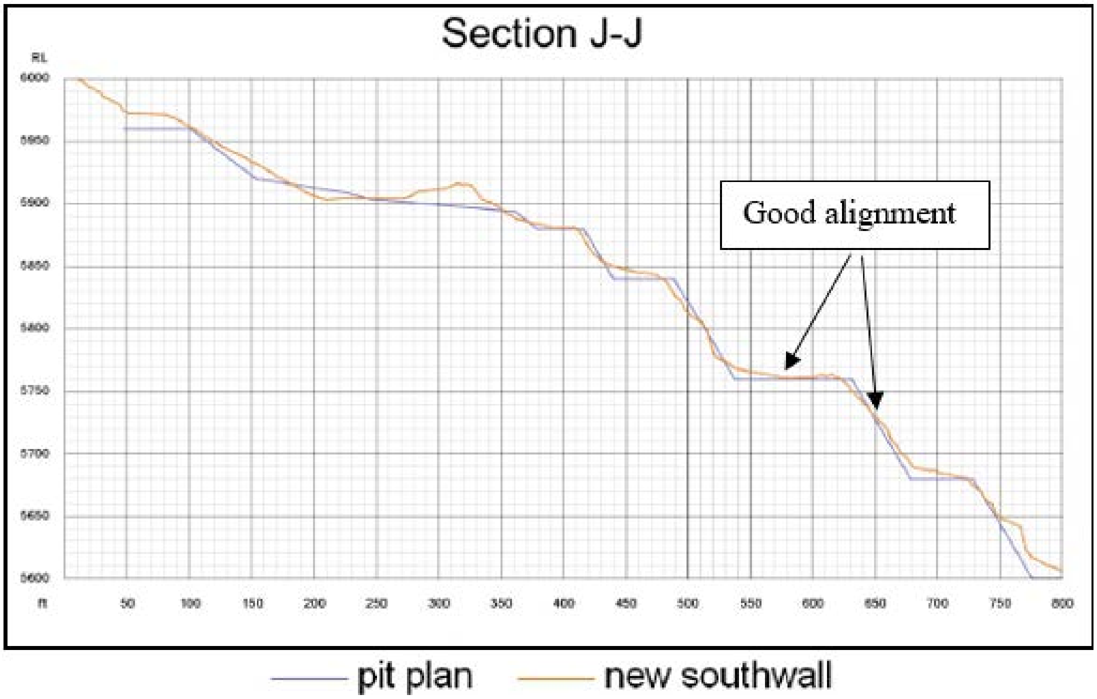

Figure 23: Good Slope Section of South wall

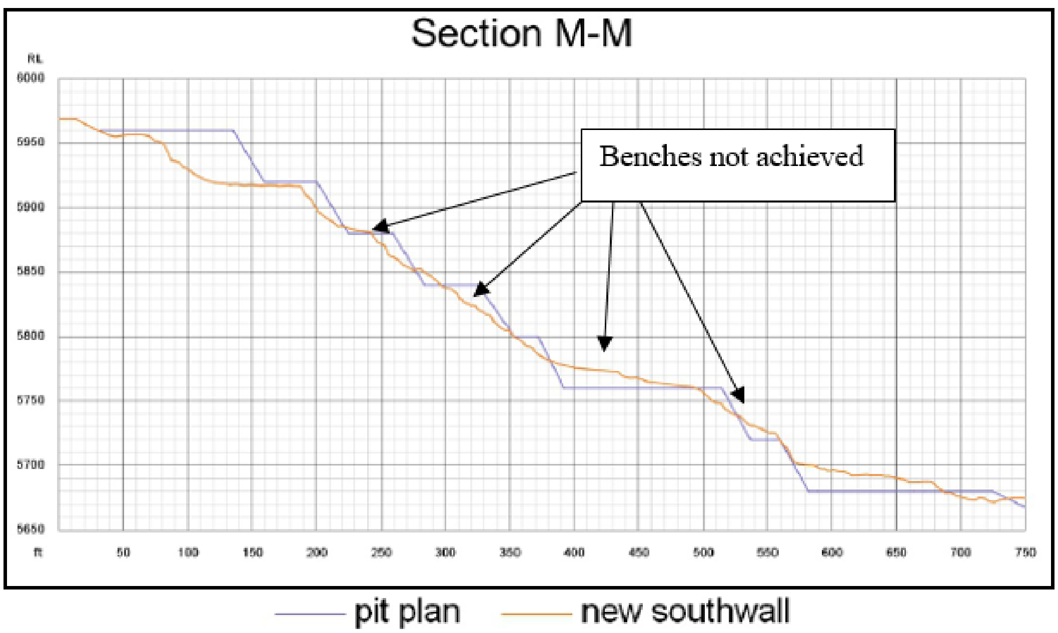

Figure 24: Worst Slope Section of South wall

4.1.4. West wall

Section D-D (Figure 24) generally shows good alignment of the as built with the pit plan. Some of the planned benches were achieved. On the other hand, section J-J (Figure 25) shows three consecutive benches that were not achieved and few areas of underdig and overdig.

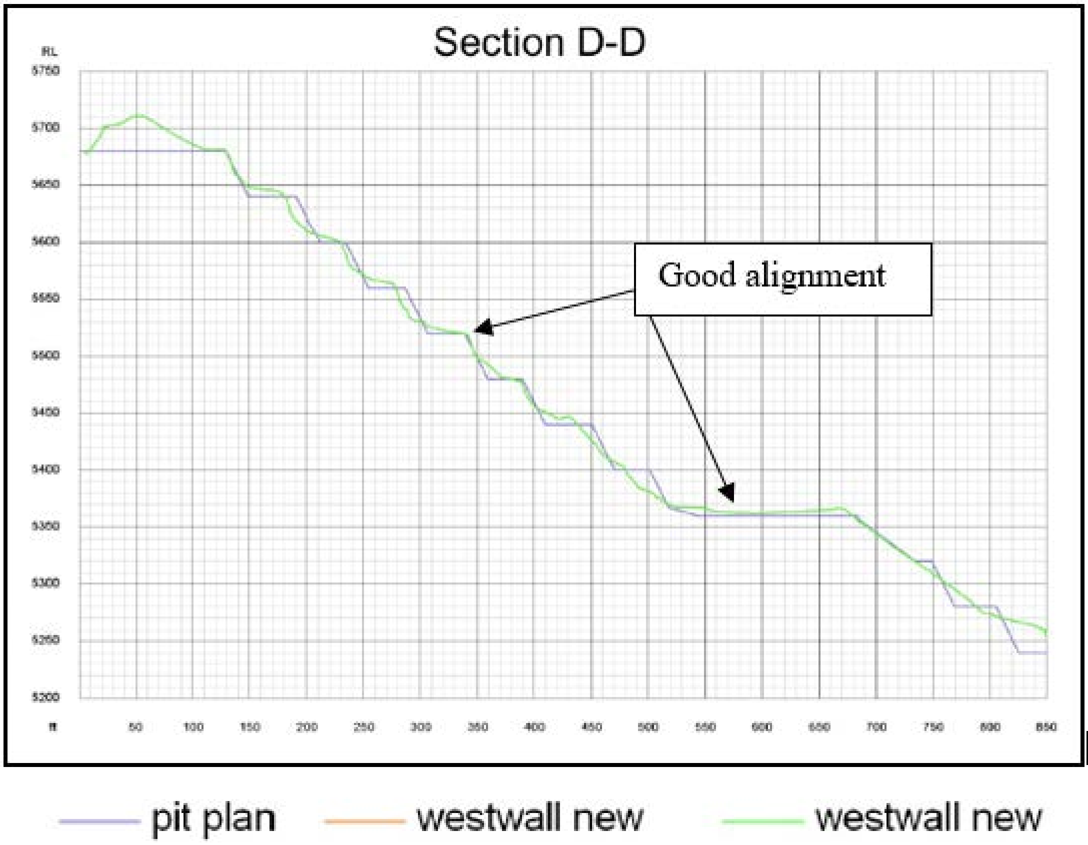

Figure 25: Good Slope of West wall

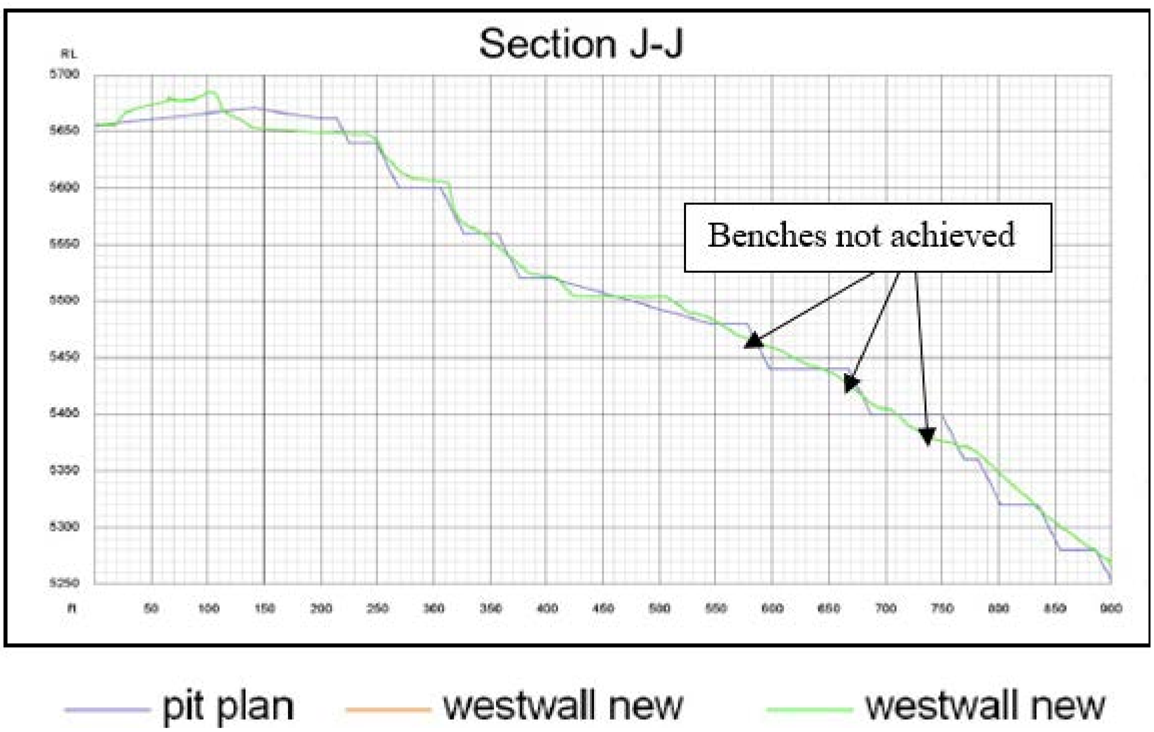

Figure 26: Worst Slope of West wall

4.1.5. East wall double bench

Section H-H (Figure 27) shows good highwall alignment whereas section E-E (Figure 28) shows areas of overdig at the 5600 and 5520 RL hence the bench at 5520RL was not achieved.

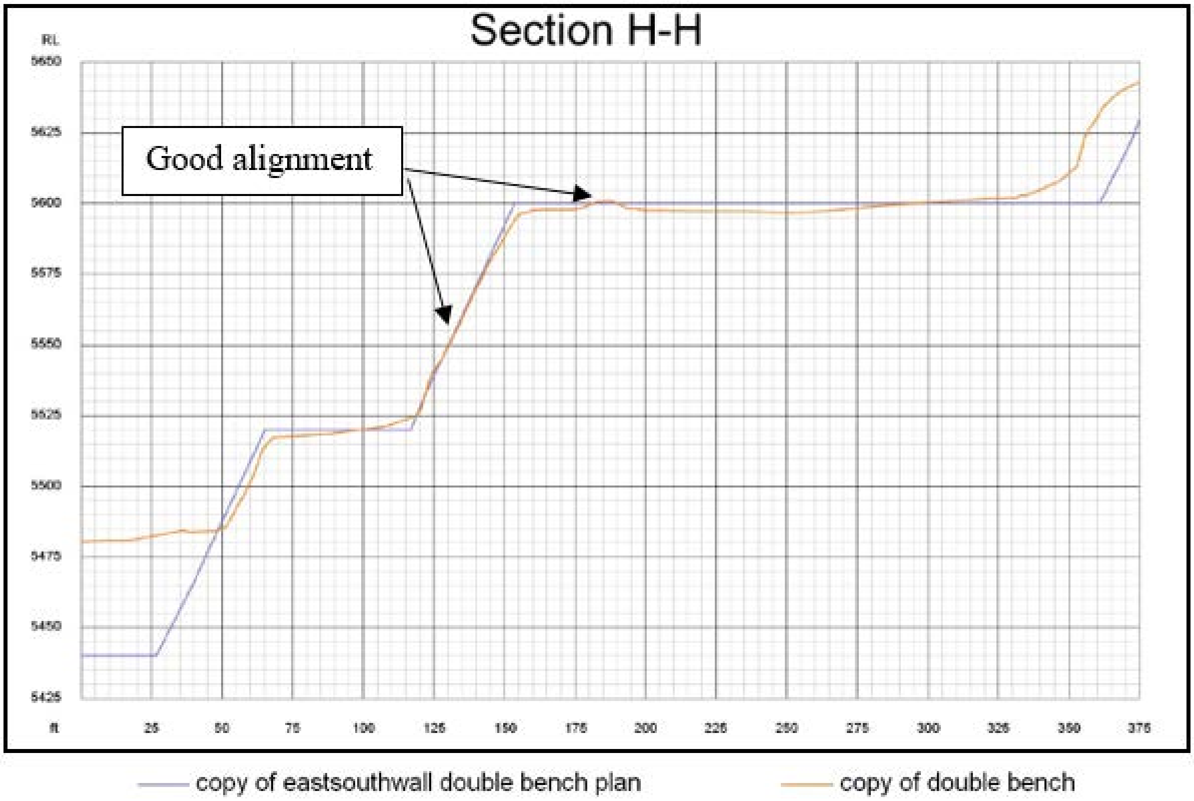

Figure 27: Good Slope of Double Bench

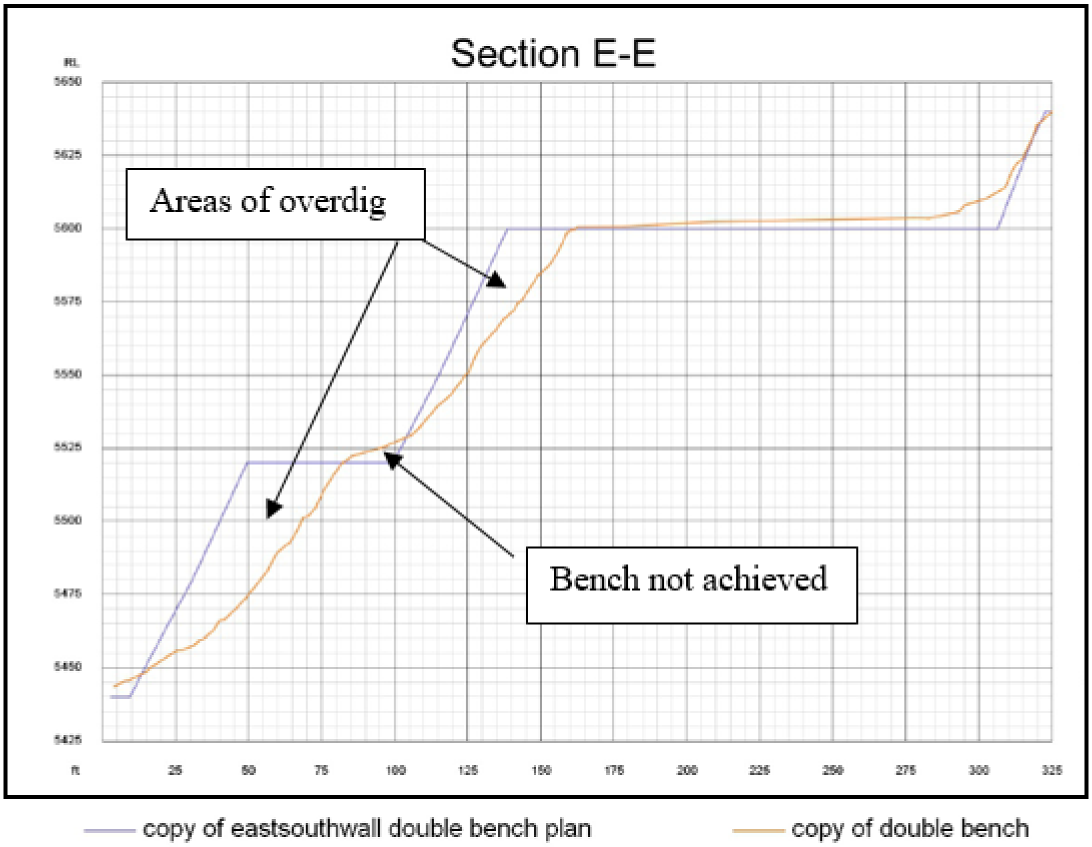

Figure 28: Worst Slope of Double Bench

4.2. Highwall Compliance

In order to measure performance of the highwall, a target of 80% was assumed for distances within 3 ft. of design and 100% for distances within 4 ft. of design. The percentage of each distance range was calculated using Equation 1 and plotted as a histogram.

$$\text{Percentage} = \frac{\textit{Frequency of each distance}}{\textit{Total frequency}} \times 100 \tag{1}$$

Ideally, there should be no variance between the plan and as-built but the effects of blasting and excavation coupled with the rock mass characteristics of the rocks present makes this impossible. The compliance of each highwall is shown in Appendix C.

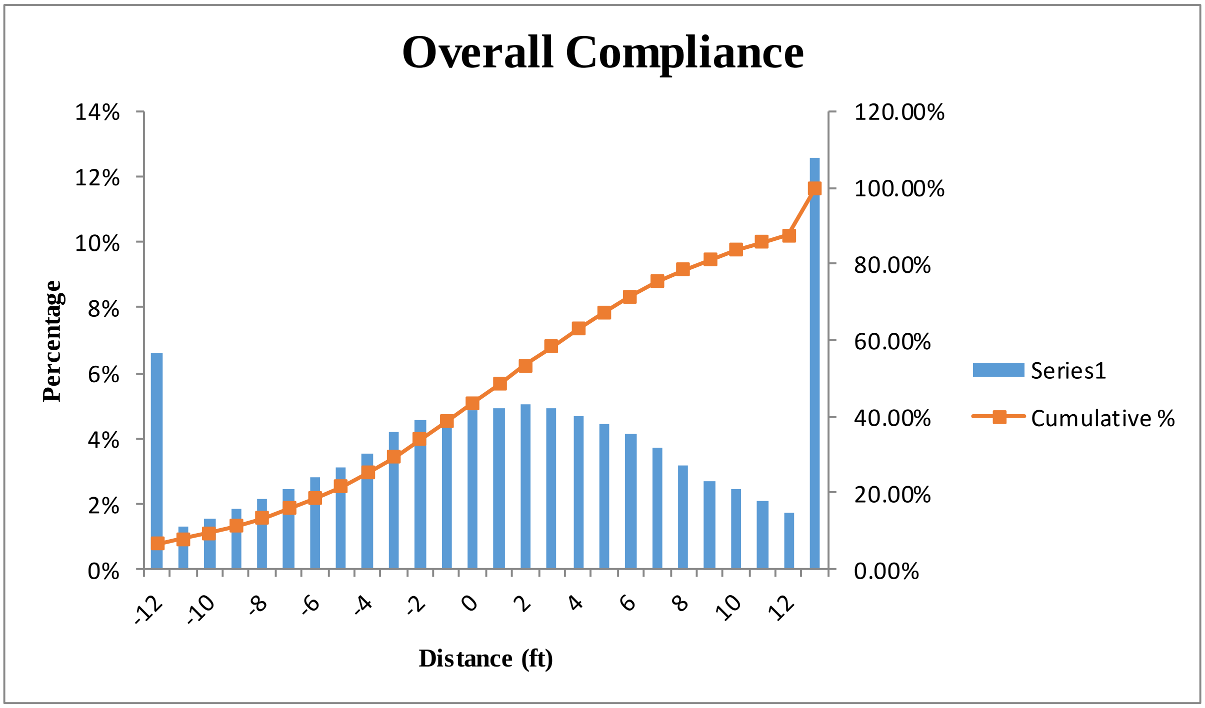

Figure 29: Overall Highwall Compliance

4.3. Rockfall Analysis

The results of a simulated rockfall event with 1000 rock paths is presented in this section. Appendix D shows the rock paths in slope view.

4.3.1. North wall

The rock path end location graph is the result of the rock fall analysis showing the distribution of rocks stopped at various locations on the slope. Ideally, most rocks should be stopped at the first or second bench on the slope as shown in Figure 29 but on the as built slope, the rocks were stopped by the barrier on the ramp. The rocks in the plan traveled down 45 feet from the point of failure (located at 36 feet) and stopped on the second bench with 34 rocks on the first bench and 966 rocks on the second bench. The average movement on the north wall plan was 34 feet. On the other hand, the rocks (Figure 30) in the as built traveled down 494 feet with 174 rocks stopped on the first bench and 433 rocks finally stopping on the ramp. On the second slope (Appendix D), the rocks traveled 250 feet down the slope. On the average, rocks travel 372 feet around the north highwall.

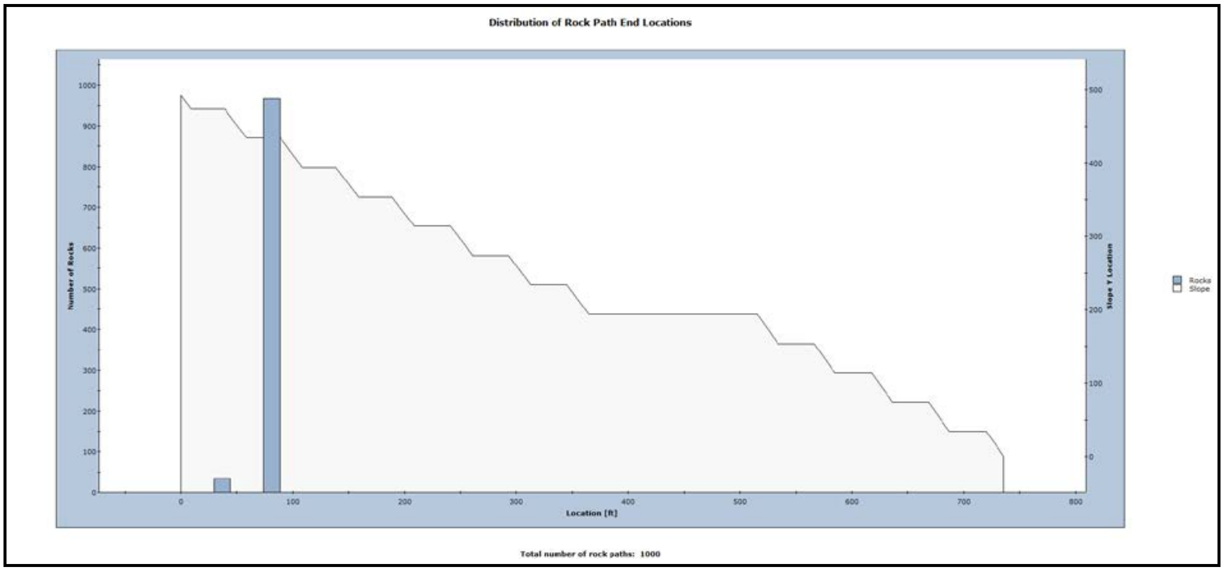

Figure 30: Rock Path End Location for North Wall Plan

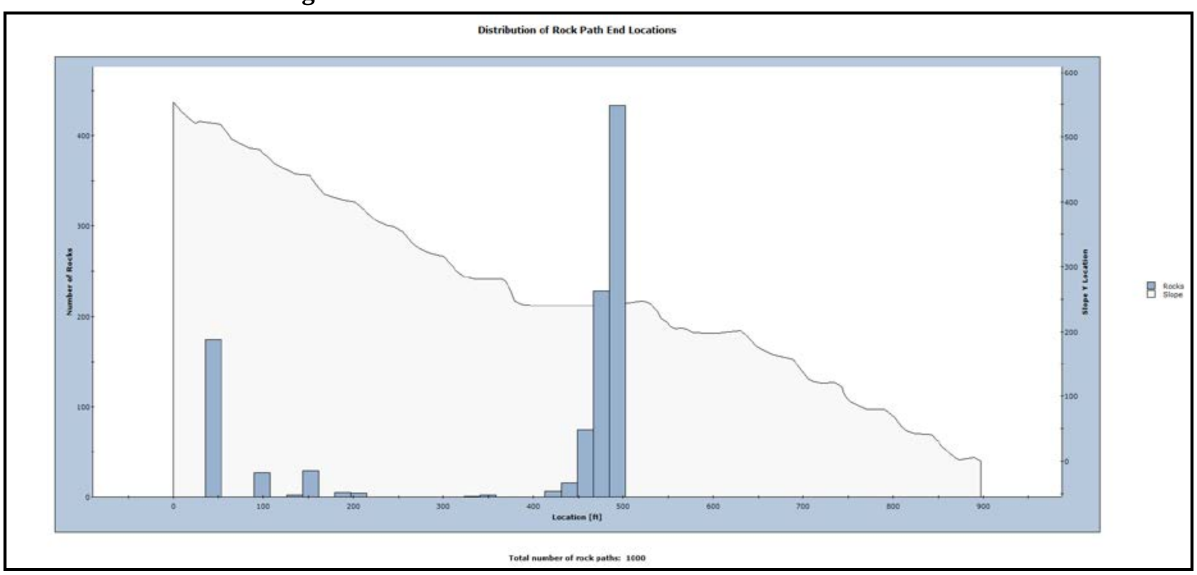

Figure 31: Rock Path End Location for North Wall As built

4.3.2. East wall

On the east wall plan, all 1000 rocks were retained on the first bench and traveled 48 feet down the slope whereas on the as built, rocks traveled 907 feet down the slope with 779 rocks retained on the second bench. The rest of the rocks were stopped on the subsequent benches and finally stopped on the lower double bench as shown in Figure 32. The bench fill material from 300 to 800 feet on the slope retarded the movement of the rocks since they have a low coefficient of restitution. The other two slopes selected from the east wall had rocks traveling down 408 feet on the second slope and 1031 feet on the third slope. The average distance traveled was 782 feet.

