Prediction of future settlement of backfill at an aggregate mining quarry site using numerical method and settlement monitoring data

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ABSTRACT

Future static settlement of a former aggregate mining quarry site in Irwindale, California is predicted based on the monitoring data and using numerical analyses that consider the total settlement of the deepest portion of the rockfill. The portion of quarry analyzed was backfilled with approximately 61 to 67 meters, has a volume of 2.6 million m^3, and covers an area of 114,900 m^2. The backfill material ranges from silty sand (SM) to silty gravel (GM) and was compacted to achieve an average relative compaction (RC) of 96%. The deepest fill area is currently being monitored with survey data to predict future 50-year settlement due to secondary compression. Settlement monument data from three different locations has been collected and made available starting from May 2009 up to now. A 3-dimensional model of the rockfill was used to determine an appropriate upper and lower bound of predicted future 50-year settlement from today in 13 stages and scenarios. The modified secondary compression index was estimated along with the modified compression index that was back calculated to match the field monitoring data. We could find good agreement between the field monitoring data and our numerical model when considering total settlement of the rockfill.

Keywords: modified secondary compression index; modified compression index; rockfill; aggregate quarry.

1. Introduction

1.1. Quarry History

Irwindale has been a hub for aggregate mining operations in southern California due to its geology and proximity to construction markets. The portion of the quarry in Irwindale analyzed here was backfilled with approximately 61 to 67 meters, has a volume of 2.6 million m^3, and covers an area of 114,900 m^2. This site was an operating aggregate production quarry until 1987. Our study area is limited to the approximately eastern one-third portion of the aggregate mining quarry site as shown on Fig. 1. In 2005, operations began which included removal, processing, and compaction of imported fill materials as shown in Fig. 2. Quarry walls were mined to an inclination of approximately 1 to 1 (horizontal to vertical). The site was backfilled with 61 to 67 meters of compacted engineered fill compacted to a volume of approximately 2.6 million m^3. The site officially reached proposed grades by March 2018.

This paper presents the total settlement of the compacted rockfill within the quarry site which combines the elastic, primary consolidation, and secondary compression settlement based on the actual settlement monument data. Secondly, the remaining secondary settlement due to the self-weight of the fill and due to the proposed building load will be predicted based on the total settlement back-analysis experienced to date.

The model was simulated by defining site geometry, material properties, and utilizing staging. For sites with compacted fills such as deep mine backfills, settlement results from the weight of the fill itself (Gustafsson 2014). The element matrix of soil was estimated using back analysis and soil parameters based on the actual settlement measurements, and the corresponding displacement was simulated in this model.

Figure 1. Aerial photo of the site with Topographic Overlay

Figure 2. Aggregate Mining Quarry Site Operation

2. Site Characterization

2.1. Materials

Materials used as fill at the site included Inert Debris Engineered Fill (IDEF) and Azusa Rock from mining activities.

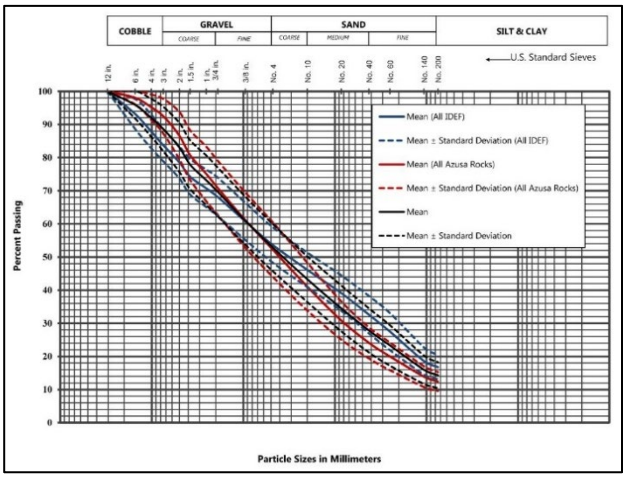


Figure 3. Gradation Results for Azusa Rock Backfill

This material ranges from silty sand (SM) to silty gravel (GM) as shown in Fig. 3. The material was compacted to achieve an average relative compaction (RC) of 96%. Azusa Rock and IDEF materials were spread by a dozer in lifts and compacted via vibratory sheepsfoot rollers and wheel rolling with 13,000-gallon water trucks.