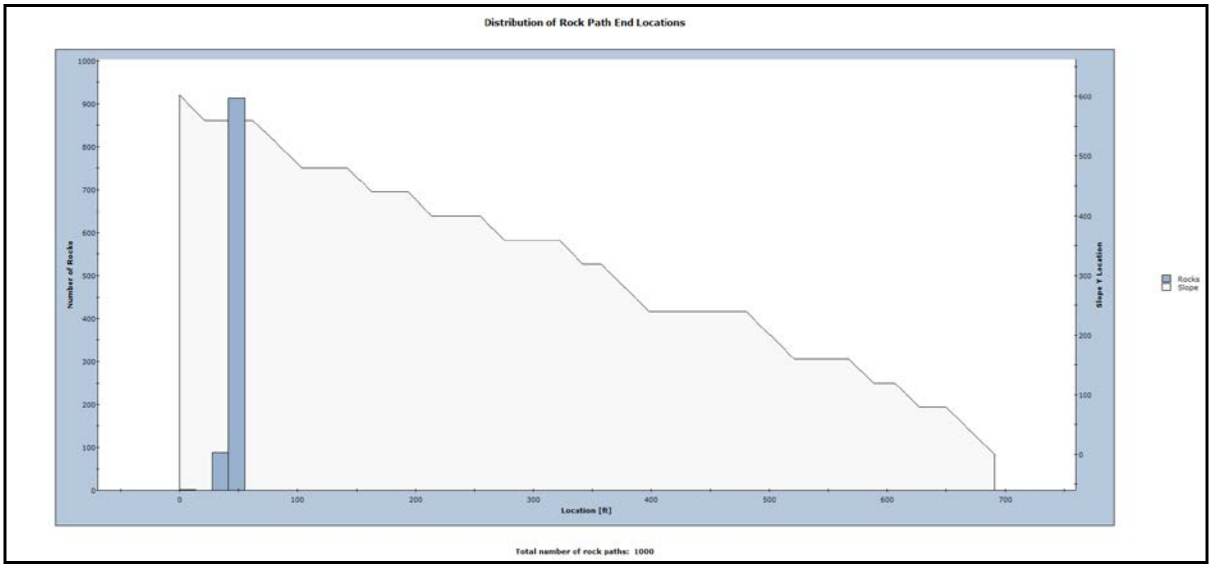

Figure 32: Rock Path End Location for East Wall Plan

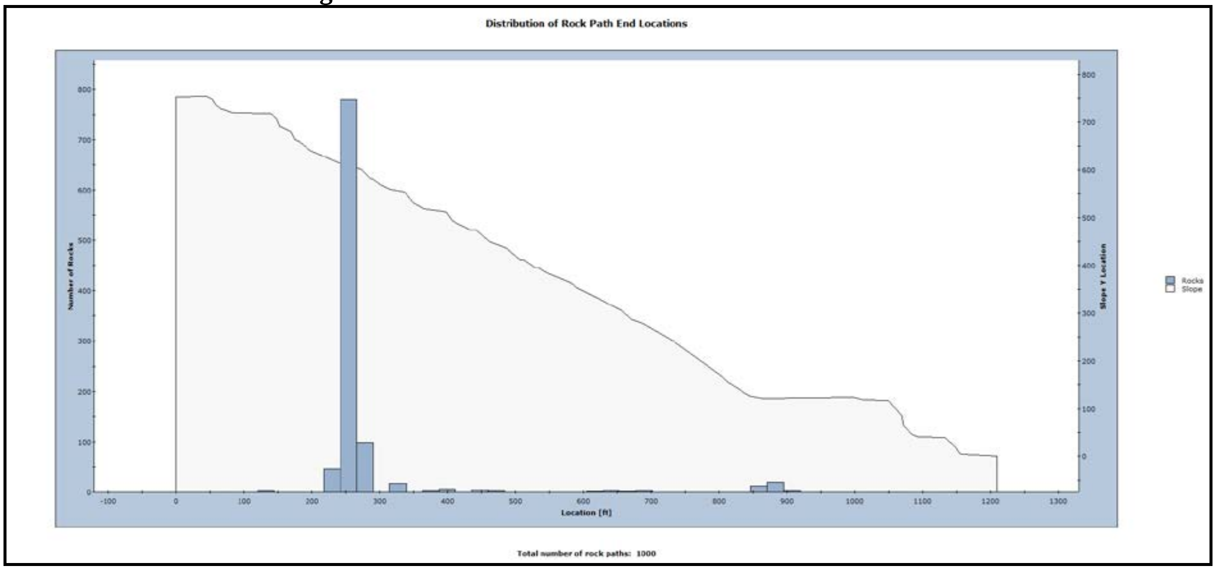

Figure 33: Rock Path End Location for East Wall As built

4.3.3. South wall

Rocks on the south wall plan (Figure 34) were also retained on the first bench. On the as built (Figure 35), the rocks traveled down 249 feet and stopped on the third bench for the first slope. On the second slope (Appendix B), the rocks moved 389 feet to the end of the slope. The average distance moved was 319 feet.

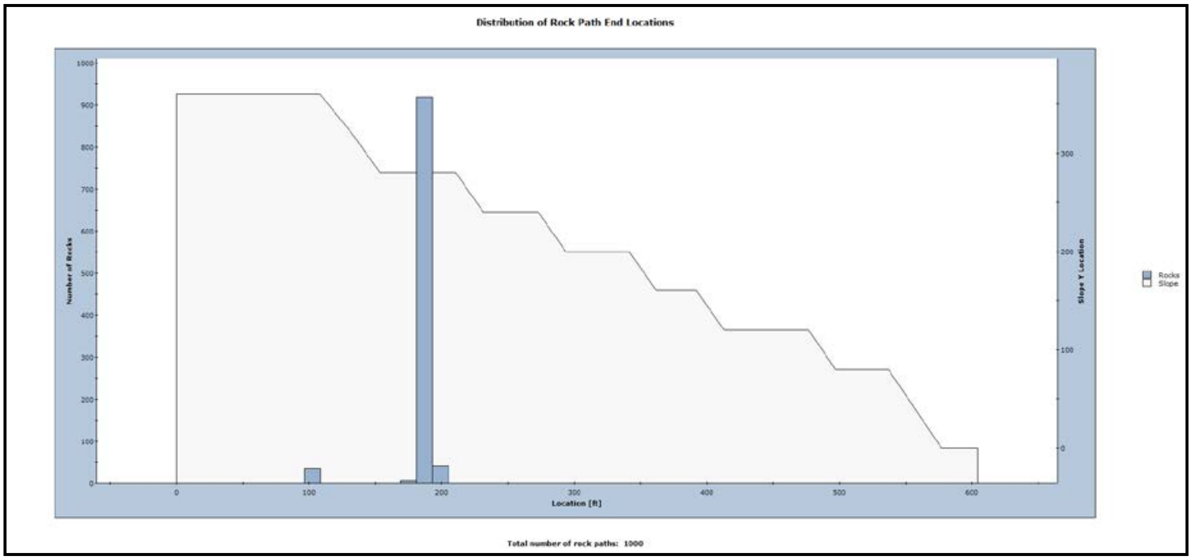

Figure 34: Rock Path End Location for South Wall Plan

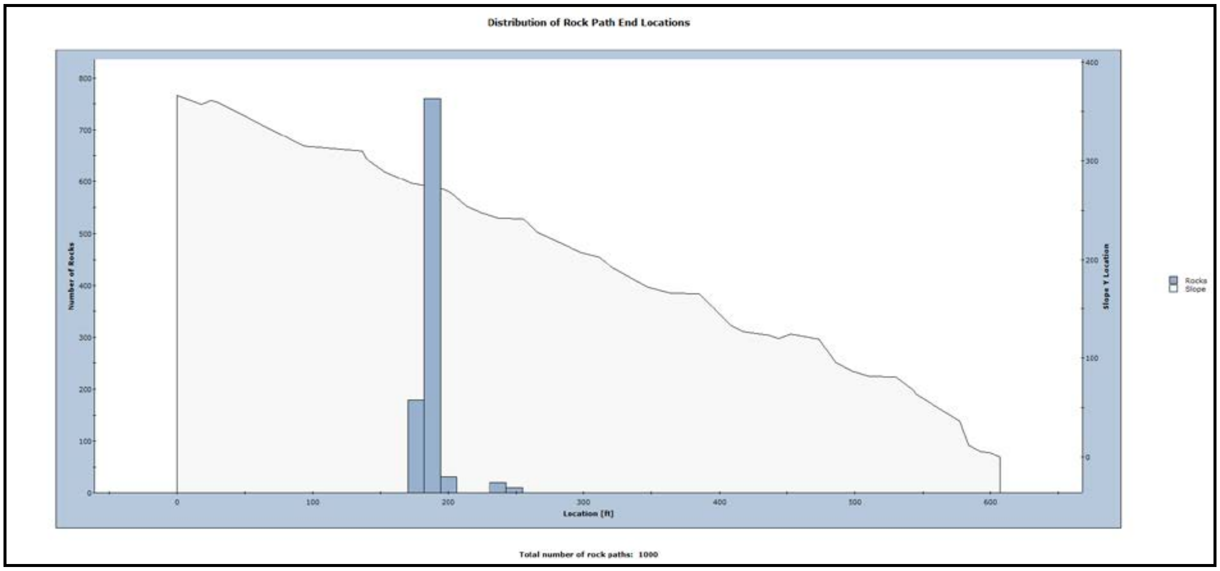

Figure 35: Rock Path End Location for South Wall As built

4.3.4. West Wall

The rocks on the as built west wall moved 380 feet from the point of failure. On the second and third slope, rocks moved 888 feet and 30 feet respectively. The third slope consists of fill material which retarded the movement of the falling rocks. The average distance moved was 433 feet.

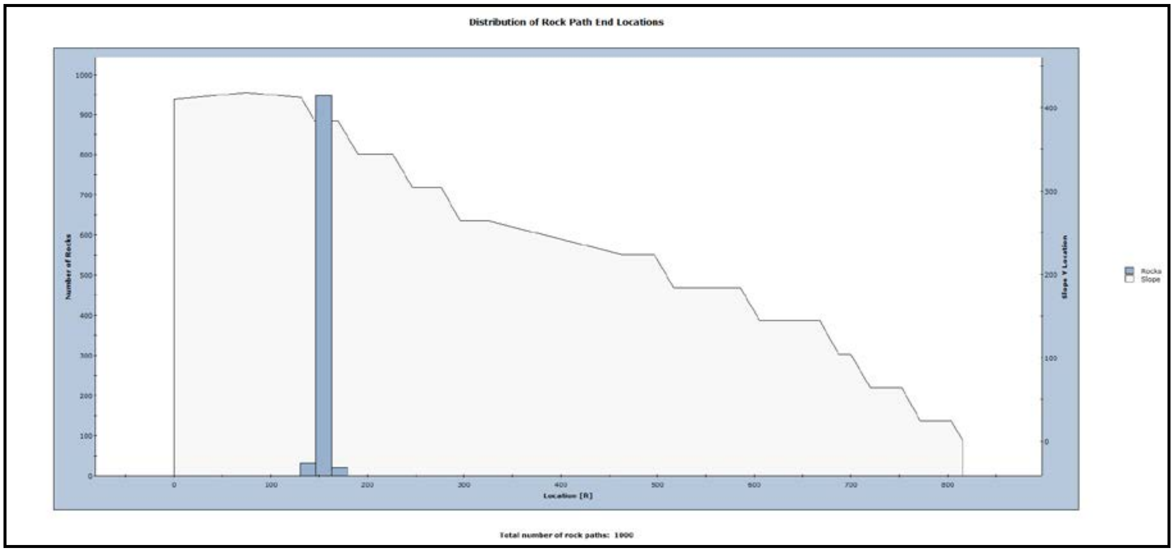

Figure 36: Rock Path End Location for West Wall Plan

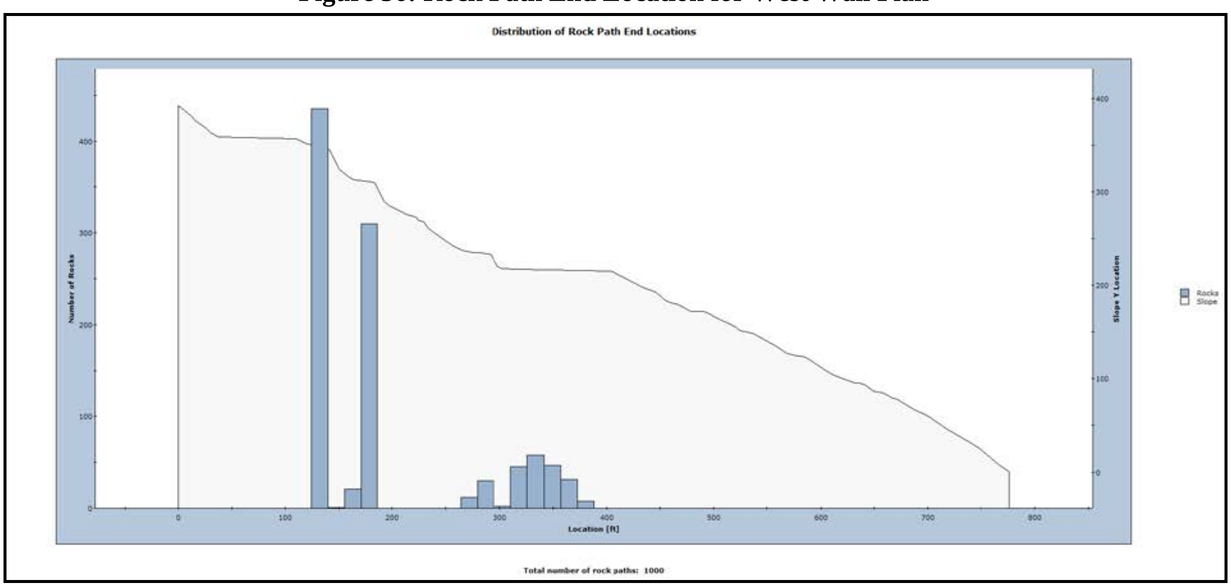

Figure 37: Rock Path End Location for West Wall As-built

A summary of the average distance traveled on each highwall is shown in Table III below. It was observed that rocks on the east wall traveled farther than rocks on the other highwall. From the cross-sectional views in Appendix A, most of the benches on the east wall was not achieved therefore the rocks traveled farther down the slope.

Table IV: Summary of Average Distance Traveled by Rock on Each Highwall

Section	Average Distance Traveled (feet) on Mine Design	Average Distance Traveled (feet) on Mine As Built
North wall	34	372
East wall	43	782
South wall	68	319
West wall	46	433

To evaluate the effects of noncompliance on the potential of rockfall, the compliance of each slope was determined together with the rockfall movement on each slope as shown in Table V. The compliance of the slopes selected from the East wall ranged from 19% to 48% while slopes on the North, South and West walls ranged from 33% to 48%, 26% to 53% and 24% to 49% respectively. The rockfall increased greatly on the East wall slopes, followed by the West, North and South walls. This confirms that noncompliance with the mine design has an effect on the potential of rockfall.

Table V: Compliance of each Slope Section with Percentage Increase of Rockfall

Slope sections	Compliance (%)		Rockfall Movement (feet)		
	± 3 feet	± 4 feet	Plan	Actual	% Increase
North wall Slope 1	33	42	45	449	898
North wall Slope 2	44	48	22	200	808
East wall Slope 1	30	38	48	1,026	2,038
East wall Slope 2	39	48	30	774	2,481
East wall Slope 3	19	24	48	393	720
South wall Slope 1	26	36	89	109	23
South wall Slope 2	40	53	47	330	602
West wall Slope 1	40	49	48	626	1,205
West wall Slope 2	24	32	32	248	676
West wall Slope 3	38	48	55	25	-54

5. Conclusion

From the results of the data analysis, the following conclusions were made;

- The design conformance of each highwall showed that the as-built slopes were flatter than the design slopes. It also highlighted areas of underdig and overdig caused by either underbreak at the toe and overbreak along the entire slope face or mining less or more material.
- The highwall was not in compliance with the design and showed that the mine was mining less material (under digging). There was 33% of the as built within 3 feet of design and 41% within 4 feet of design.
- The rock fall analysis showed that rocks travel farther at the east and west walls followed by the north wall. Rocks travel much less at the south wall.
- Noncompliance with the mine design has an effect on the potential of rockfall.

6. Recommendations

The process outlined in this study should be adopted by the mine to measure performance of final pit highwall. The design conformance tool in I-Site helps to highlight areas that are in alignment with the mine design. A study of the bench face should be done when a final highwall is exposed to know the blast performance and help make adjustments to the blast design.

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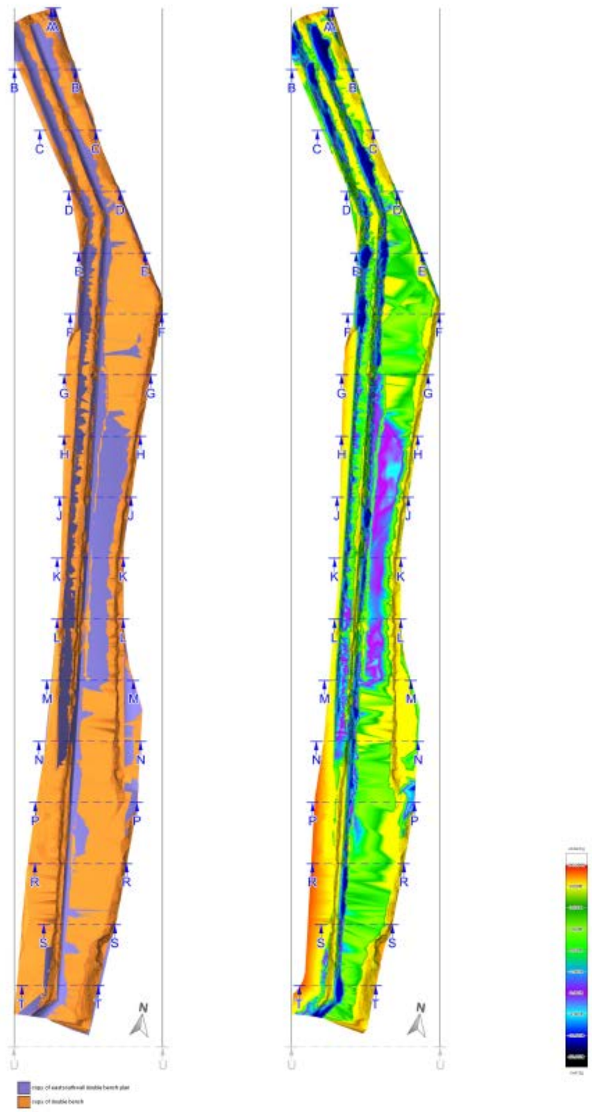
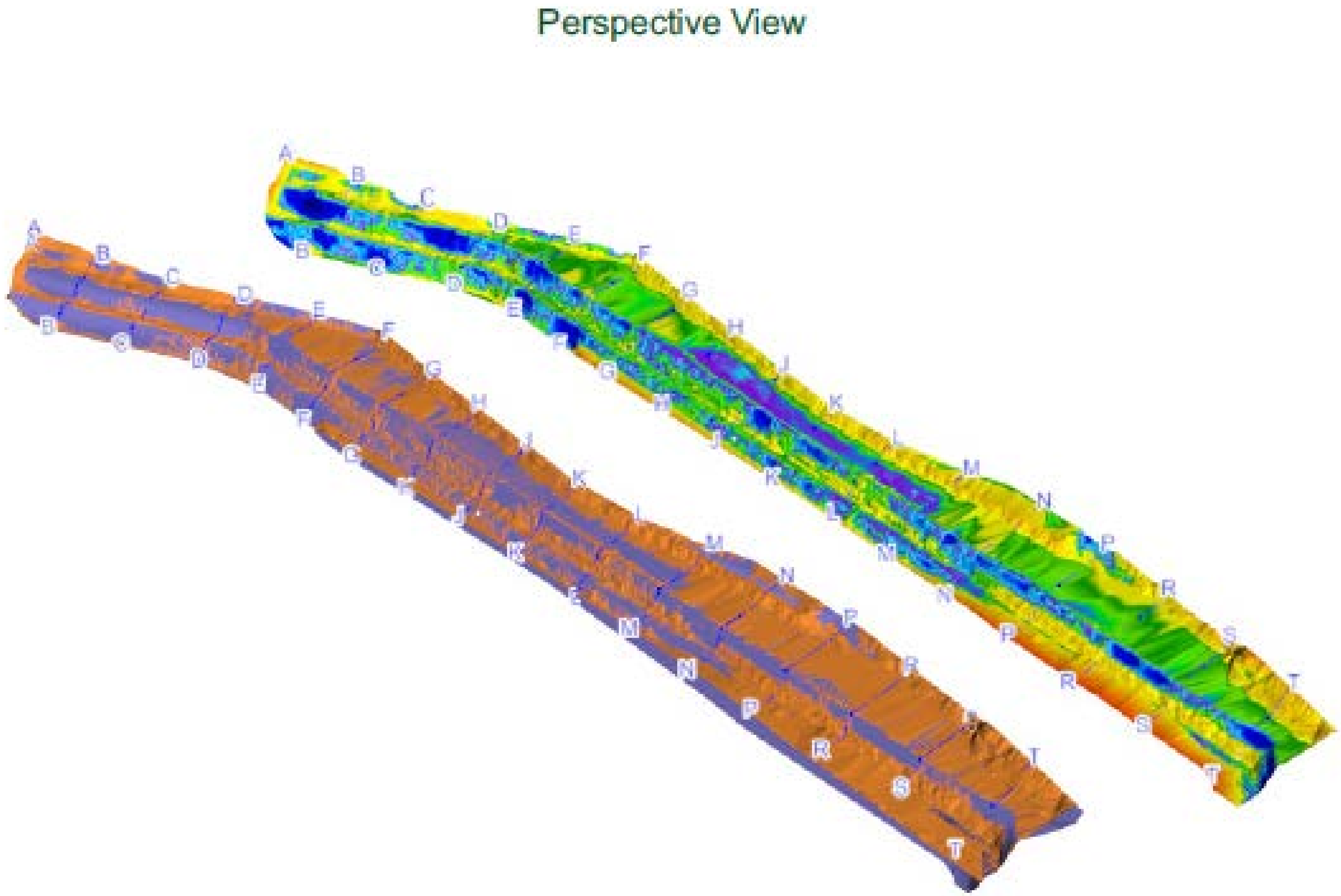
8. APPENDIX A: CROSS SECTIONAL VIEWS OF EACH HIGHWALL