The site specific geophysical study consisted of collecting dynamic soil properties of the rockfill using Multi-Channel Analysis of Surface Waves (MASW) approach as presented in Table 1 The average shear wave velocity to a depth of 30 m ($V_{s,30}$) is 420 m/s which correlates to Site Class C, very dense soil and soft rock.

Table 1. Shear Wave Velocity

Depth to Top of Layer (m)	Layer Thickness (m)	S-Wave Velocity (m/s)	Inferred Poisson's Ratio	Assumed Density kN/m^3
0	1.5	428	0.3	19.5
1.5	2.1	359	0.3	19.2
3.7	3.0	338	0.3	19.0
6.7	4.6	372	0.3	19.2
11.3	6.7	417	0.3	19.3
18.0	8.5	450	0.3	19.5
26.5	9.8	572	0.3	20.0

3. Data

3.1. Settlement Monuments

Settlement monuments (SM) were installed throughout the site at approximately 12-meter vertical intervals. Monuments consist of a 25-mm diameter steel pipe embedded in a concrete pad of 1.5 m × 1.5 m × 1 m placed within the fill. The survey pipe was placed within PVC casings and extended in 1.8-meter-long segments as the height of fill increased. The PVC casings were used to provide separation of the monument casing from subsequent monument foundations. No more than 20% of the foundation bearing surface was placed on hand compacted soil. The area immediately surrounding the monument pipes and casings have been hand compacted to the extent possible. The hand compacted zone was kept to a minimum around the monument pipes and casings, about 0.3 m. radius. A new monument was then installed above after 12 m of fill placed. Each monument level is designated by a number and followed by letters A, B, C, D, and E. A monument level followed by an A would represent the lowest monument elevation and E would represent the highest monument elevation at the surface. Typical Monument setup is shown on Fig. 4. Final Installation of Settlement Monument (SM) 15 at the surface is presented as Fig. 5.