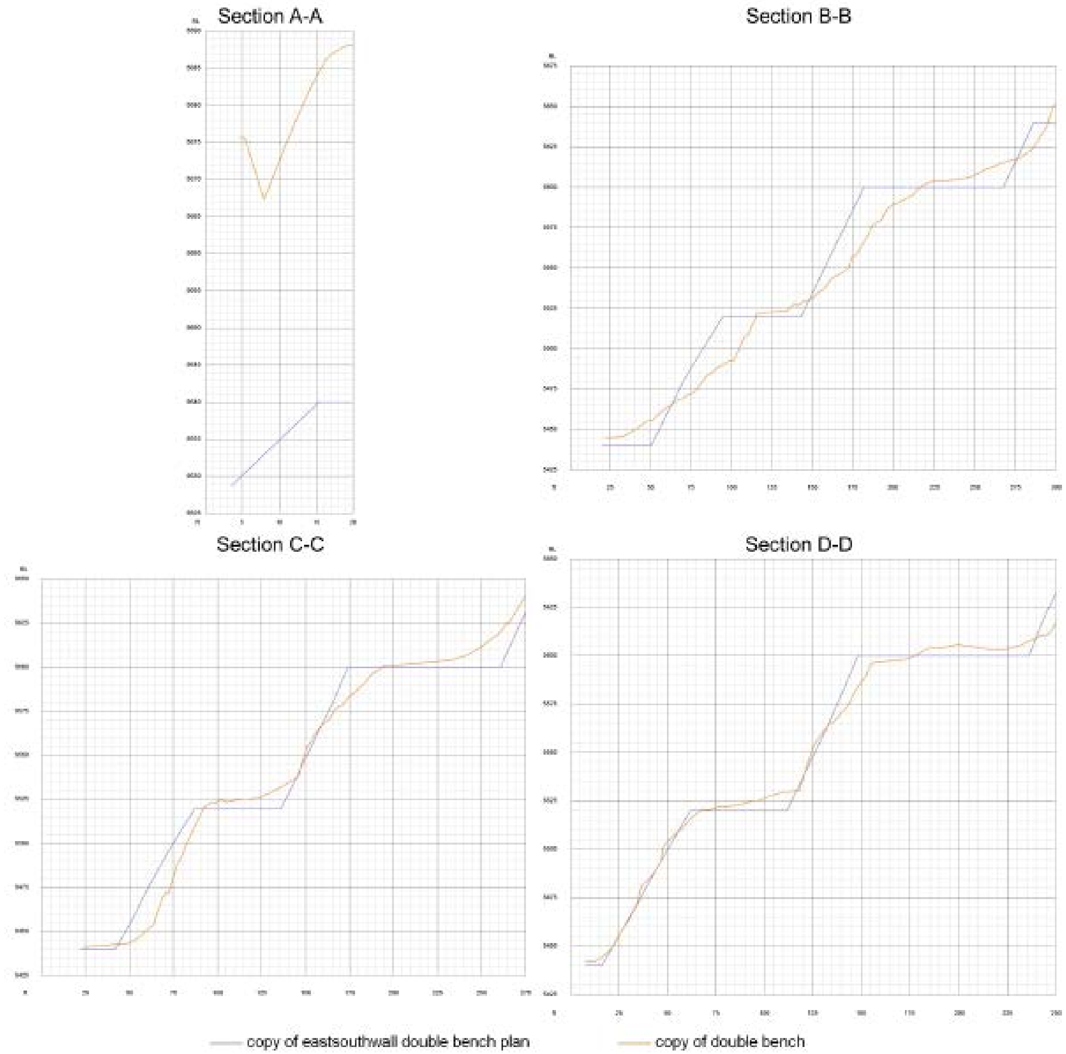
The figures below show the design conformance report for each highwall.

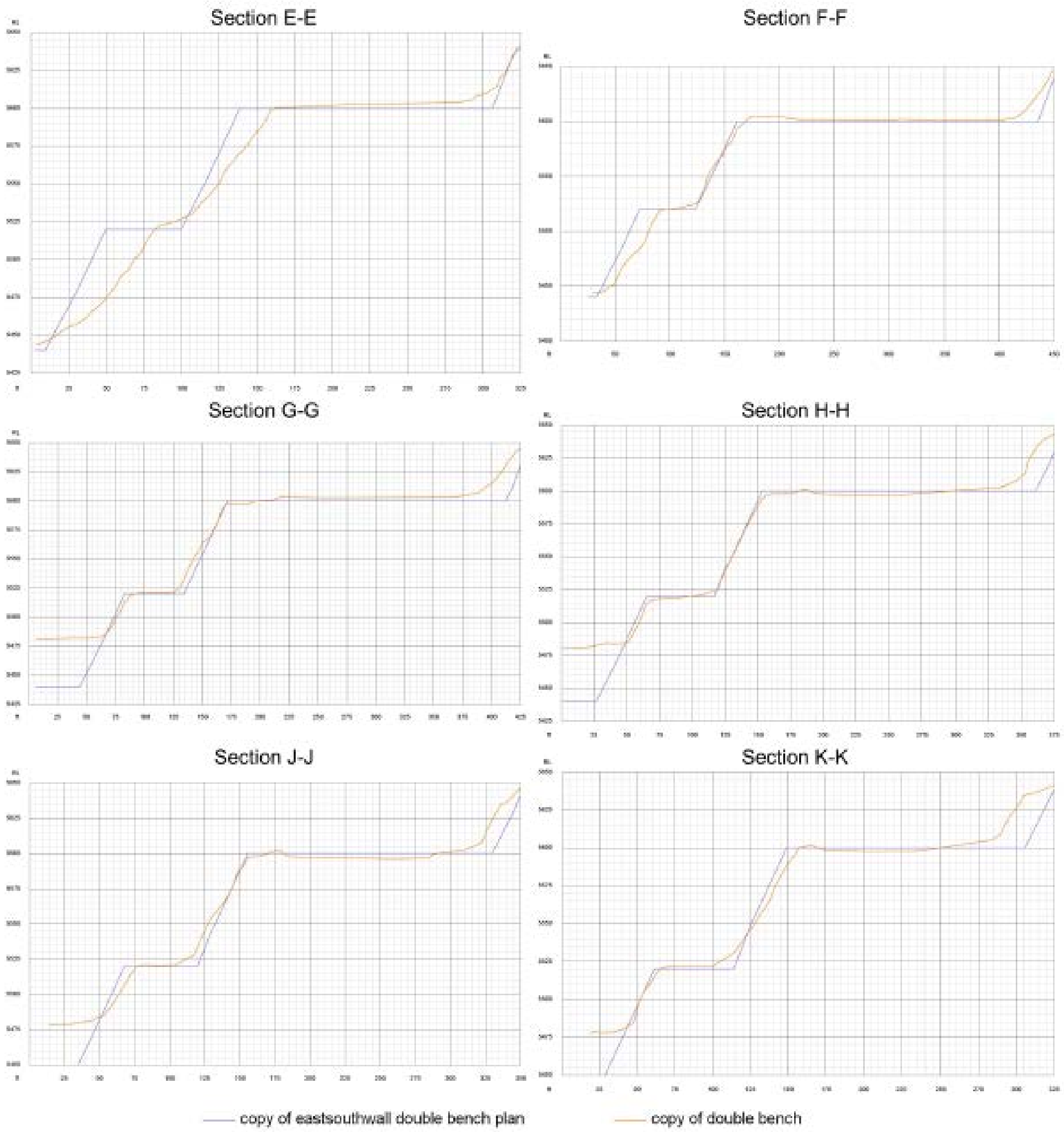
Design: copy of eastsouthwall double bench plan
As-built: copy of double bench

Plan View






Section A-A
Section B-B
Section C-C
Section D-D
copy of eastsouthwall double bench plan
copy of double bench



Section E-E
Section F-F
Section G-G
Section H-H
Section J-J
Section K-K
copy of eastsouthwall double bench plan
copy of double bench

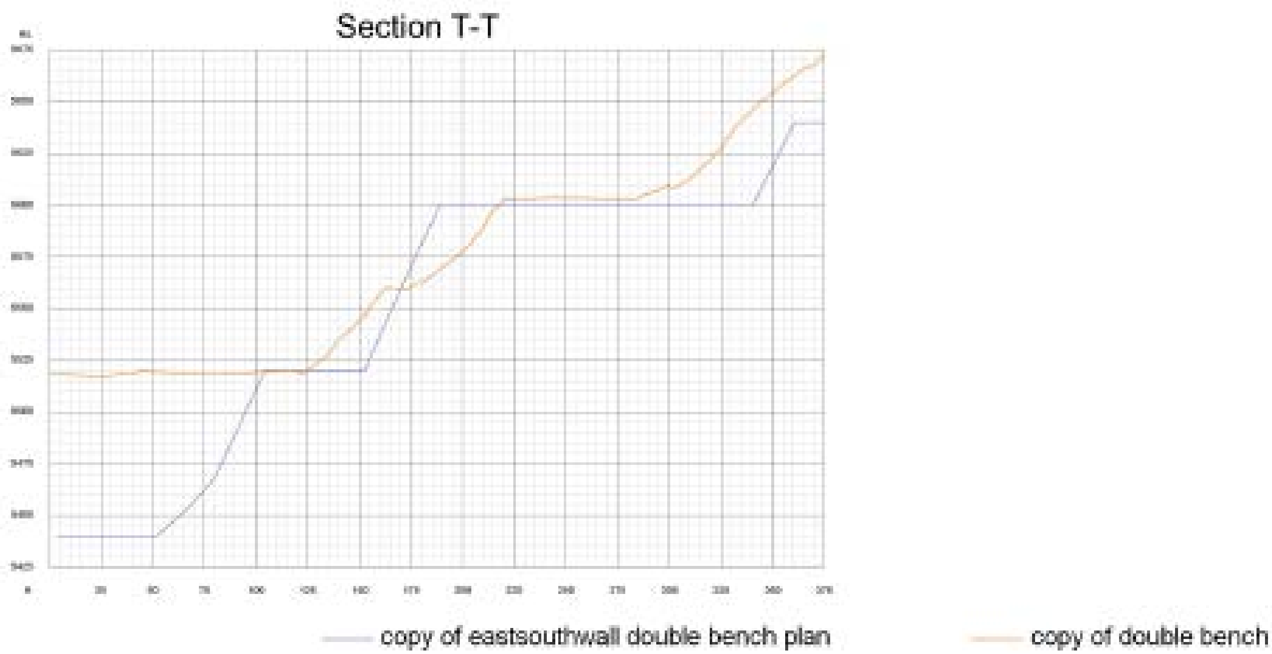
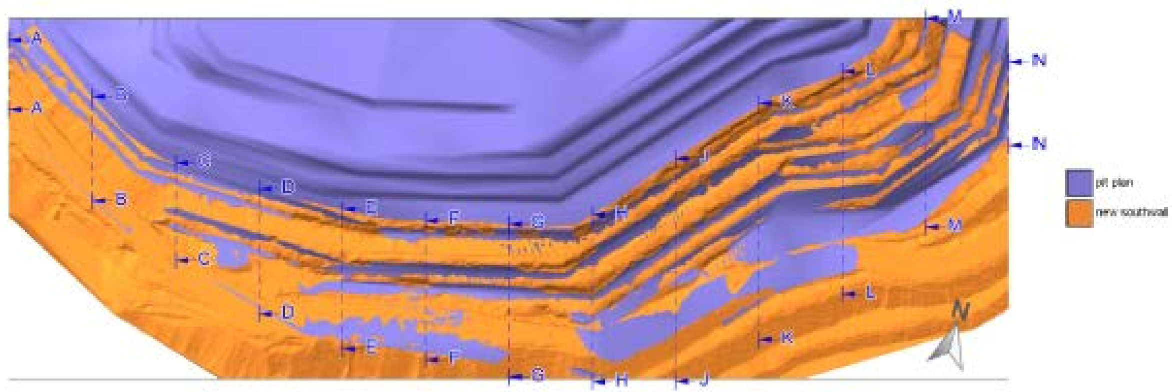
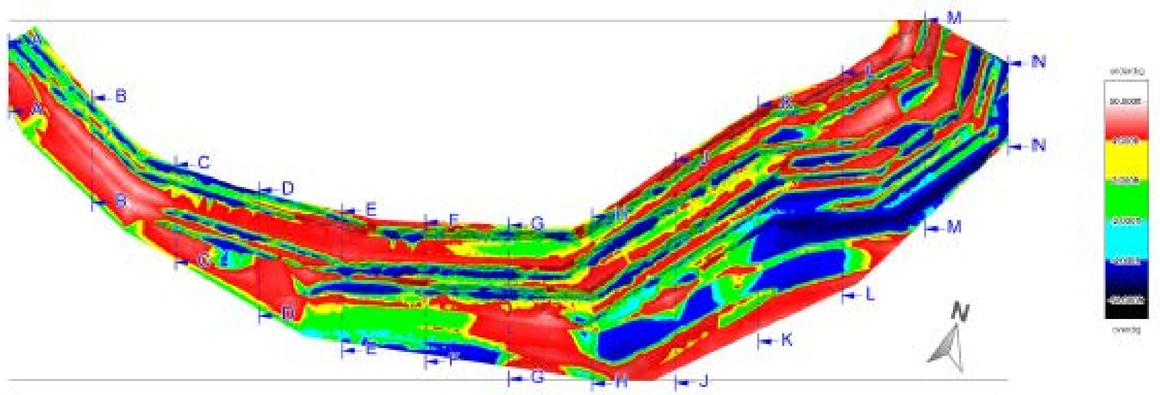


Figure 38: Cross Sectional Views of East wall Double Bench

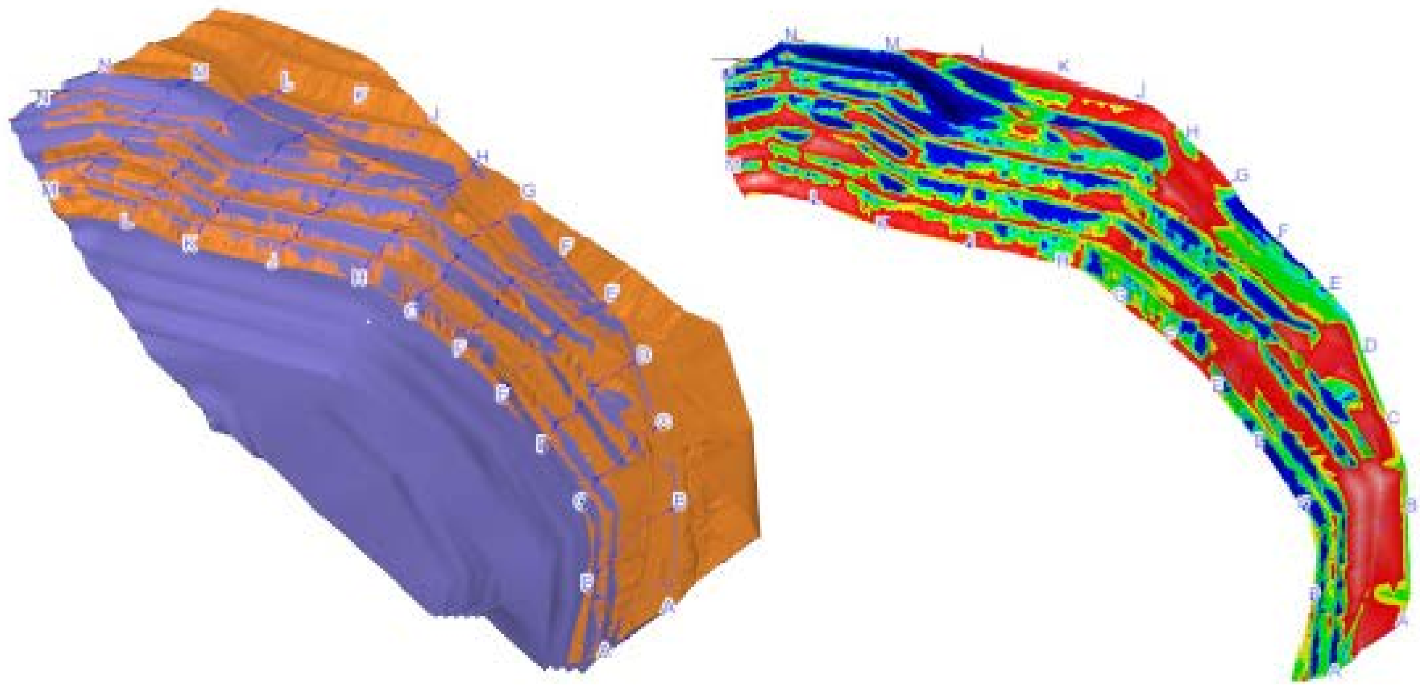
Design: pit plan
As-built: new southwall

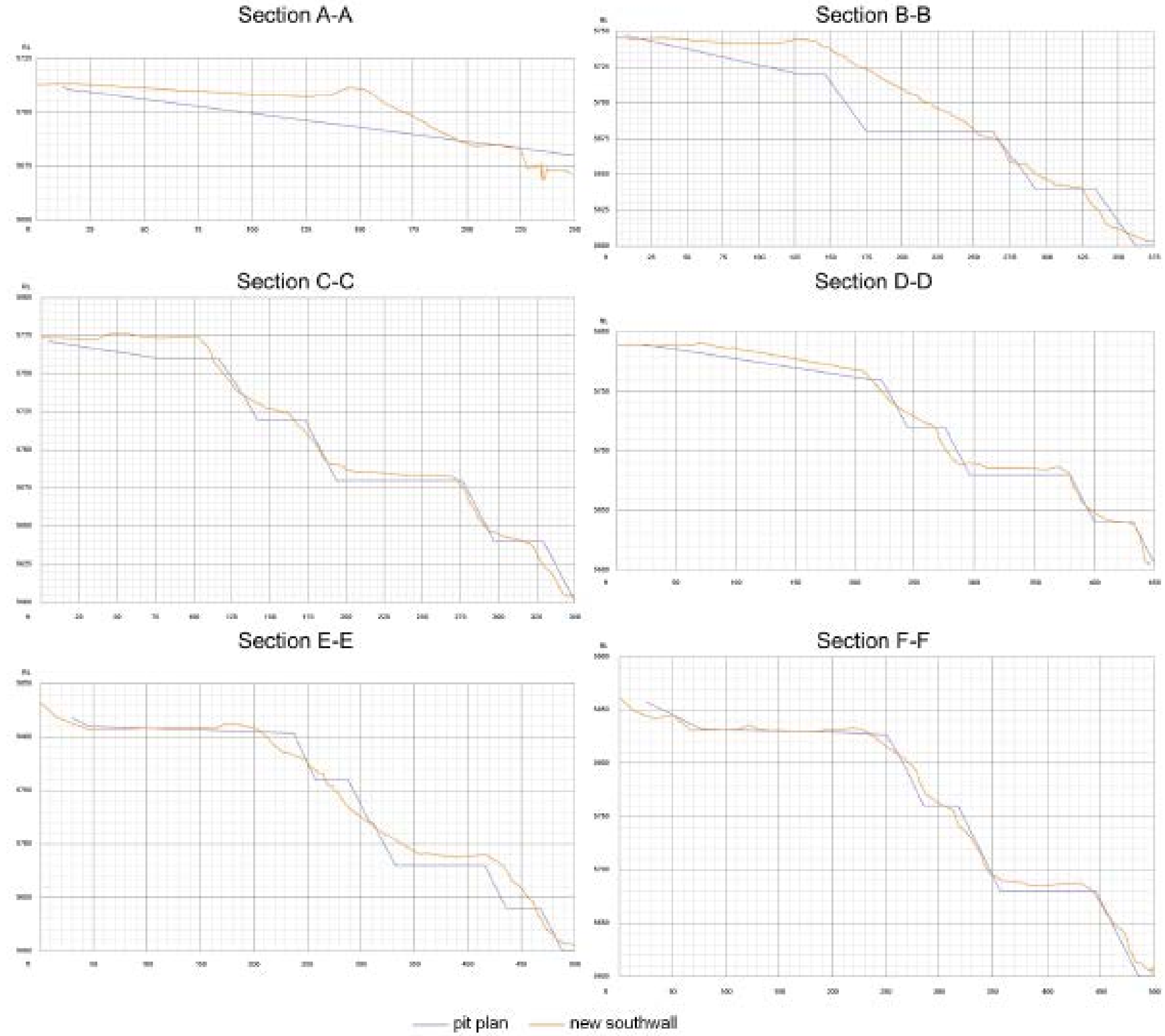
Plan View

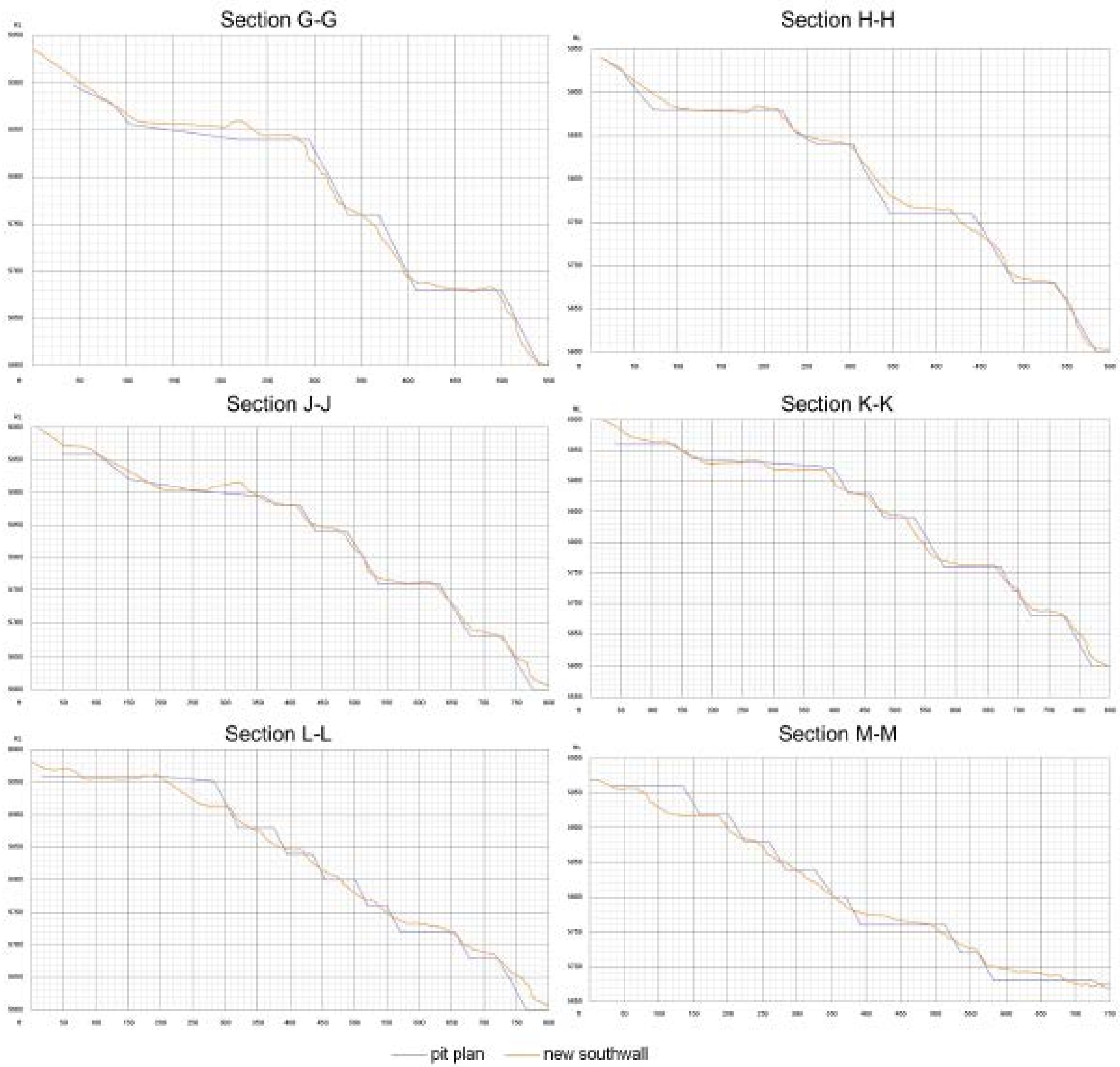




Perspective View




Section A-A
Section B-B
Section C-C
Section D-D
Section E-E
Section F-F
pit plan
new southwall


Section G-G
Section H-H
Section J-J
Section K-K
Section L-L
Section M-M
pit plan
new southwall

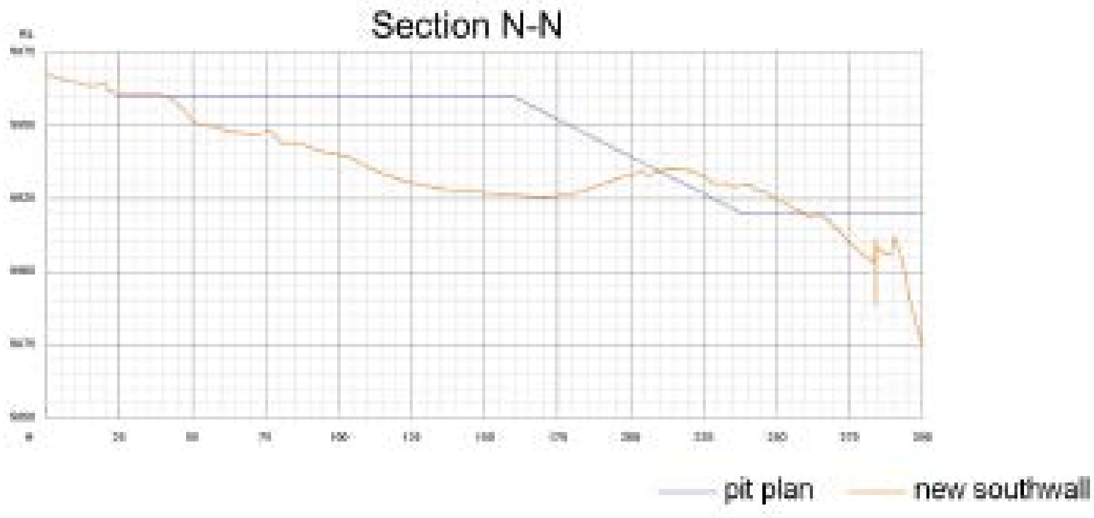
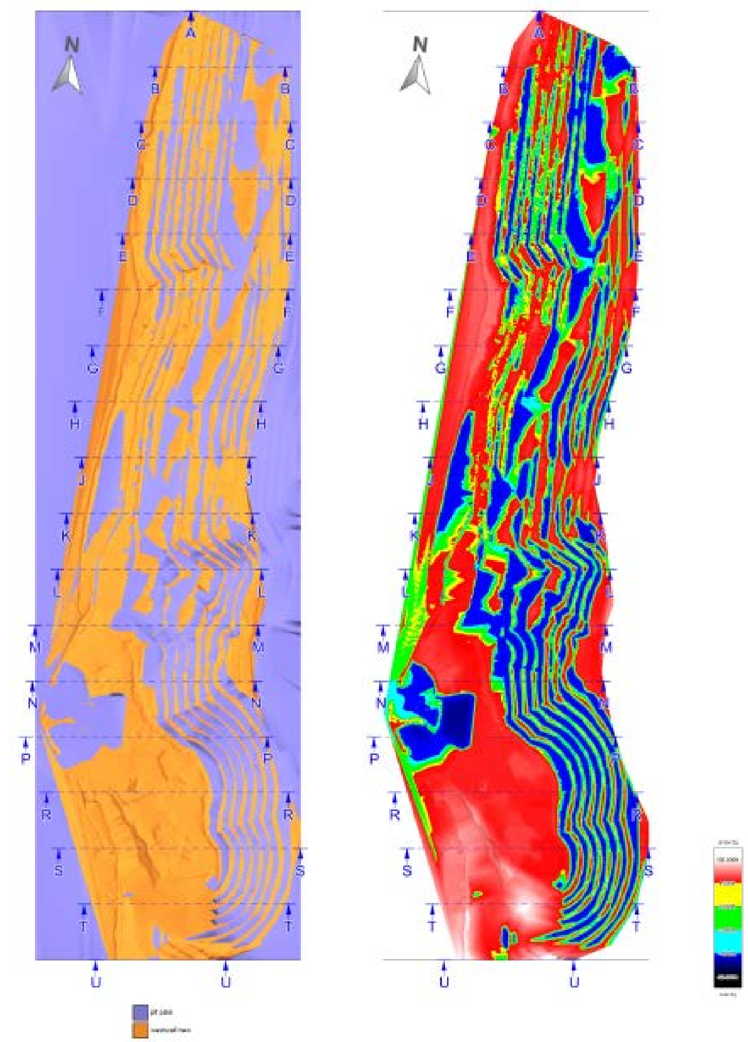


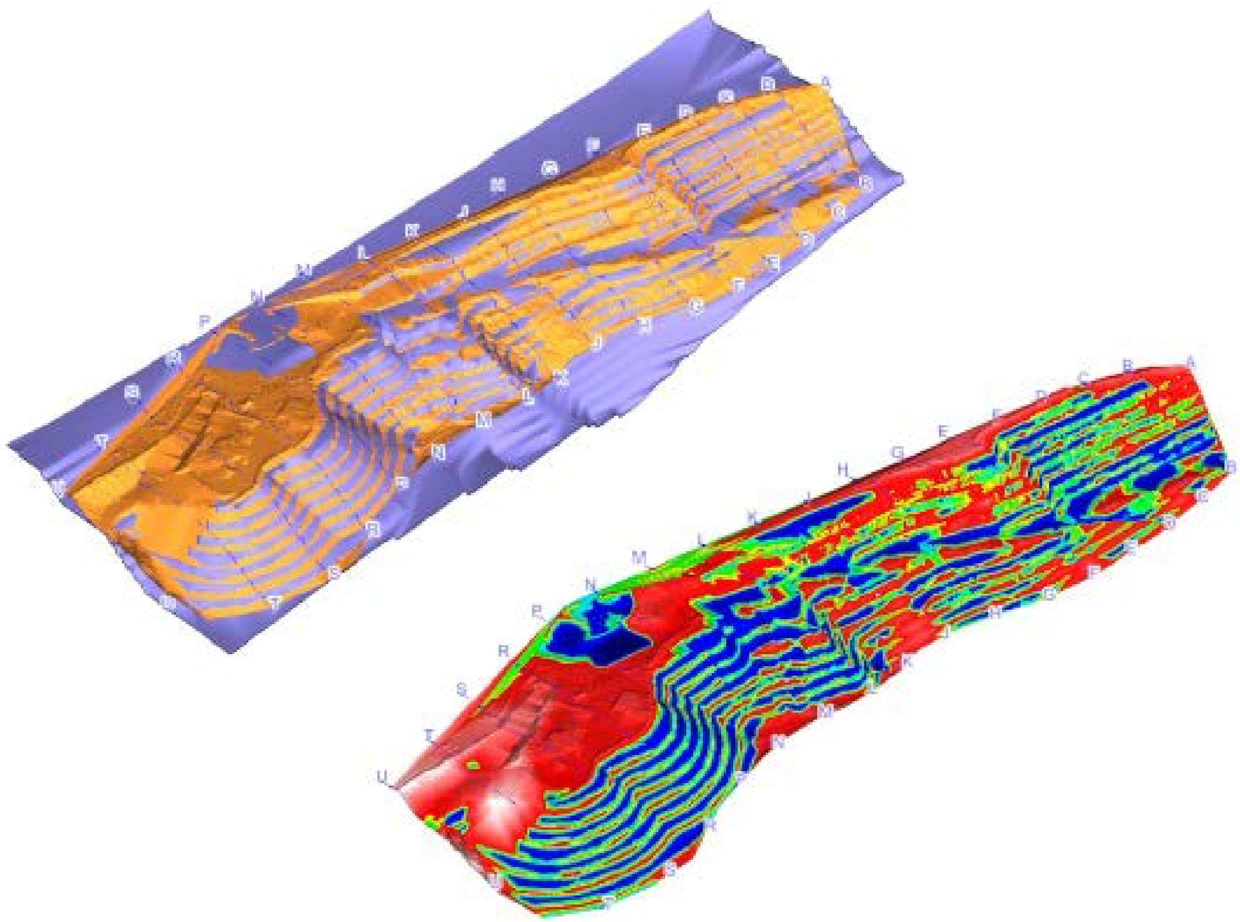
Figure 39: Cross-Sectional Views of South wall

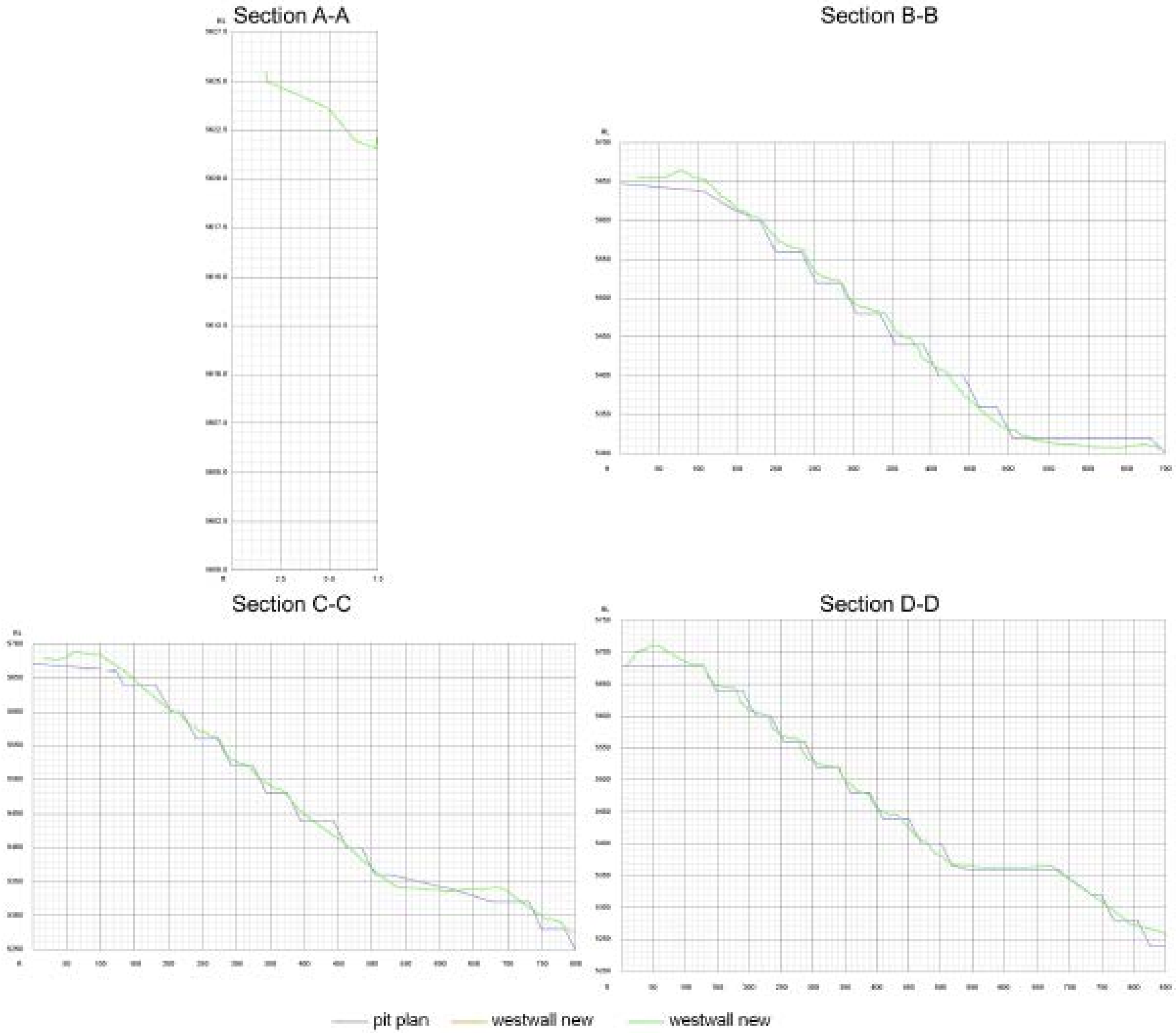
Design: pit plan
As-built: westwall new

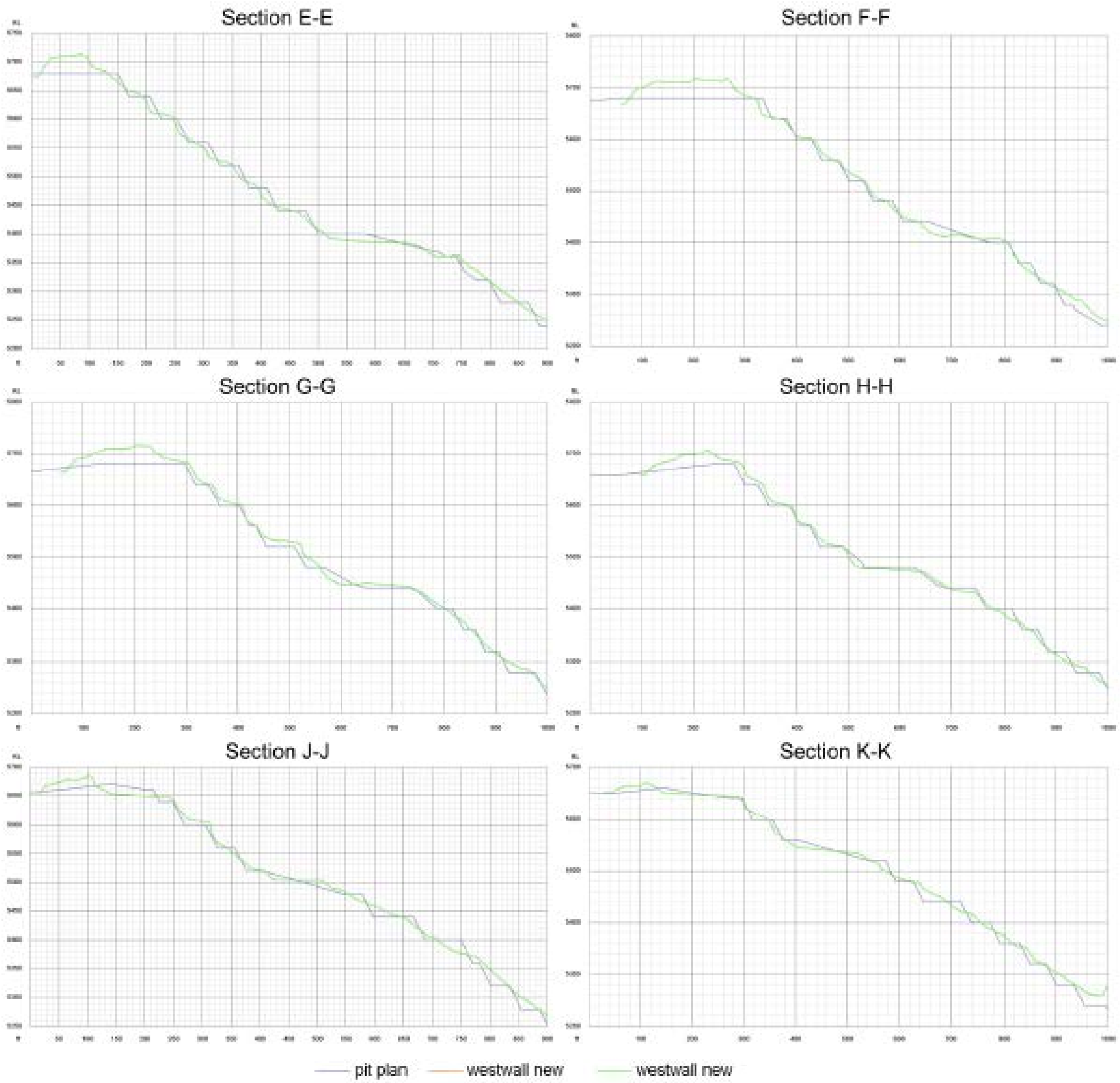
Plan View



Perspective View




Section A-A
Section B-B
Section C-C
Section D-D
pit plan
westwall new
westwall new


Section E-E
Section F-F
Section G-G
Section H-H
Section J-J
Section K-K
pit plan
westwall new
westwall new

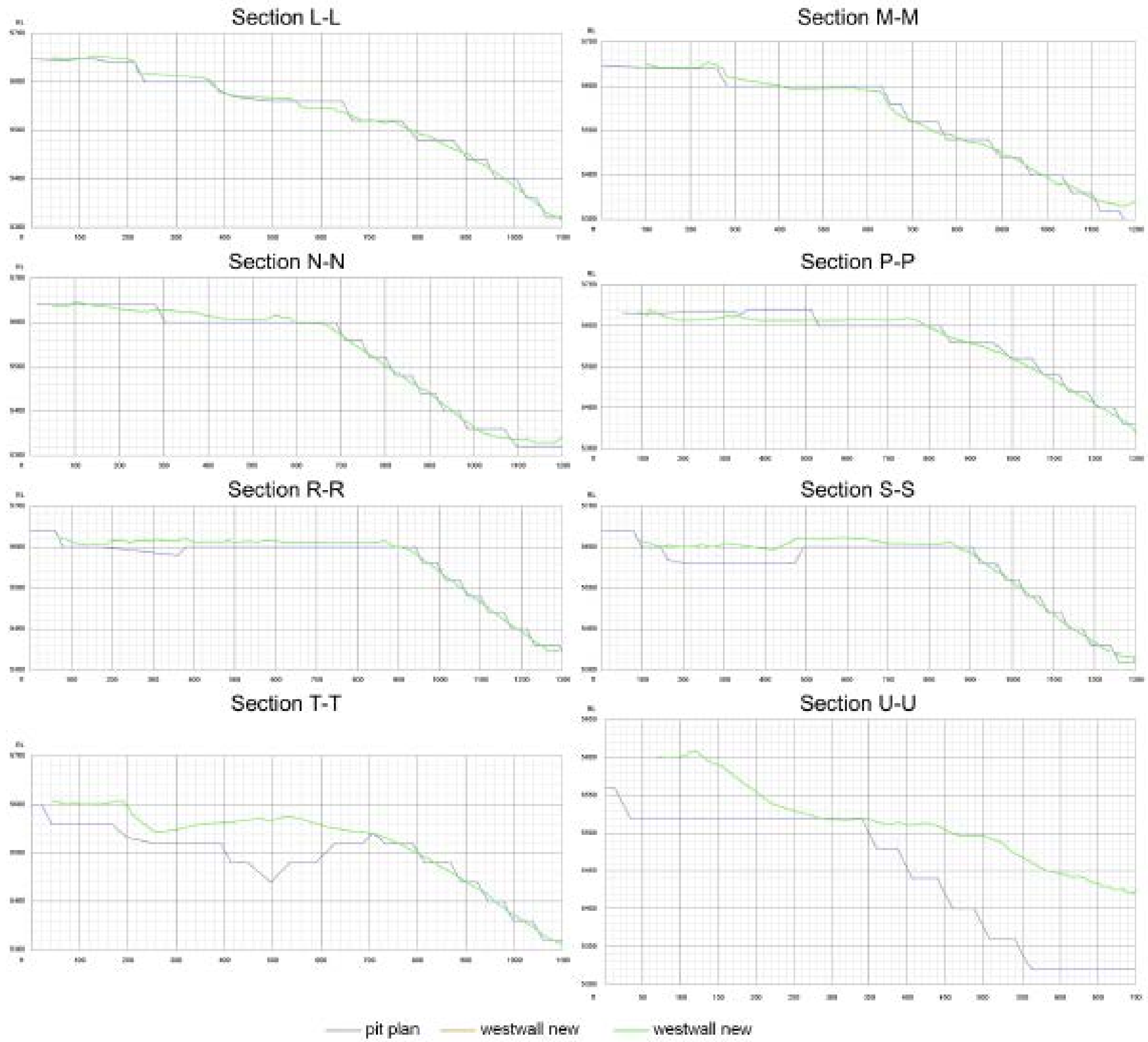
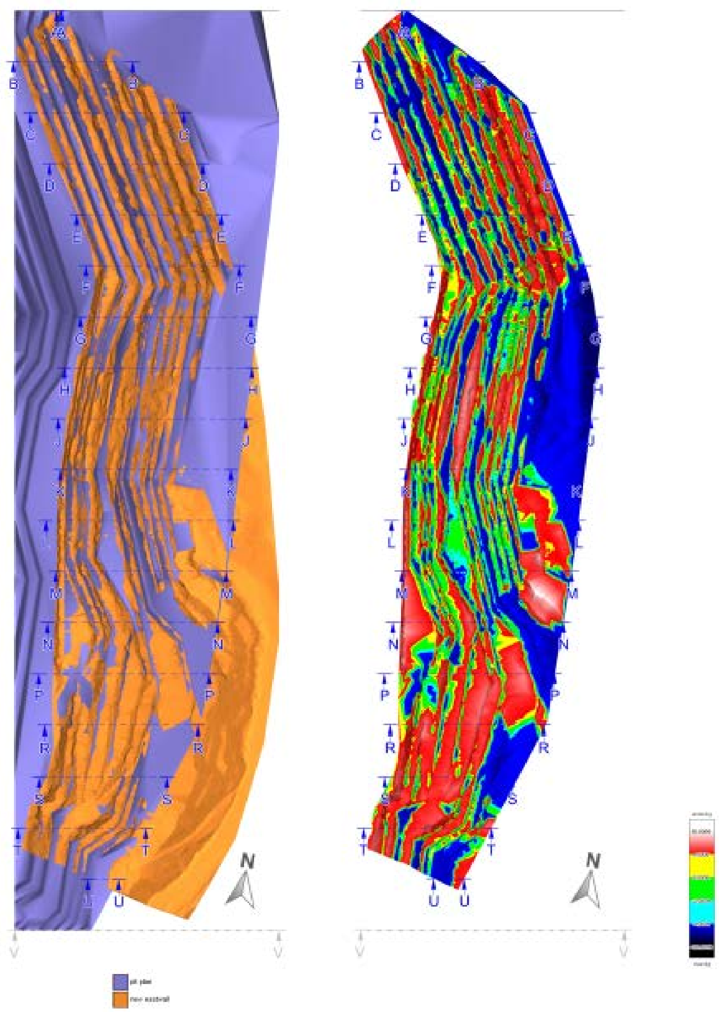