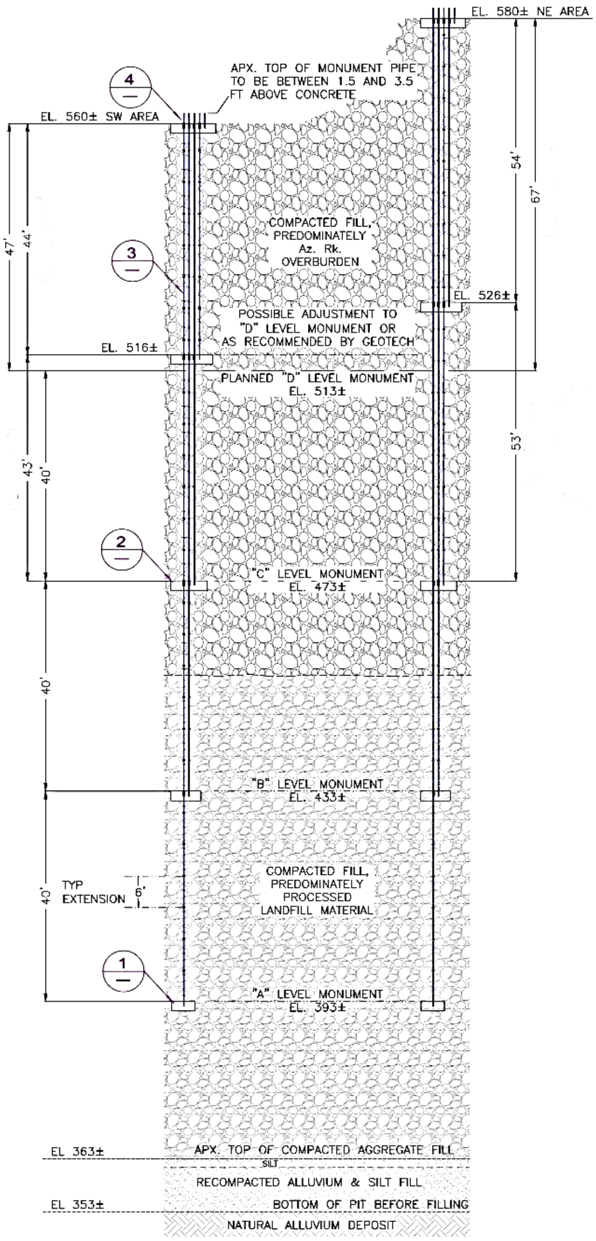


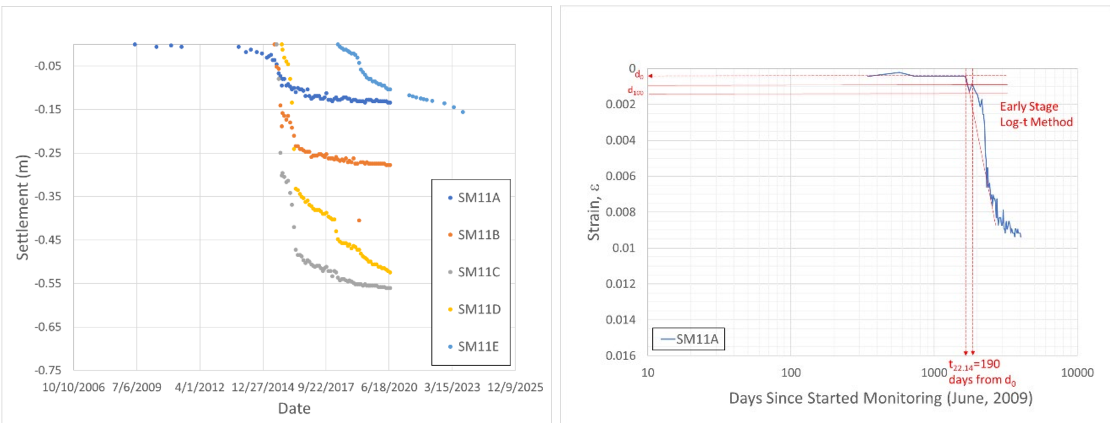
Figure 4. Typical Settlement Monument Setup

Figure 5. Final Installation of Settlement Monument (SM) 15

Additional settlement monuments were installed to monitor secondary settlement at the current ground surface. Monuments were constructed by drilling an approximately 0.6- to 1.2-meter deep and 30.5-cm diameter auger hole, pouring concrete, and inserting a 12-mm steel rebar vertically into the center of the fresh concrete. The SMs included in this evaluation are: SM11, SM12, and SM15. Settlement monument survey points have been read to 3×10^{-5} meters and the survey run generally closes with a closure error of less than 0.0015 meters. Surveys were conducted ranging from a weekly to a bi-annual basis.

3.2. Settlement Monument (SM) Data and Geotechnical Parameters

The SM survey data were studied to assess the compression characteristics of the compacted rockfill. This involved determining rates of compression over time during the primary consolidation and secondary compression resulting in coefficient of consolidation (C_v) and coefficient of secondary compression ($C_{\alpha\varepsilon}$) respectively. C_v was determined using the early-stage log-t method (Das and Sobhan 2018) and $C_{\alpha\varepsilon}$ was identified by the starting date of secondary compression based on the fill placement and the linear projection of settlement over logarithmic time at each depth level and for each SM location. The SM graphs used to evaluate $C_{\alpha\varepsilon}$ and C_v are presented on Fig. 6 through Fig. 8 and followed by Tables 2 through 4 that present values summarized at each settlement monument.



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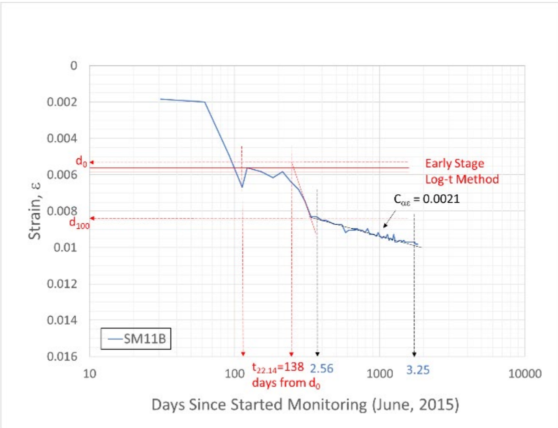

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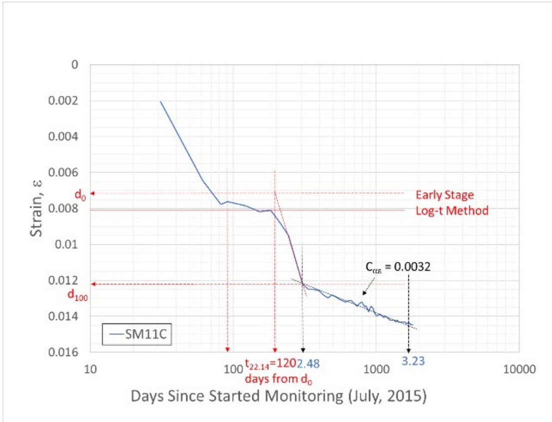

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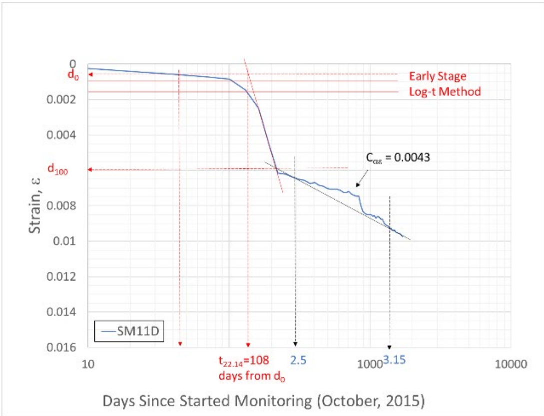

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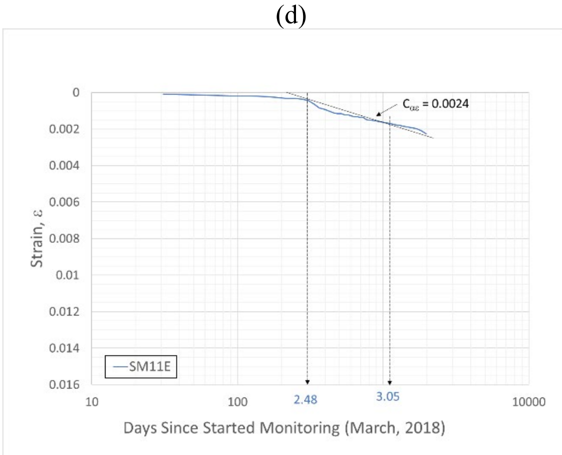

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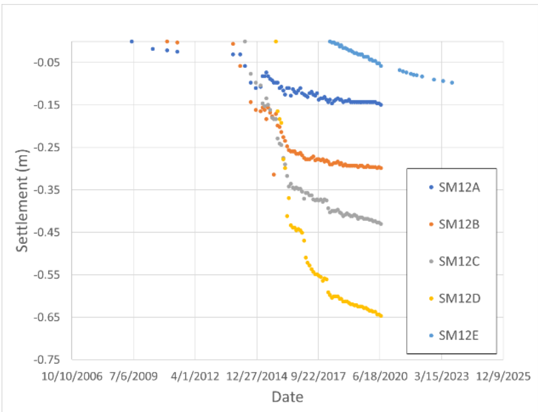
Figure 6. Settlement Monument (SM) 11 (Levels A to E)



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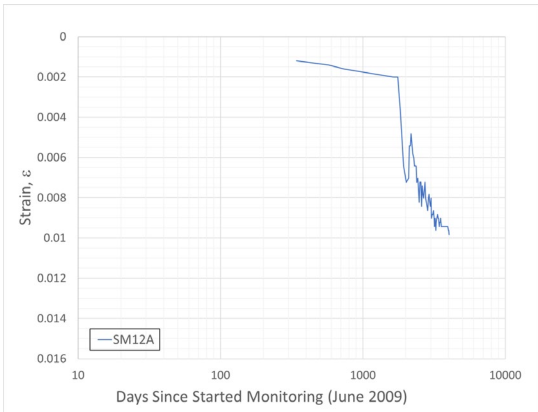

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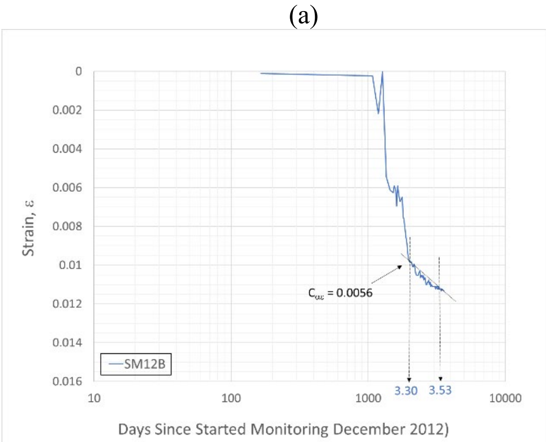