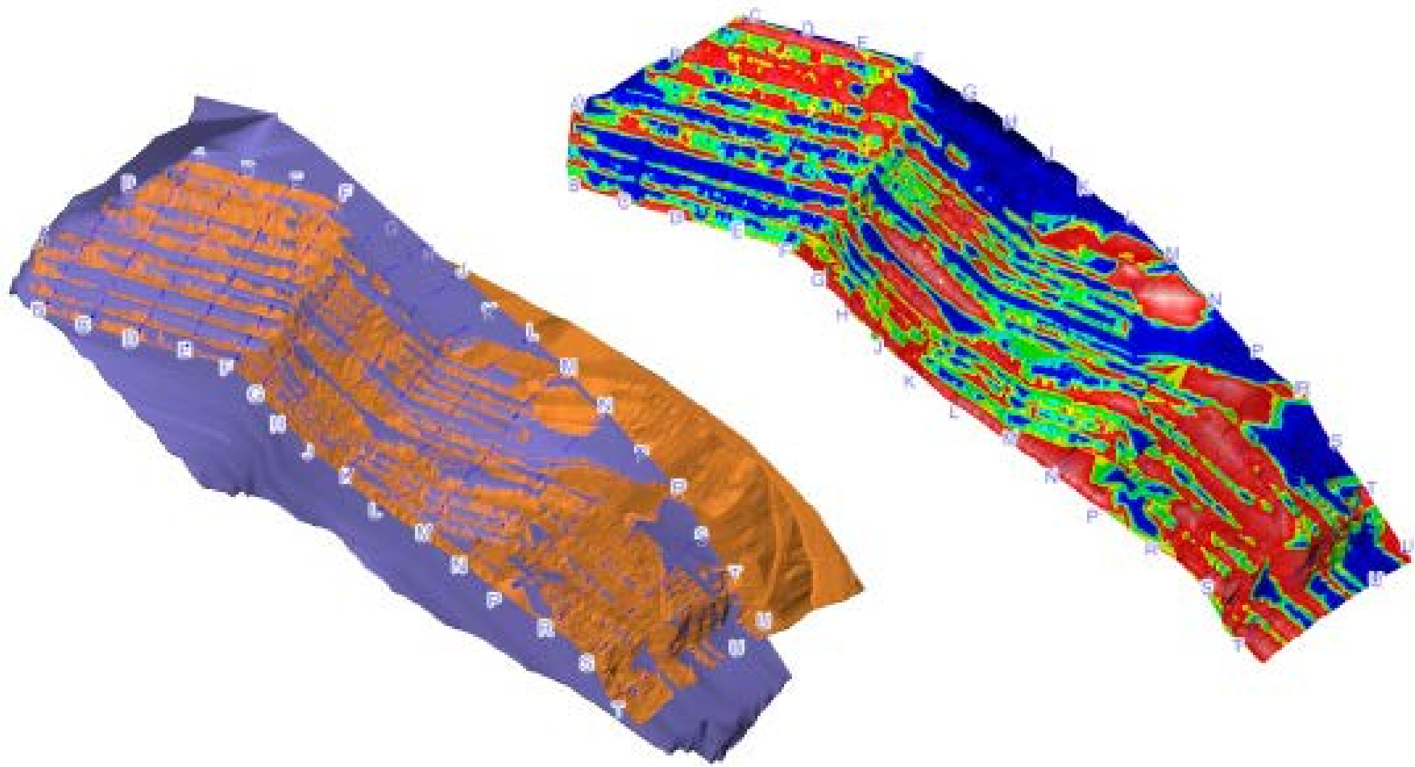
Figure 40: Cross-Sectional Views of West wall

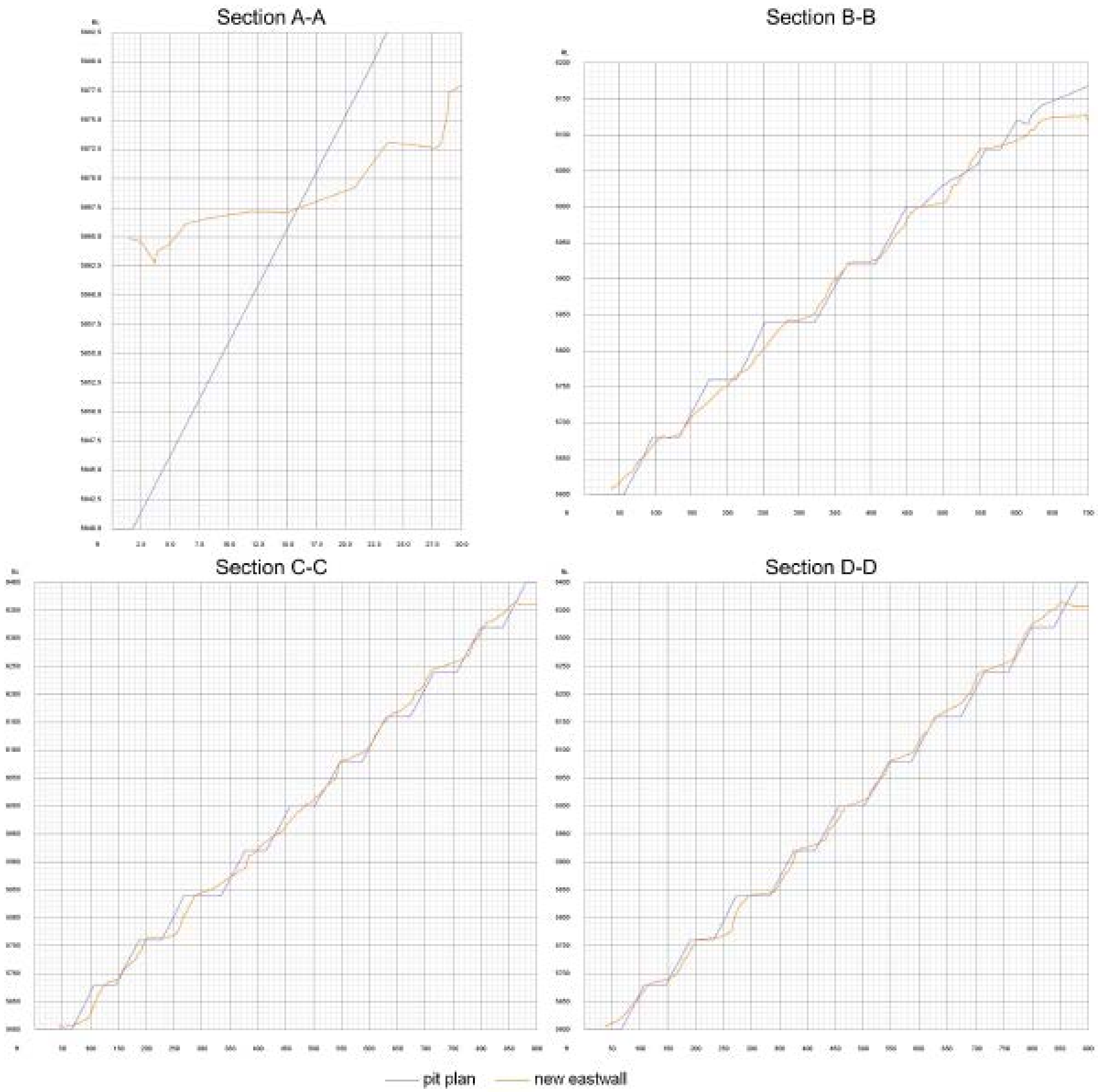
Design: pit plan
As-built: new eastwall

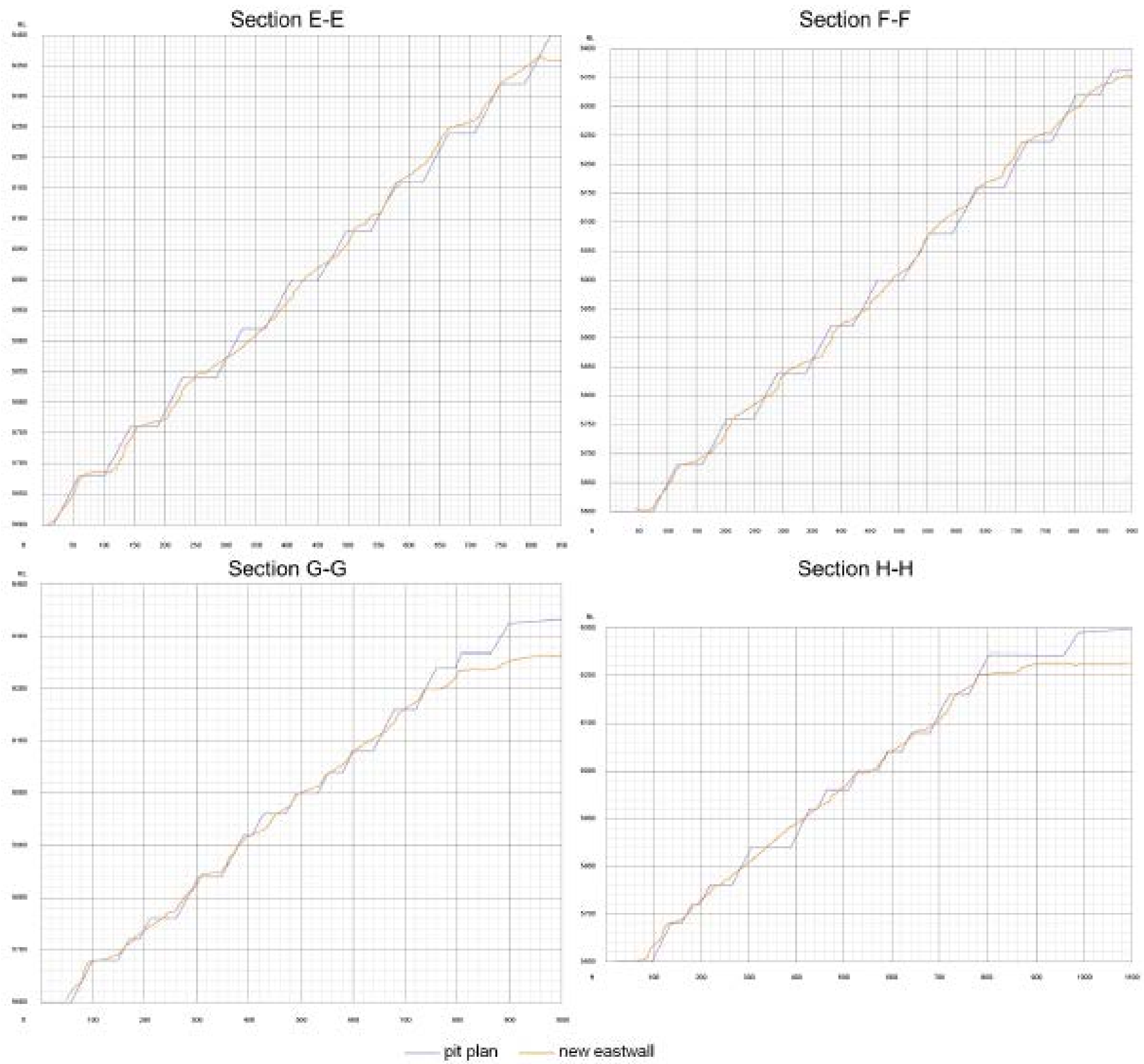
Plan View

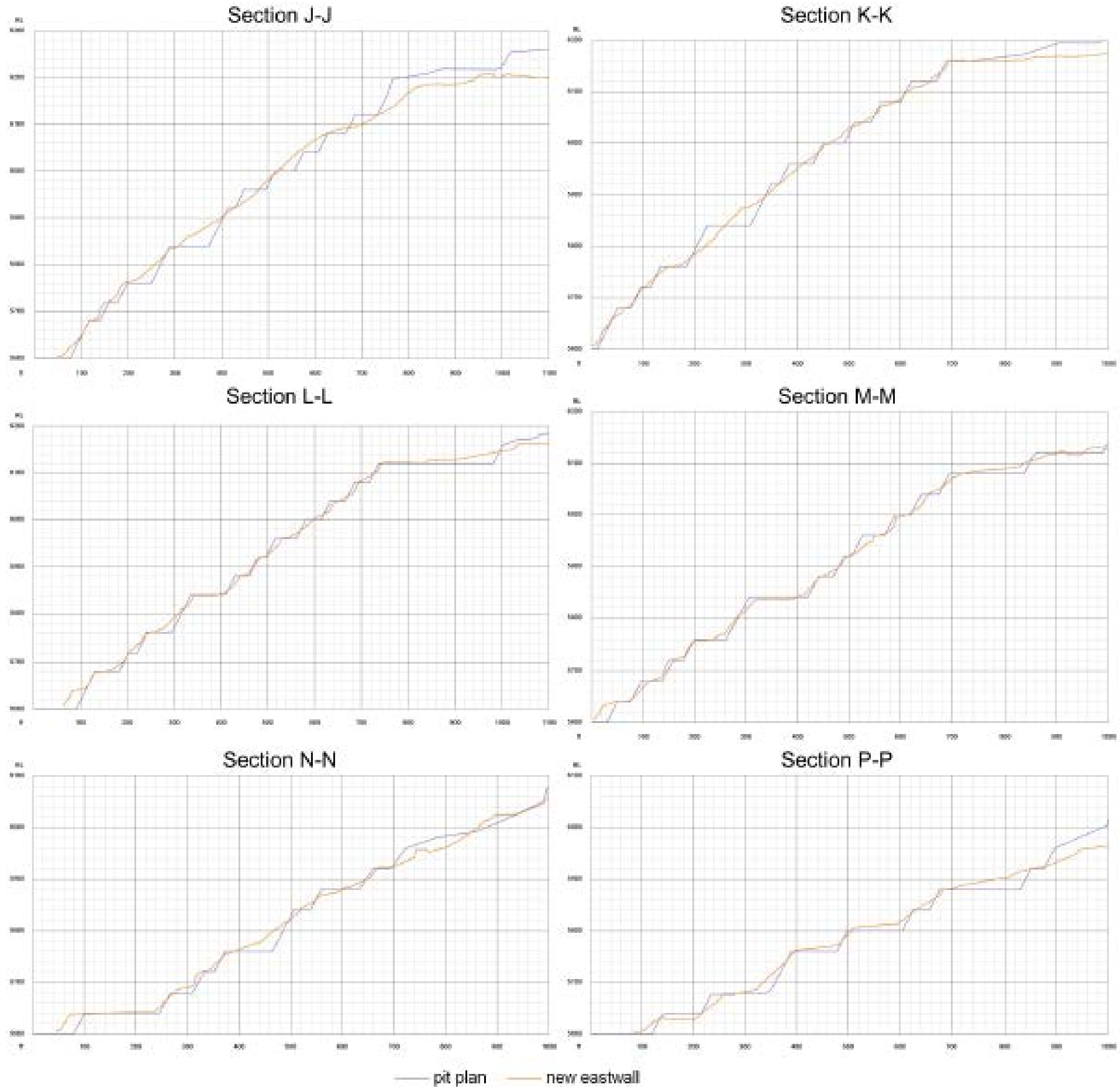


Perspective View




Section A-A
Section B-B
Section C-C
Section D-D
pit plan
new eastwall


Section E-E
Section F-F
Section G-G
Section H-H
pit plan
new eastwall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Section N-N
Section P-P
pit plan
new eastwall

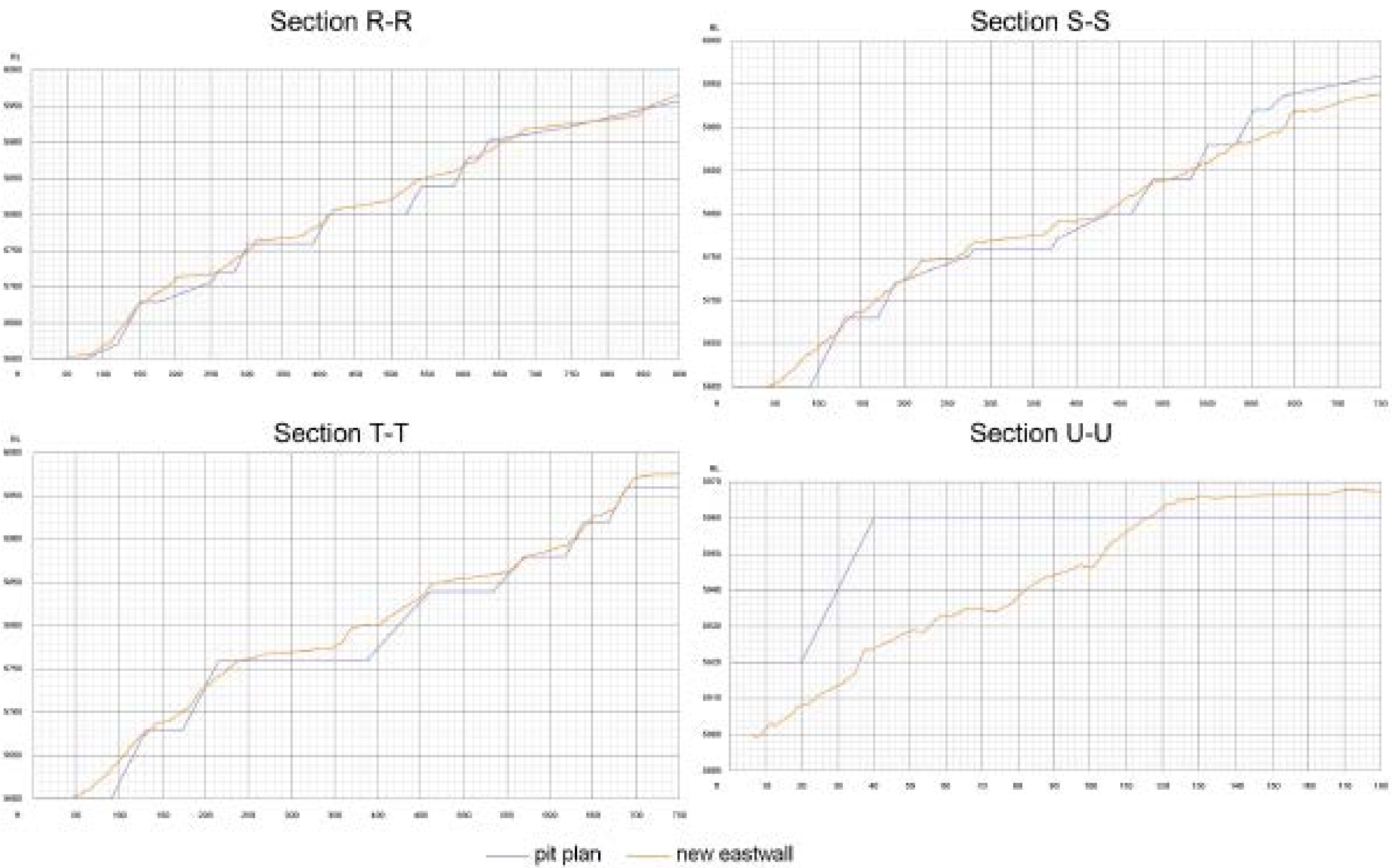
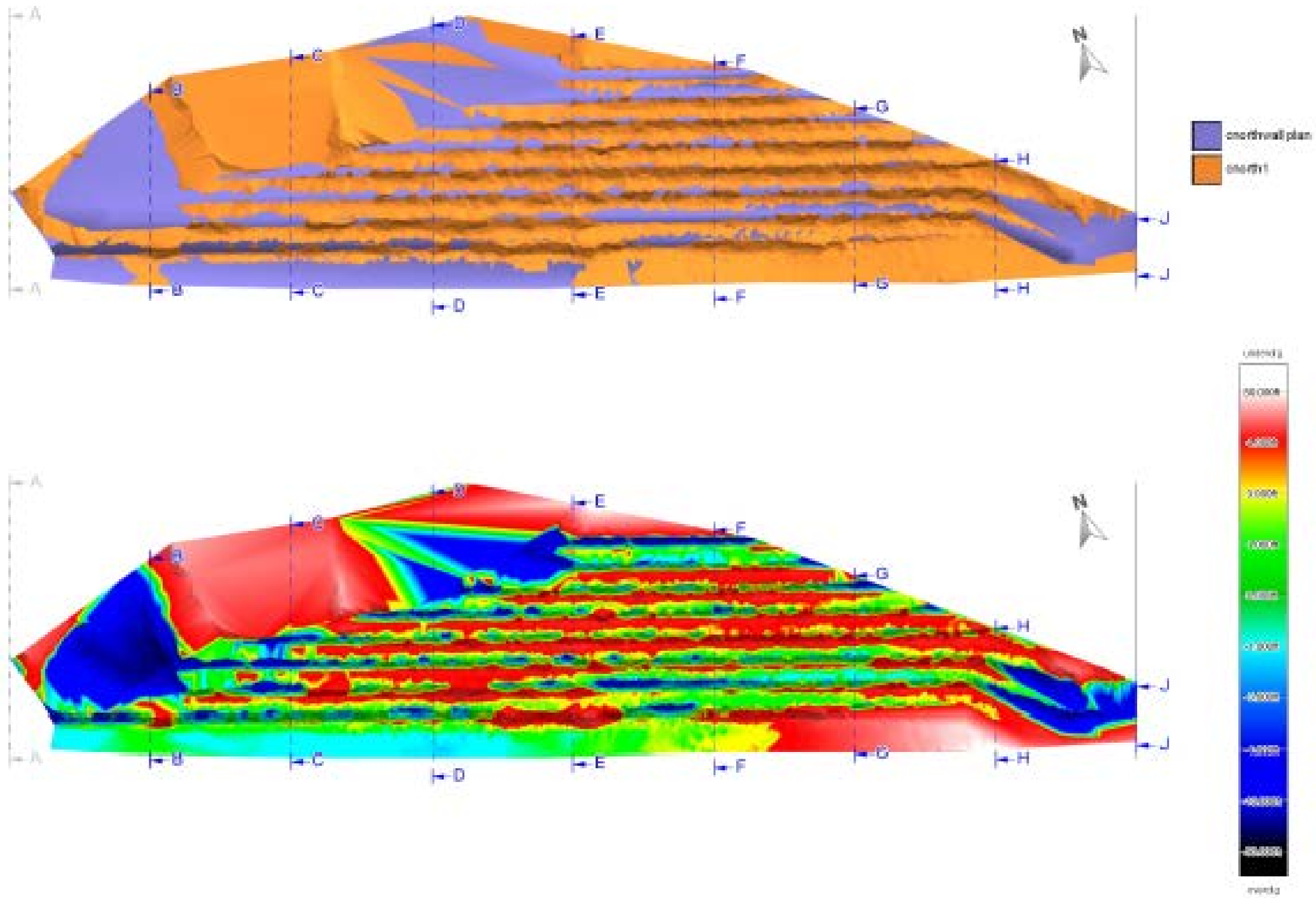


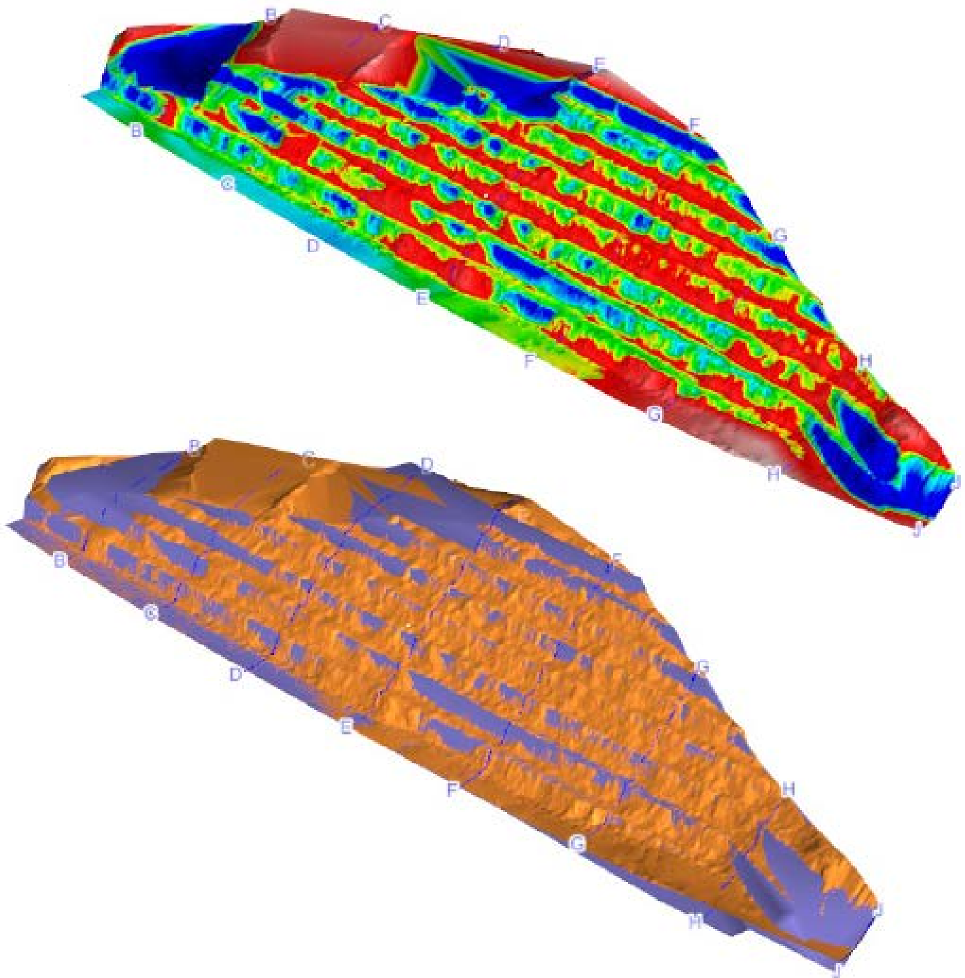
Figure 41: Cross Sectional Views of East wall

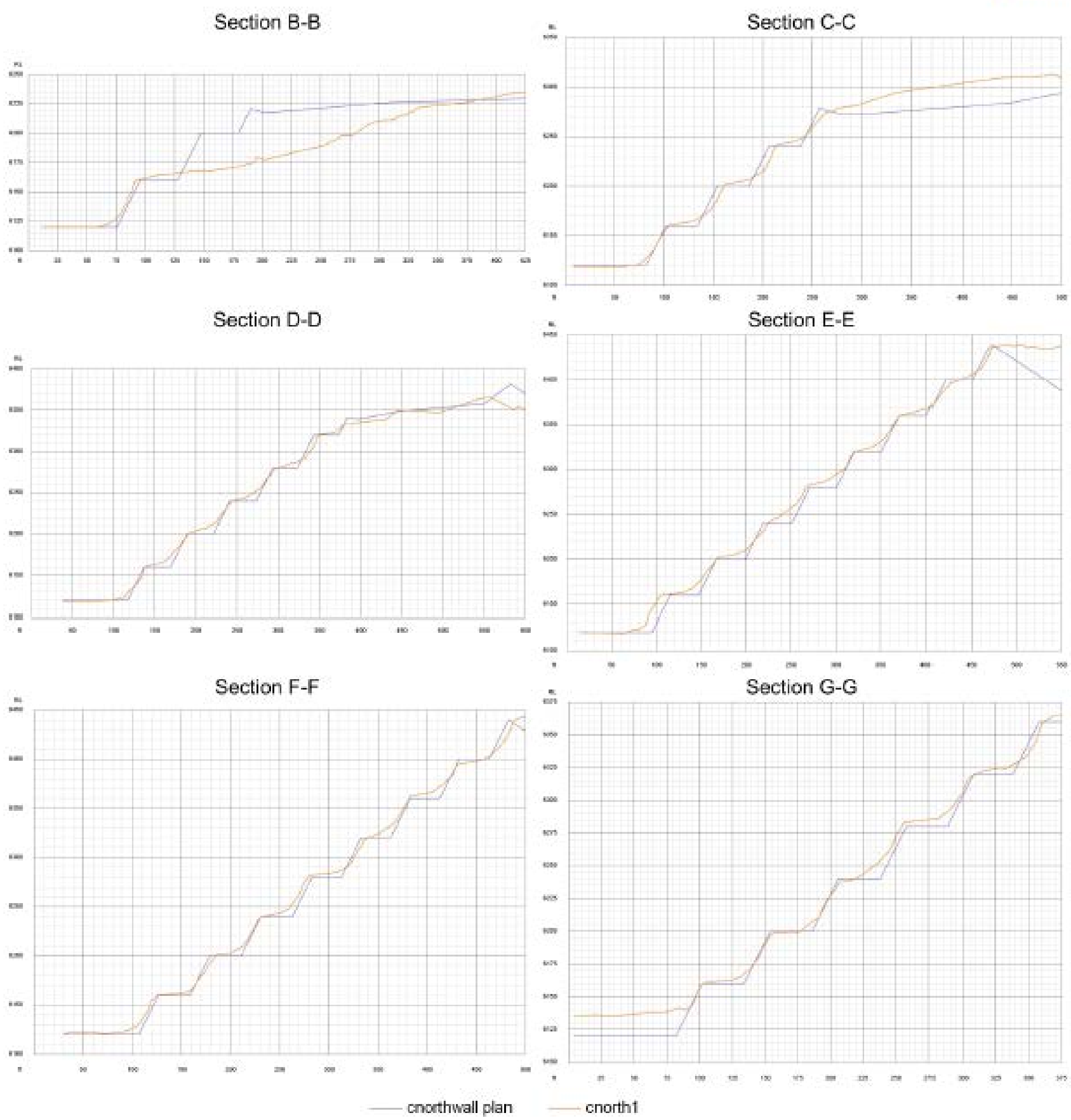
Design: cnorthwall plan
As-built: cnorth1

Plan View



Perspective View

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Section C-C
Section D-D
Section E-E
Section F-F
Section G-G
cnorthwall plan
cnorth1