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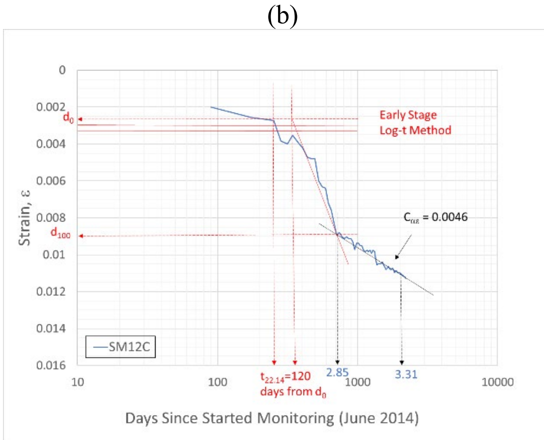

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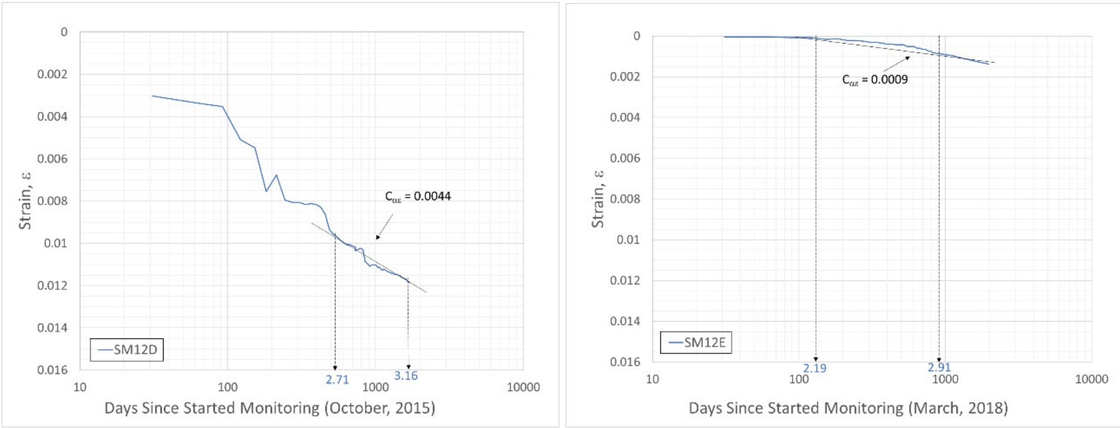

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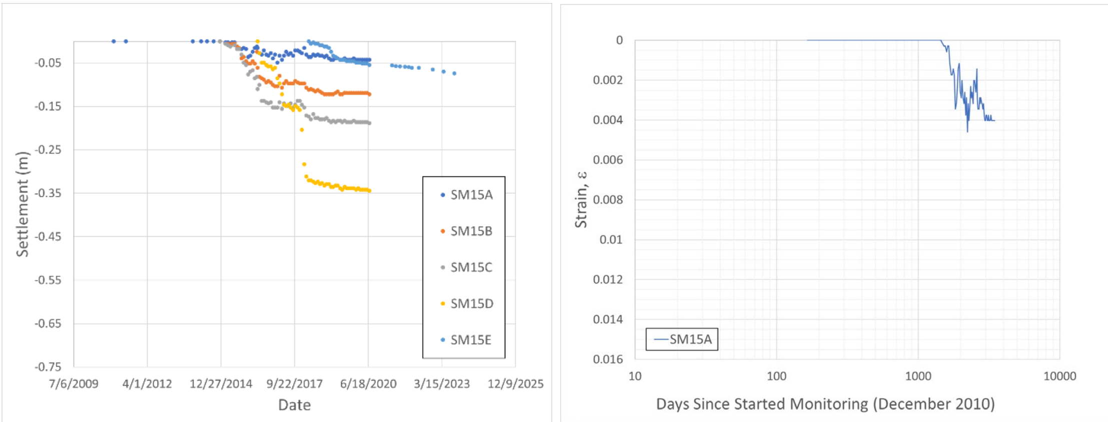
Figure 7. Settlement Monument (SM) 12 (Levels A to E)