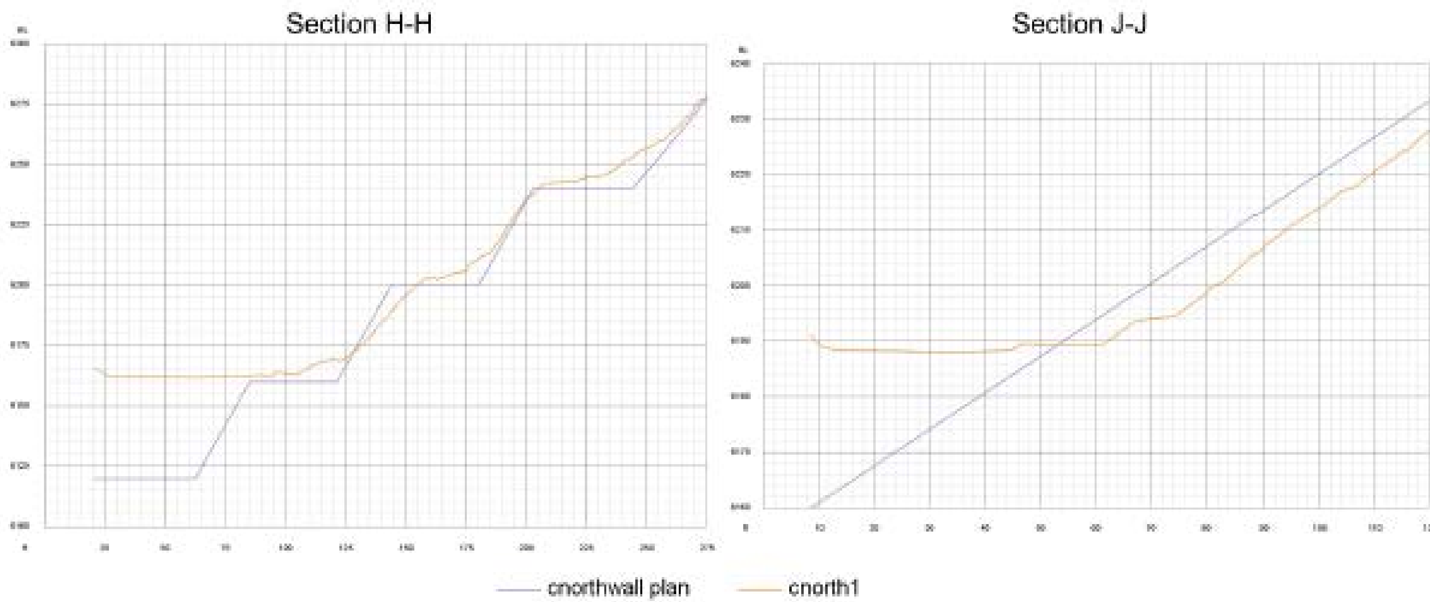

Figure 42: Cross Sectional Views of North wall

9. APPENDIX B: SLOPE SECTIONS SELECTED FOR ROCKFALL ANALYSIS FROM PLAN VIEW

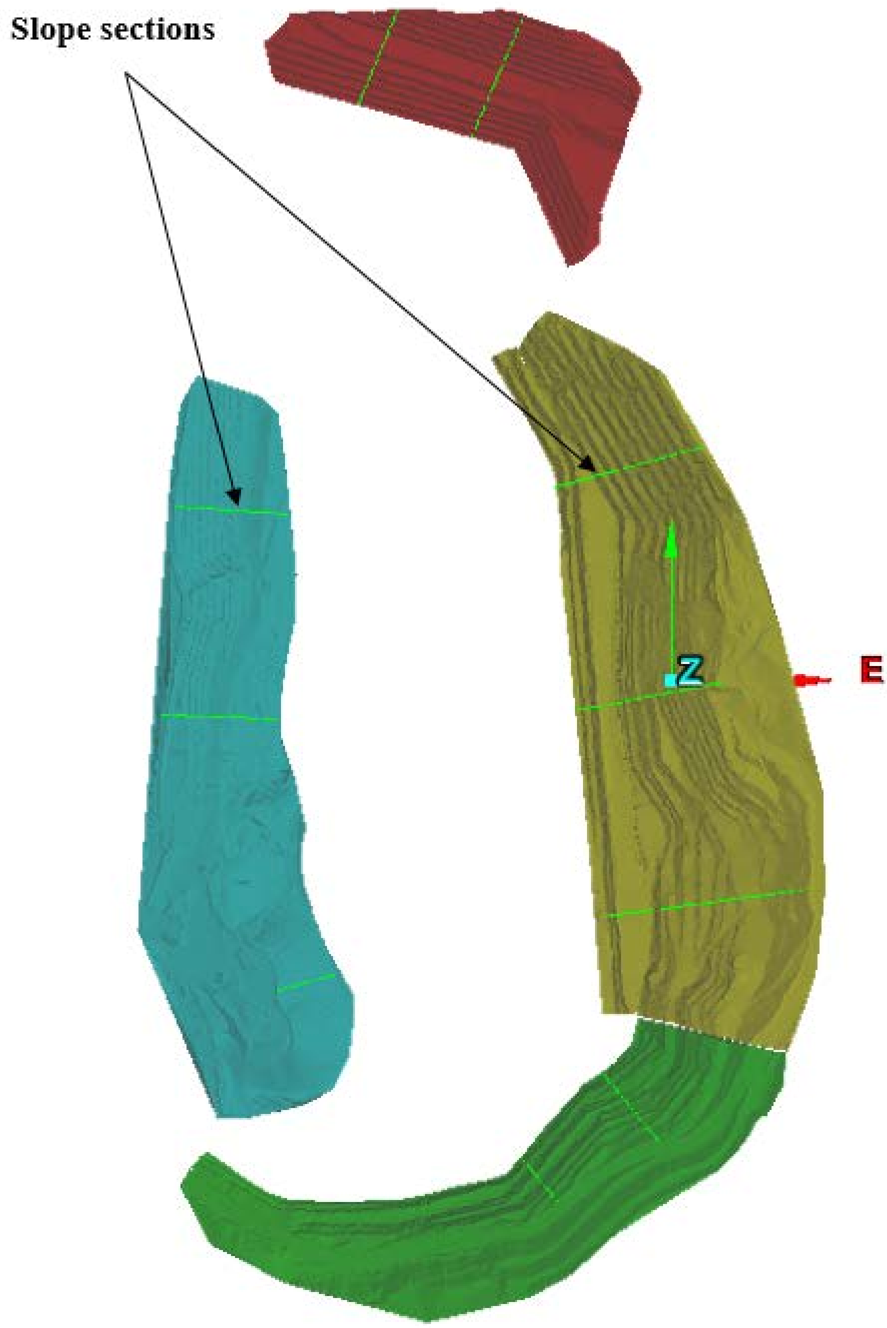

Figure 43: Slope Sections Selected for Rockfall Analysis

10. APPENDIX C: COMPLIANCE OF EACH HIGHWALL

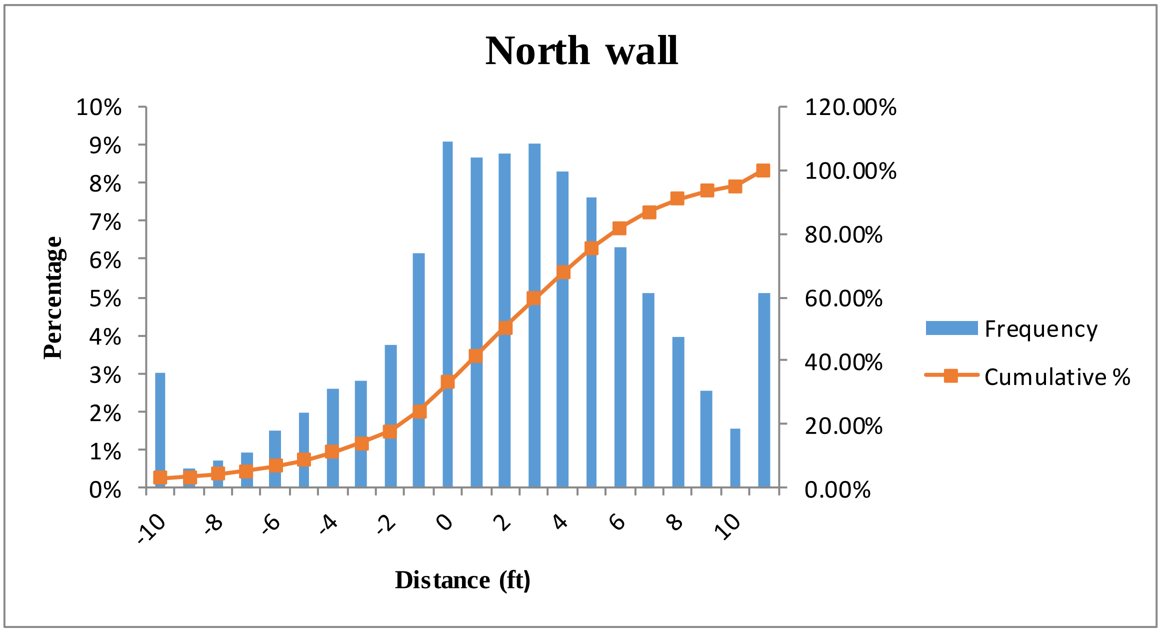

Figure 44: North wall Compliance

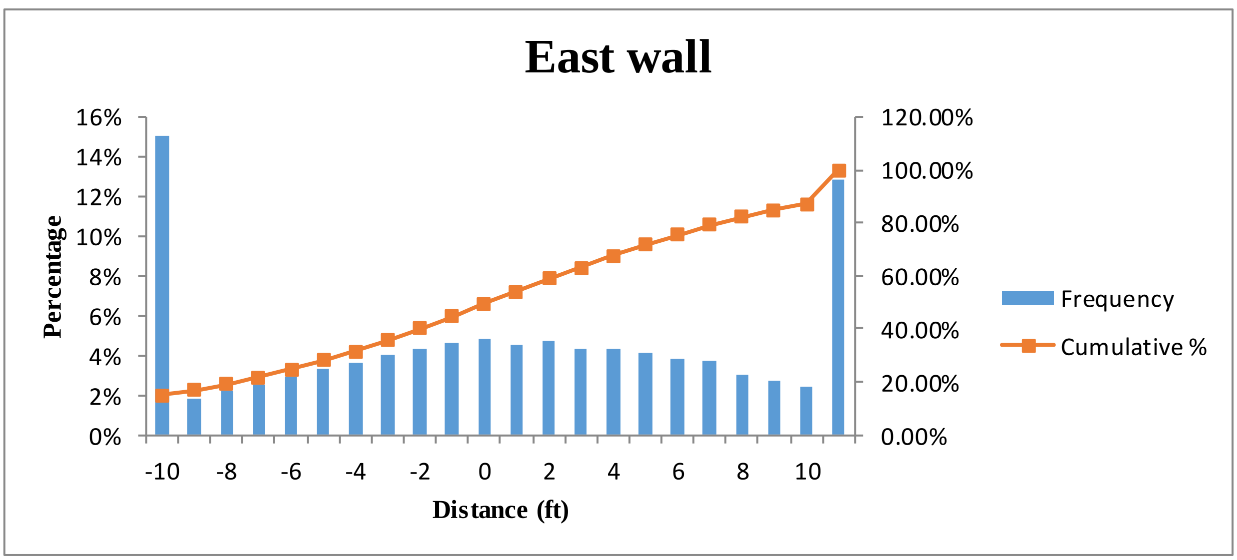

Figure 45: East wall Compliance

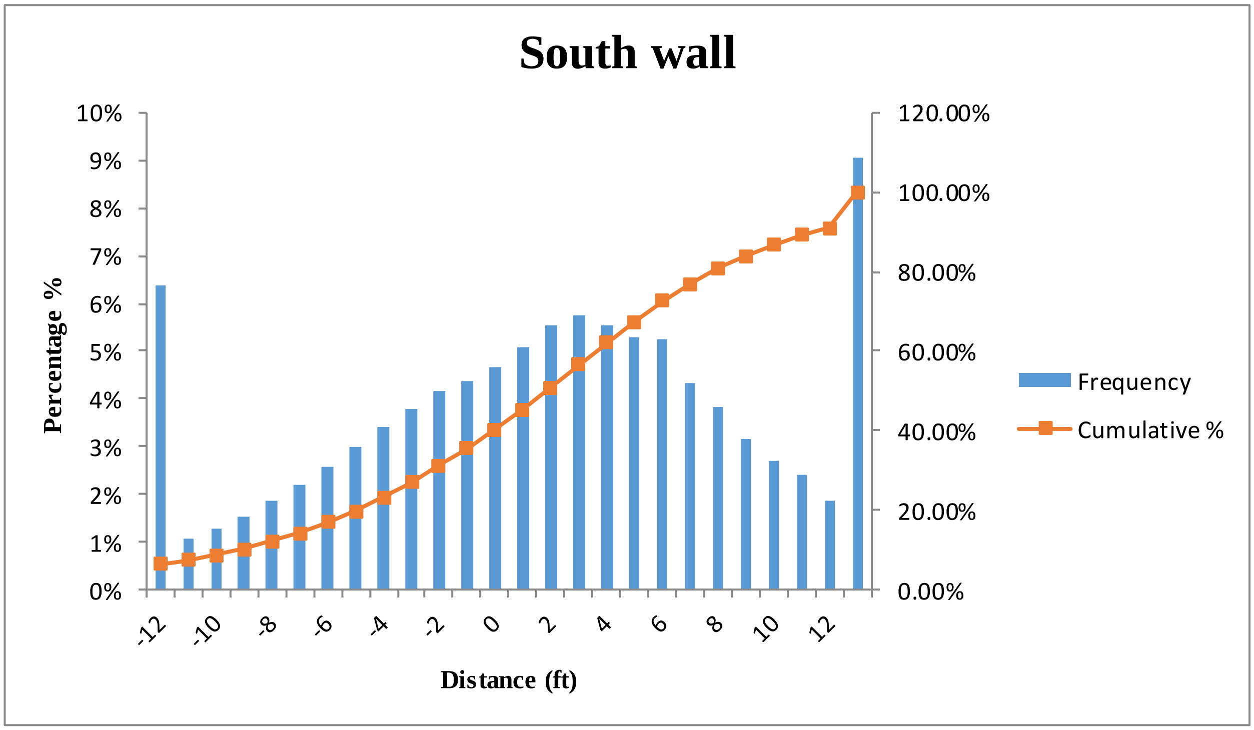

Figure 46: South wall Compliance

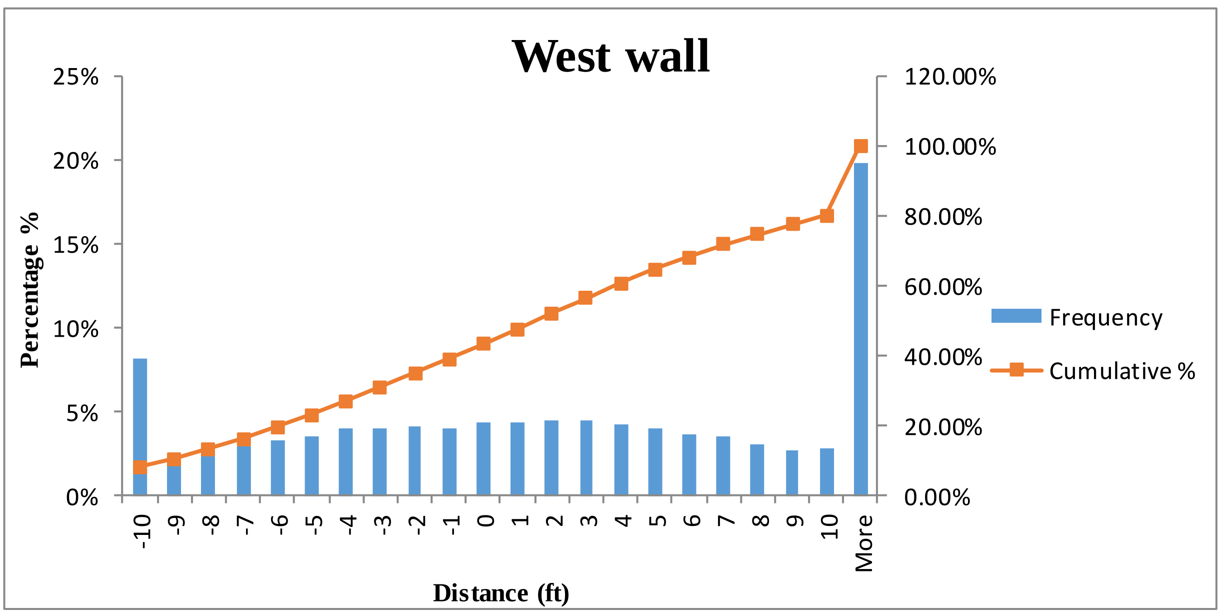

Figure 47: West wall Compliance

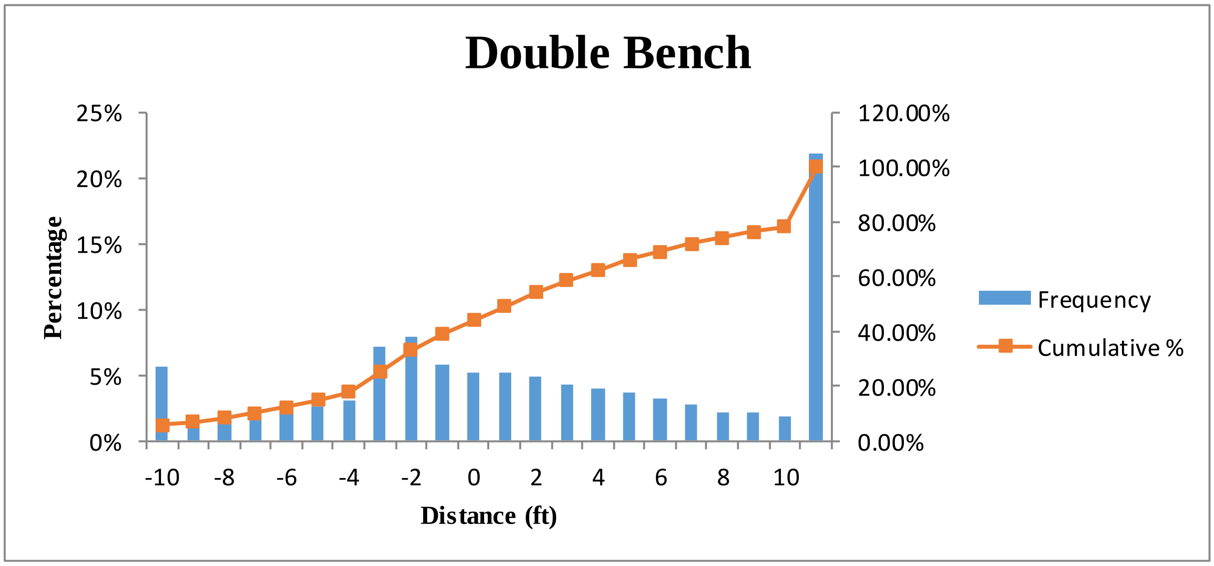

Figure 48: East wall Double Bench Compliance

11. APPENDIX D: ROCK PATHS IN SLOPE VIEW

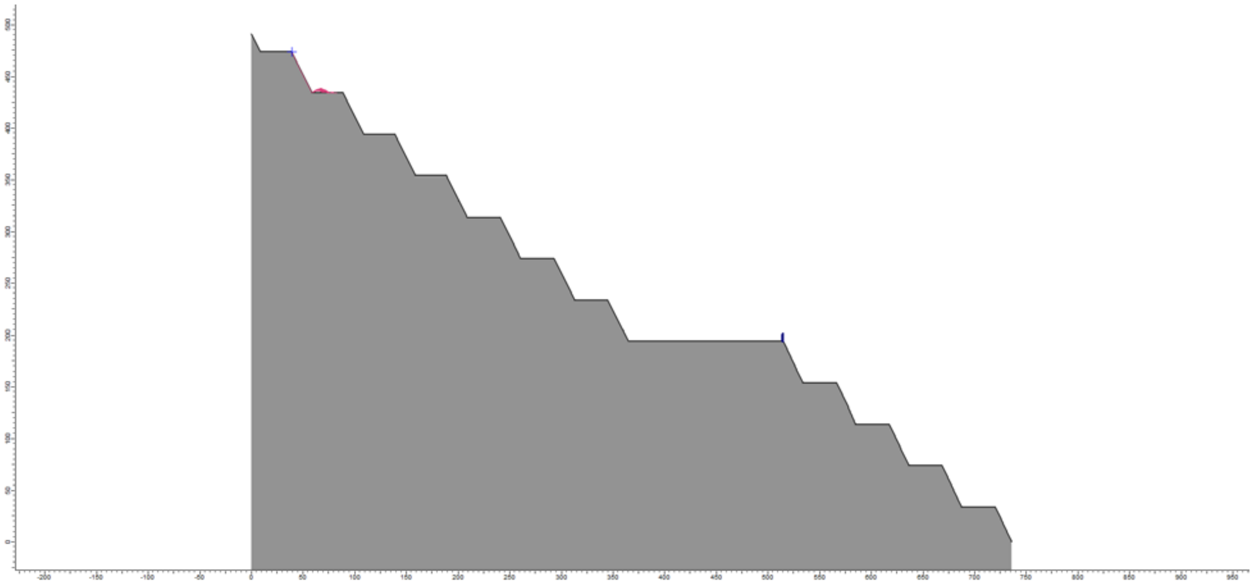

Figure 49: North wall Plan Slope 1

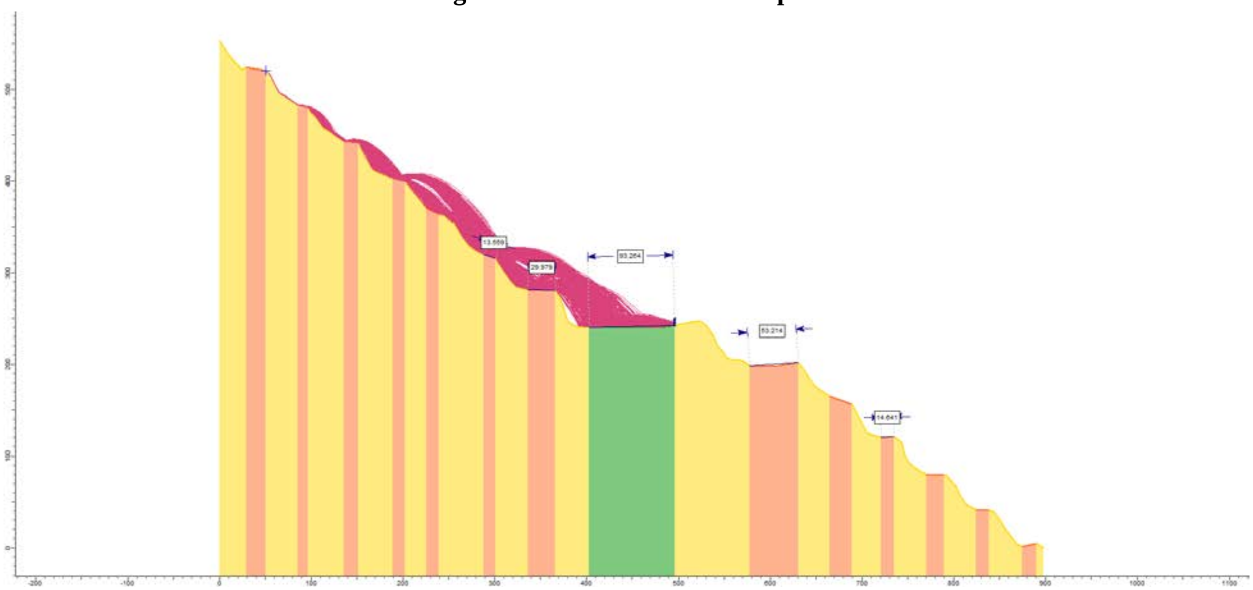

Figure 50: North wall Actual Slope 1

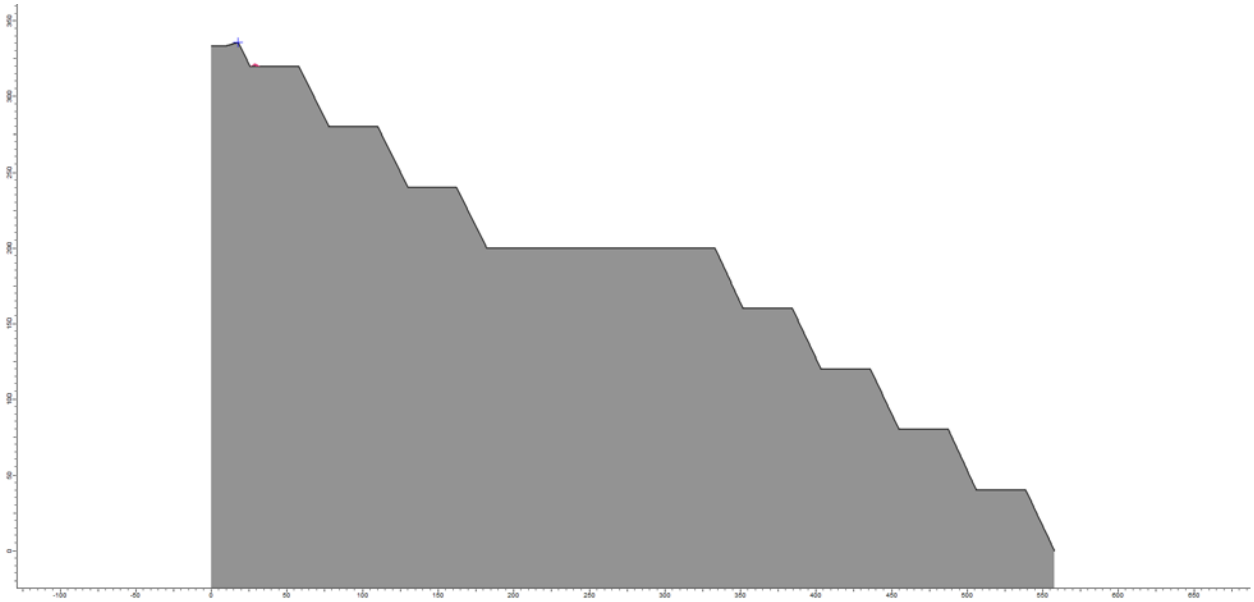

Figure 52: North wall Plan Slope 2

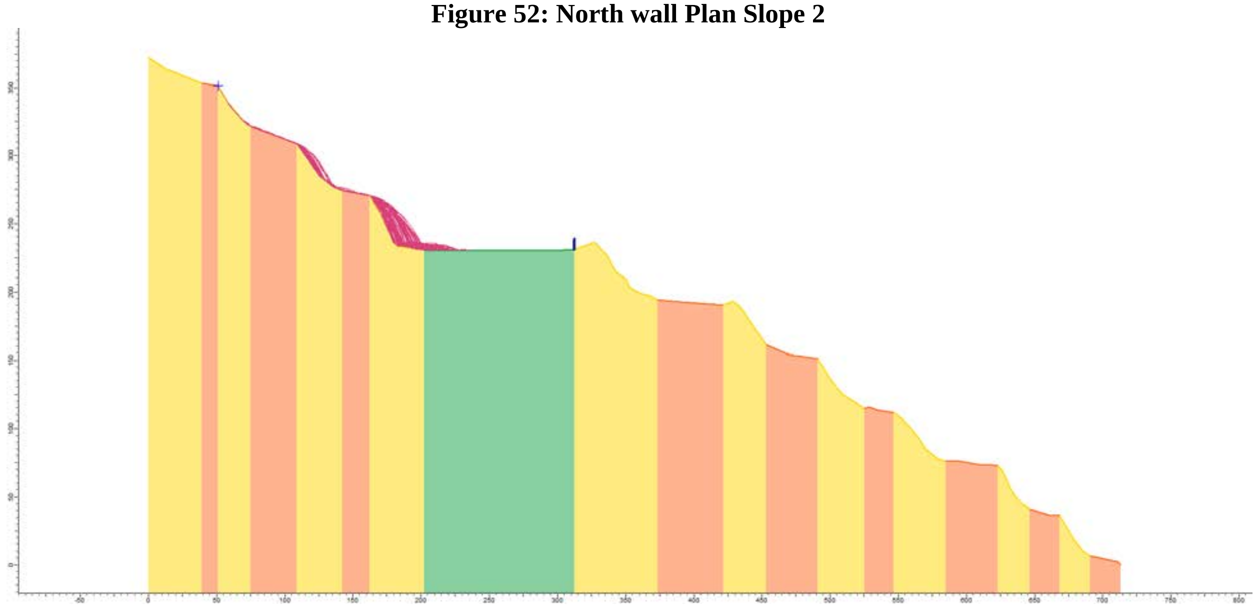

Figure 51: North wall Slope 2

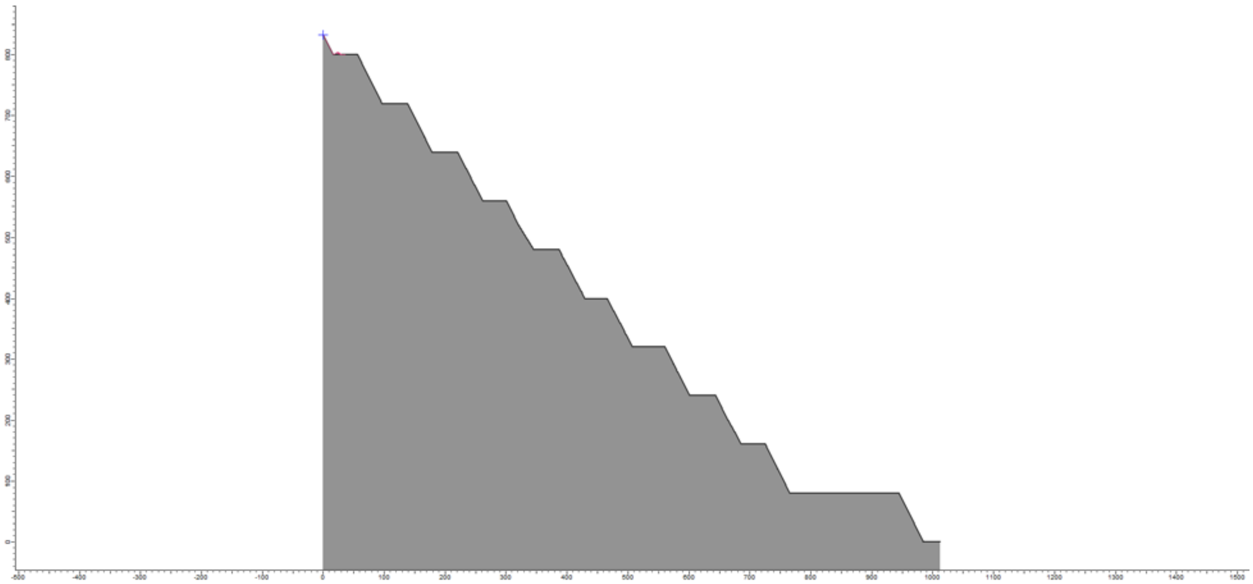

Figure 53: East wall Plan Slope 1

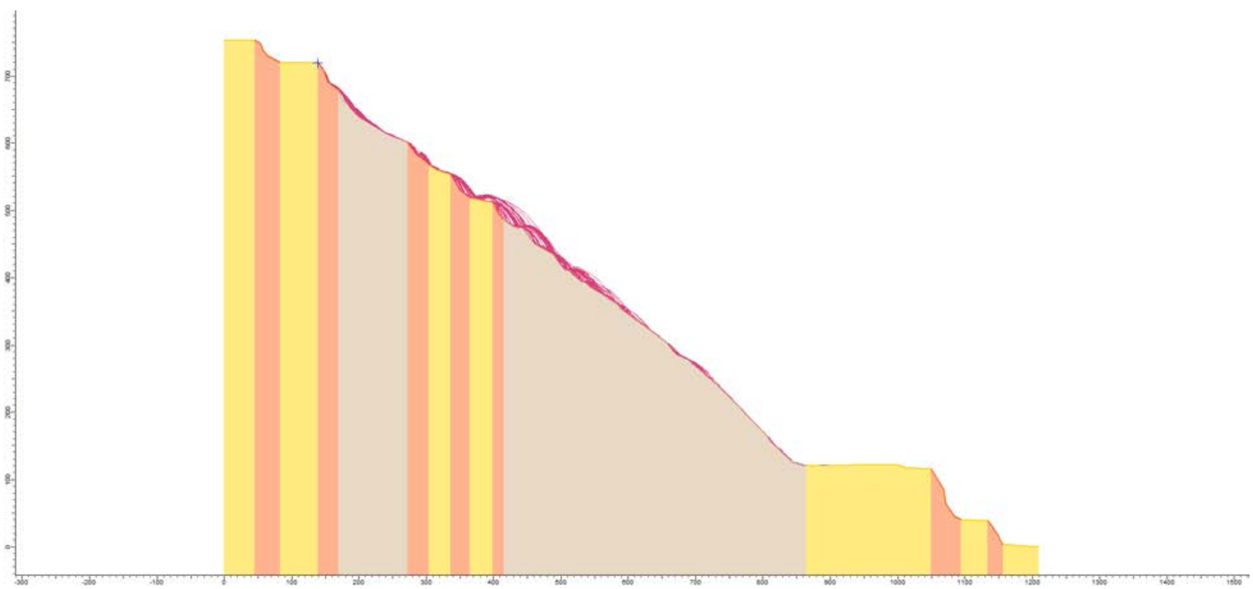

Figure 54: East wall Actual Slope 1

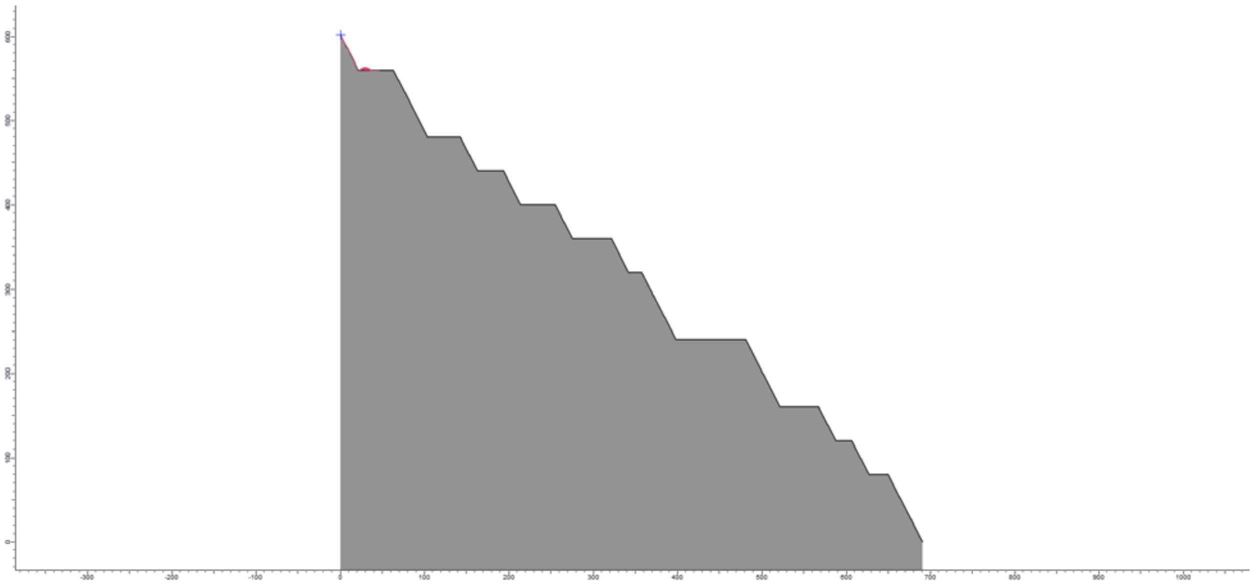

Figure 55: East wall Plan Slope 2

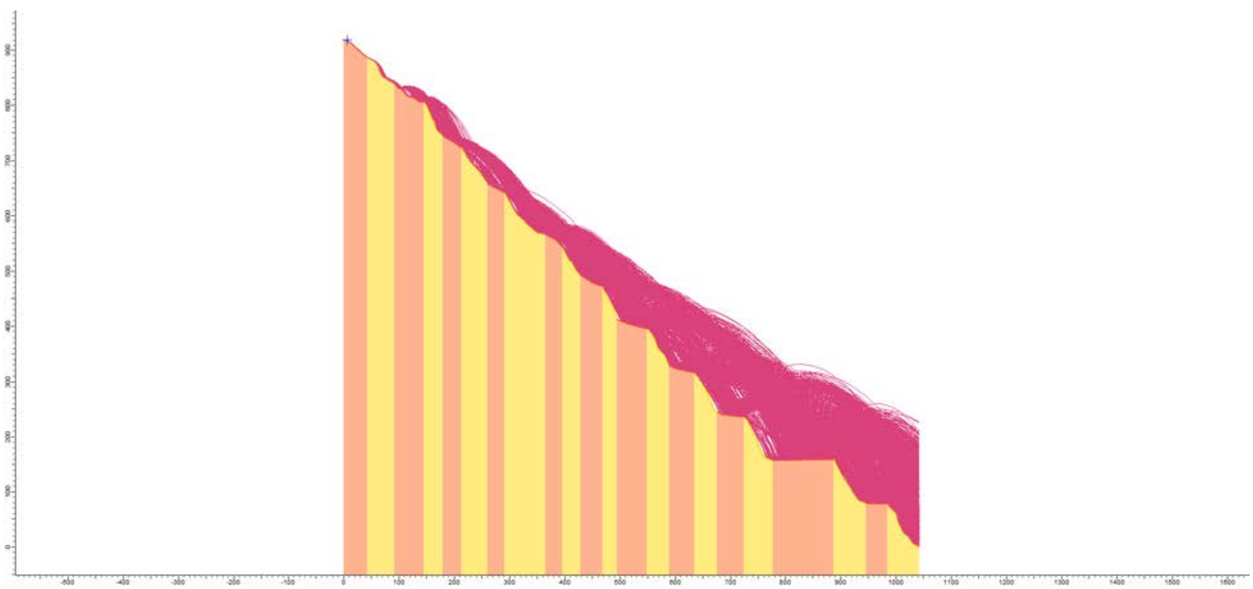

Figure 56: East wall Actual Slope 2

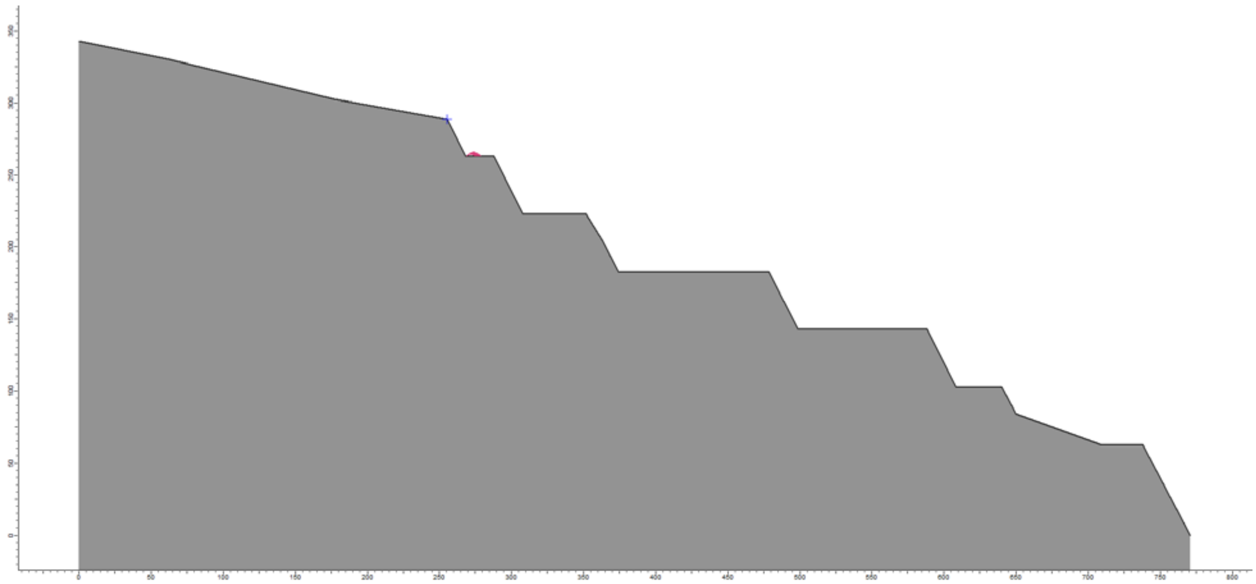

Figure 57: East wall Plan Slope 3

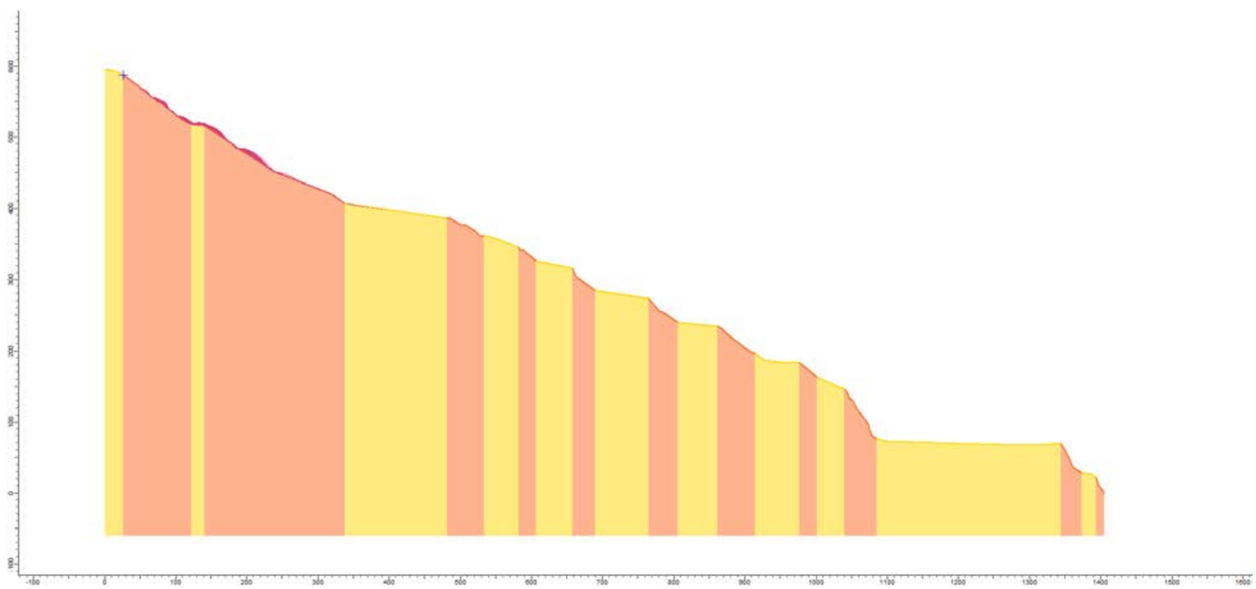

Figure 58: East wall Actual Slope 3

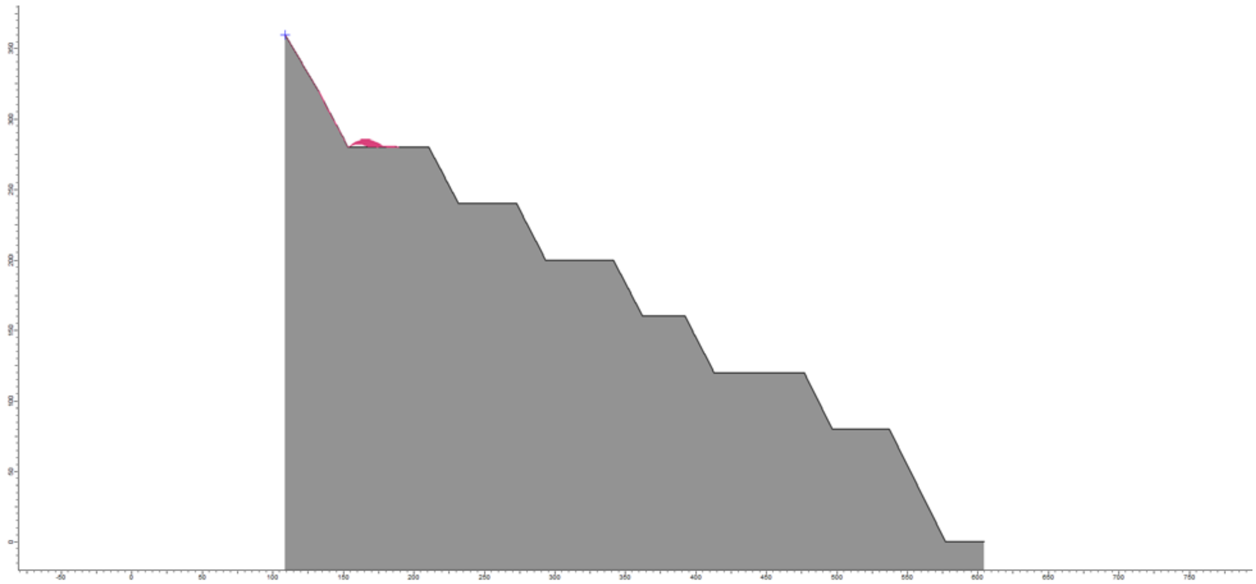

Figure 59: South wall Plan 1

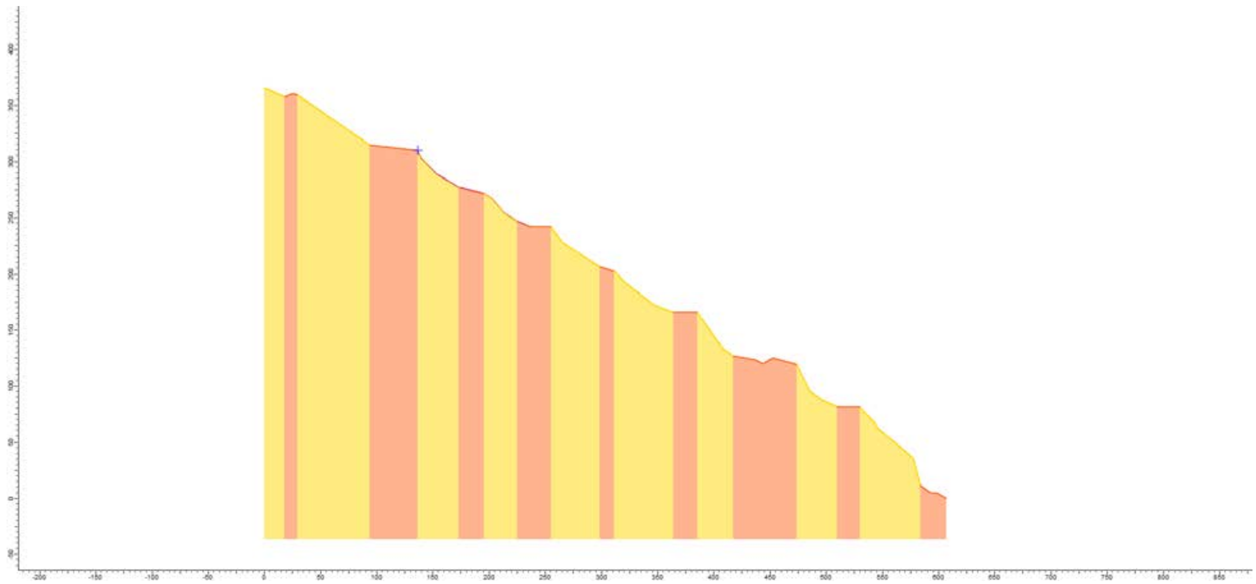

Figure 60: South wall Slope 1

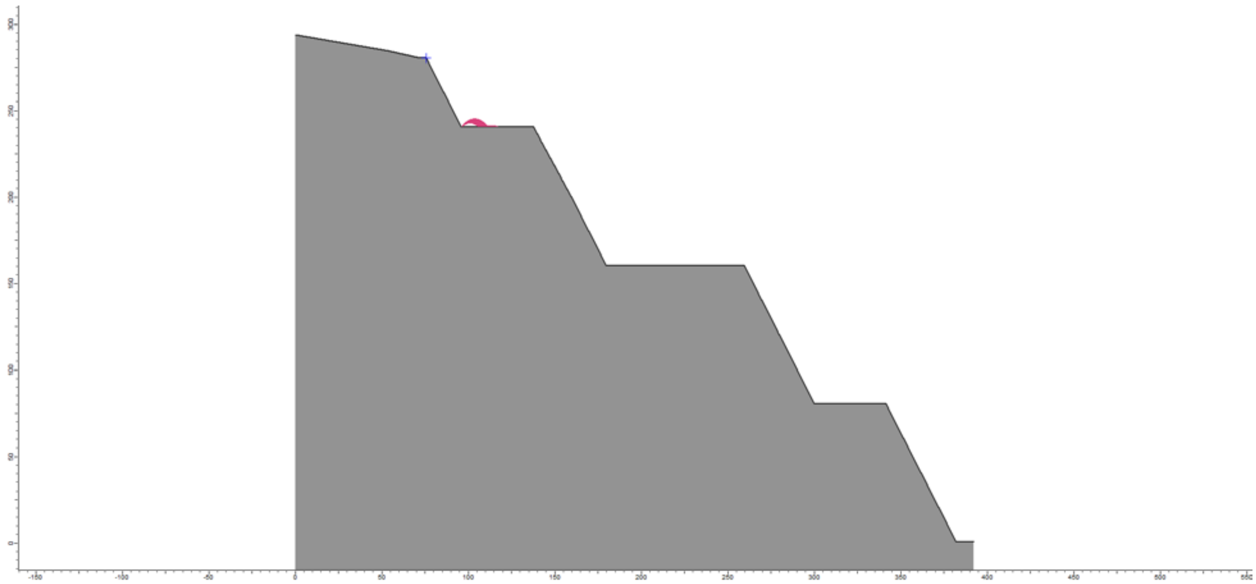

Figure 61: South wall Slope 1

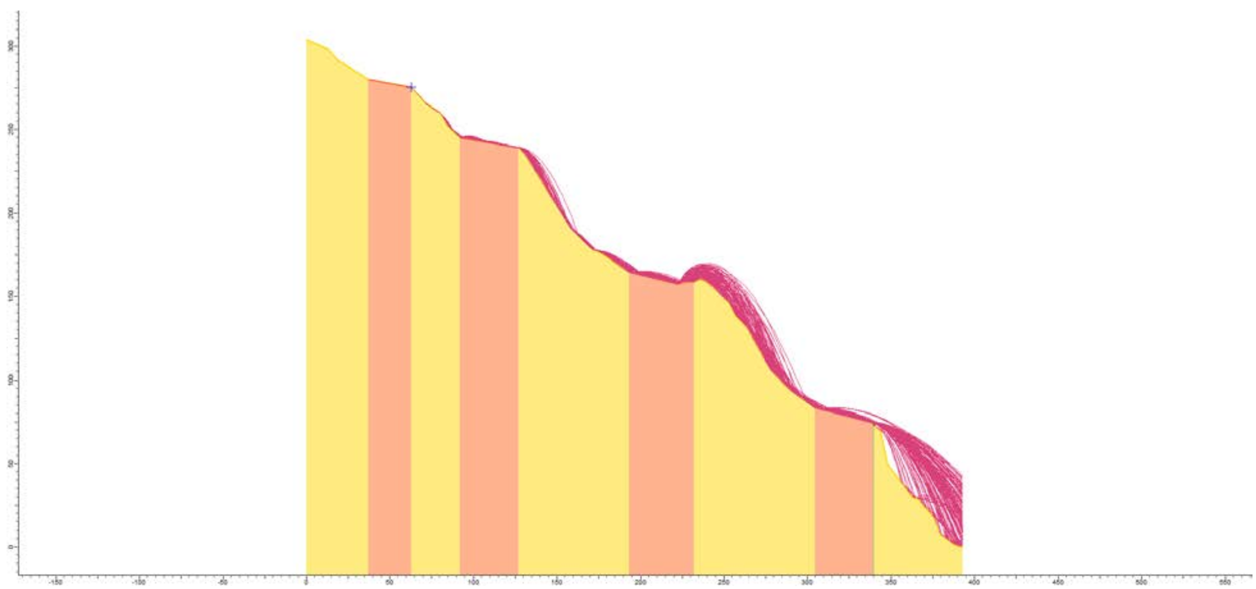

Figure 62: South wall Slope 2

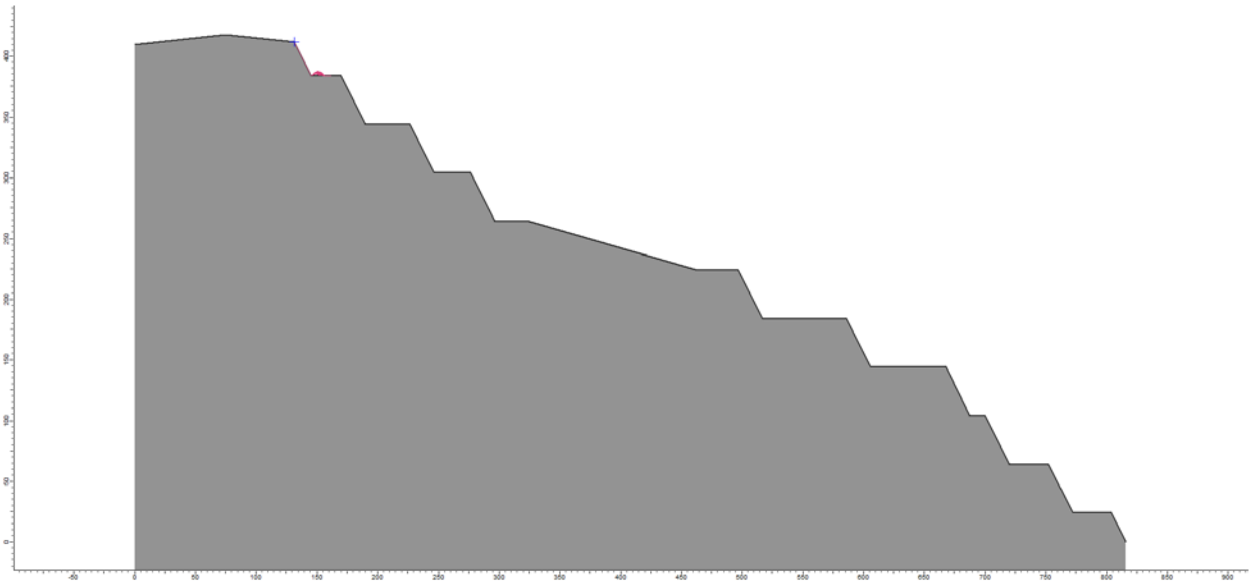

Figure 63: West wall Plan Slope 1

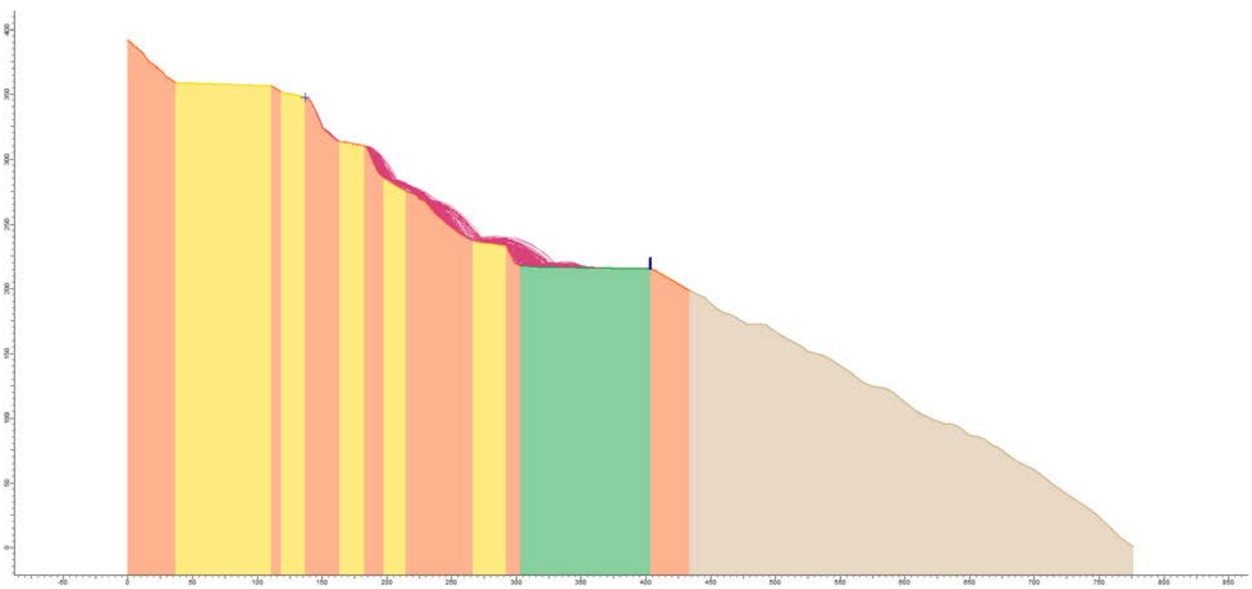

Figure 64: West wall Actual Slope 1

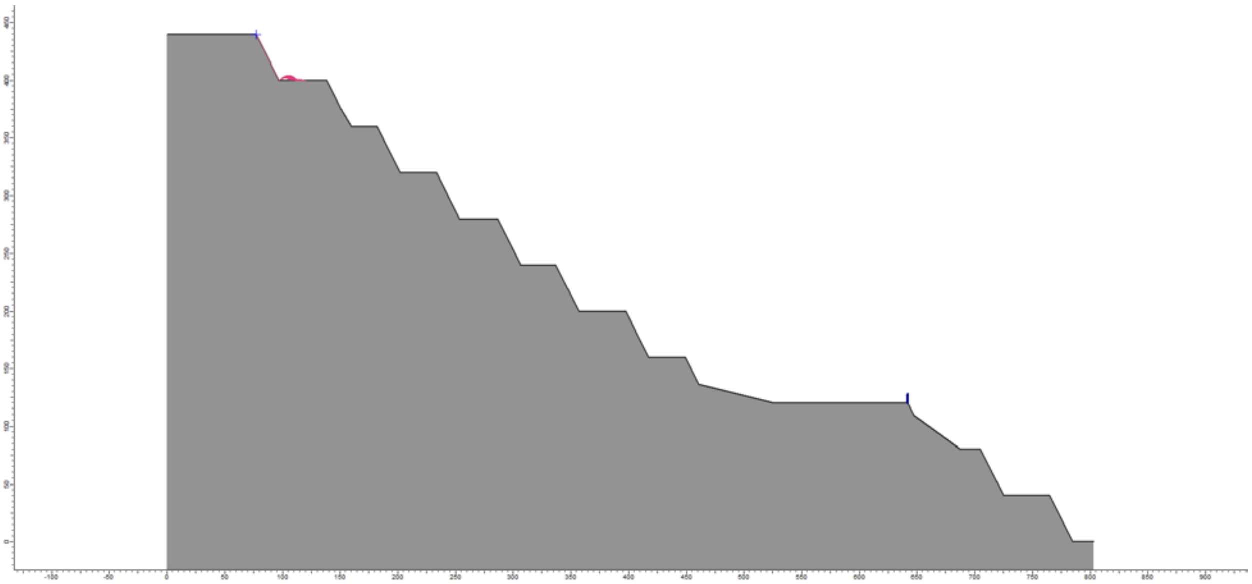

Figure 65: West wall Plan Slope 2

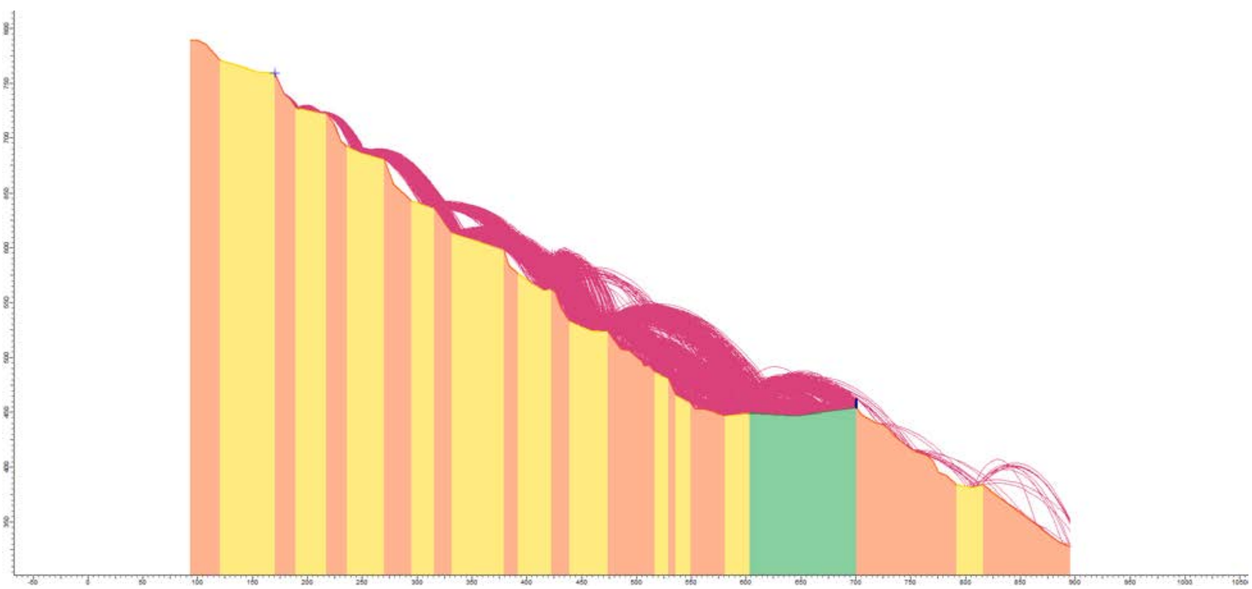

Figure 66: West wall Actual Slope 2

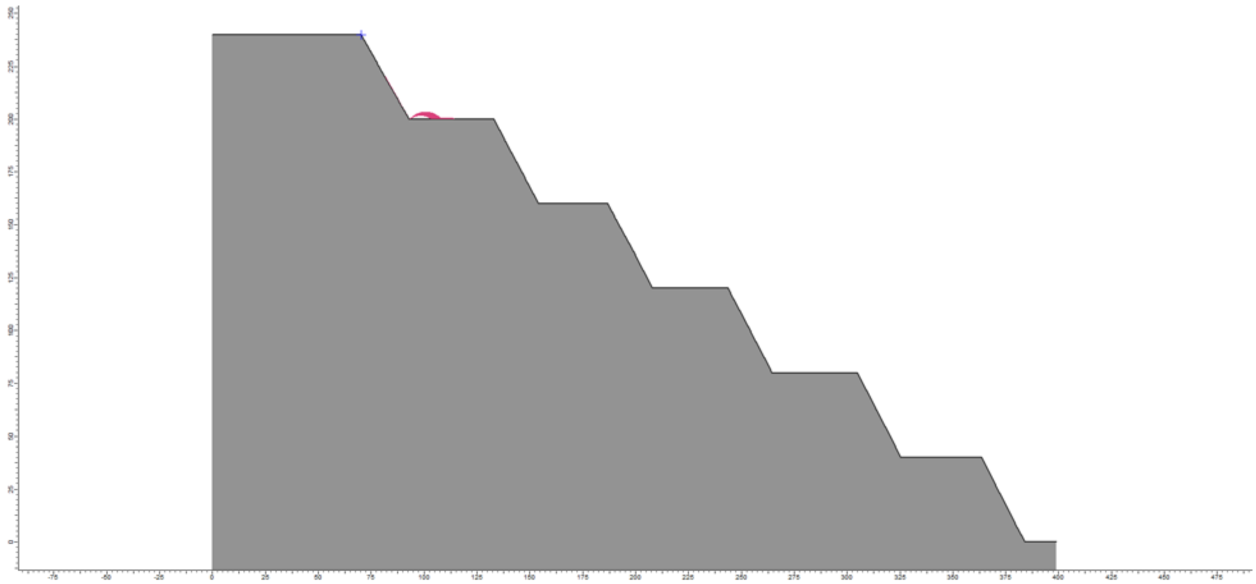

Figure 67: West wall Plan Slope 3

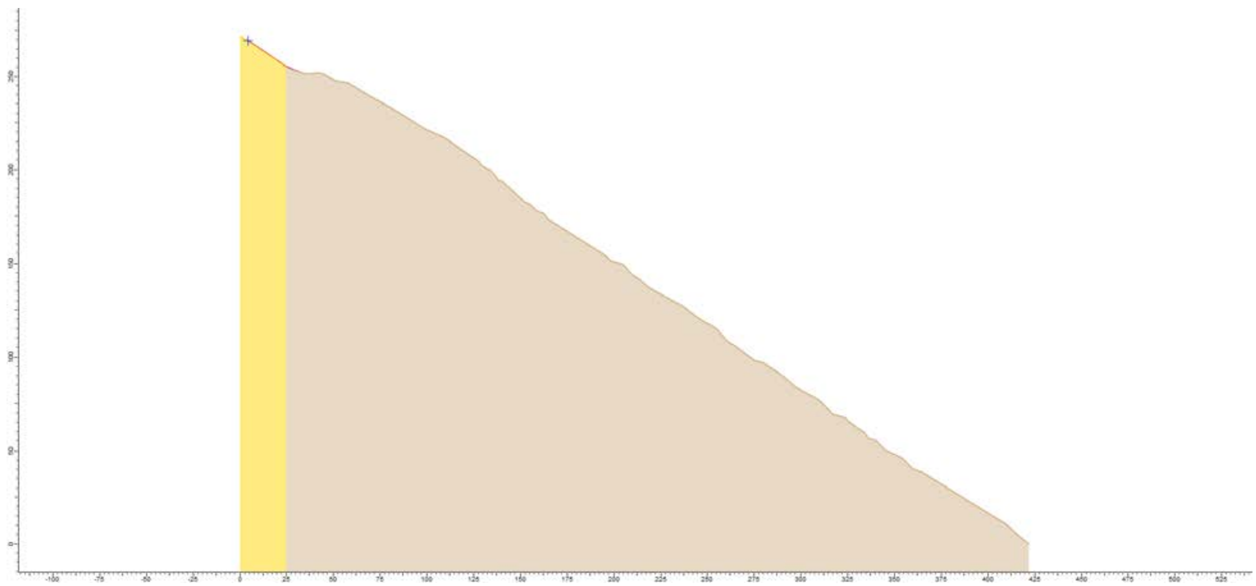

Figure 68: West wall Actual Slope 3

12. APPENDIX E: DISTANCE MEASUREMENT DATA

Available on a CD.

SIGNATURE PAGE

This is to certify that the thesis prepared by Judith A. Buaba entitled "Evaluation of Open Pit Highwall Dig Compliance" has been examined and approved for acceptance by the Department of Mining Engineering, Montana Tech of The University of Montana, on this 9th day of April, 2018.

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