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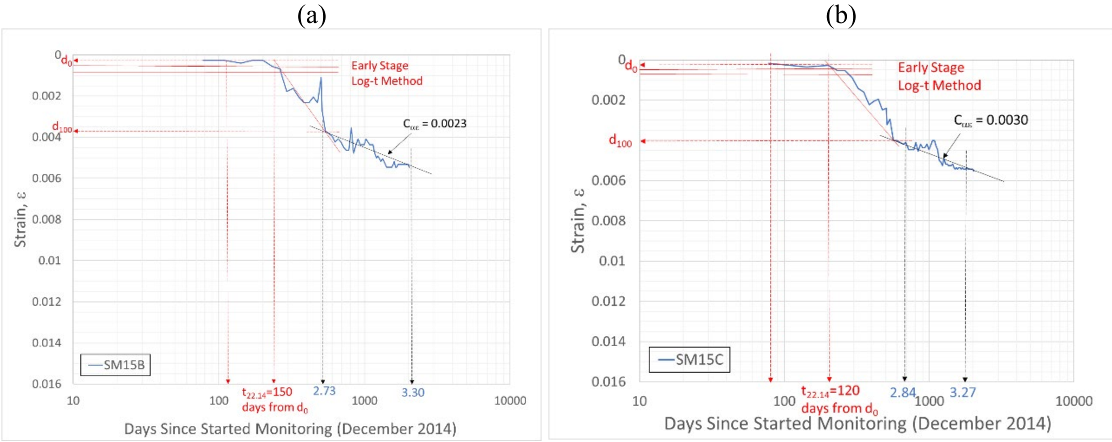

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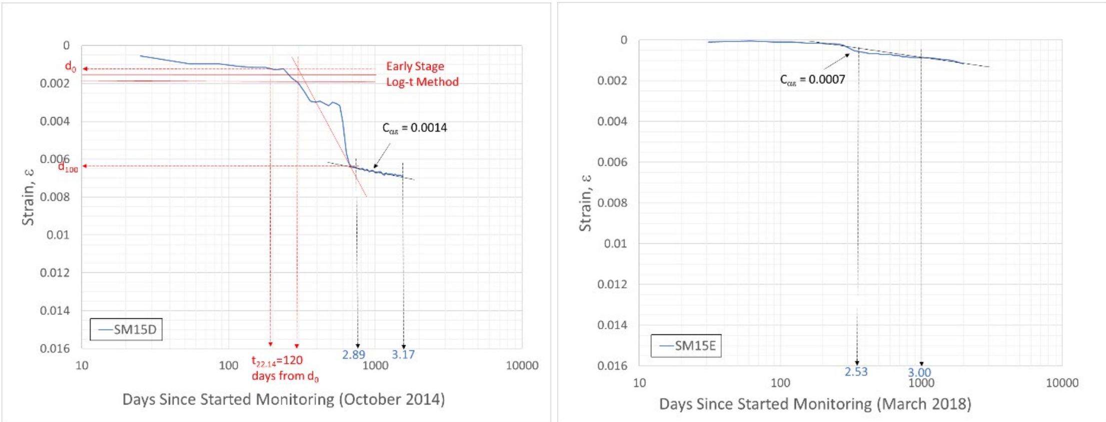

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Figure 8. Settlement Monument (SM) 15 (Levels A to E)

Table 2. Summary of Settlement Monument SM11 Geotechnical Parameters

Settlement Monument	C_v m²/year	$C_{\alpha\varepsilon}$
SM 11A	3.7	--
SM 11B	20.3	0.0021
SM 11C	44.0	0.0032
SM 11D	94.4	0.0045
SM 11E	--	0.0038
		Σ0.0136

Table 3. Summary of Settlement Monument SM12 Geotechnical Parameters

Settlement Monument	C_v m²/year	$C_{\alpha\varepsilon}$
SM 12A	--	--
SM 12B	--	0.0056
SM 12C	18.2	0.0046
SM 12D	--	0.0044
SM 12E	--	0.0009
		Σ0.0155

Table 4. Summary of Settlement Monument SM15 Geotechnical Parameters

Settlement Monument	C_v m²/year	$C_{\alpha\varepsilon}$
SM 15A	--	--
SM 15B	11.6	0.0023
SM 15C	13.3	0.0030
SM 15D	29.1	0.0014
SM 15E	--	0.0007
		Σ0.0074

As shown in summary Tables 2 through 4 C_{ae} was not measured at the "A" elevation since secondary compression had not begun yet. Similarly, C_v was not measured at the "E" elevation because primary consolidation has already started when the monuments were being surveyed. C_v was not measured in some levels (such as SM12 in Table 3) due to too much "static" in the settlement readings. This static was likely due to heavy earth moving equipment placing fill throughout the site and causing inconsistent dynamic loadings. This variable increase in the ground surface elevation along with inaccuracy of survey readings were likely the cause of the error in the settlement data. The average summation of $C_{\alpha\varepsilon}$ is approximately 0.012.

4. Data Analysis

4.1. Soil Input Parameters

We used the computer program Settle 3 (Rocscience Inc. 2007-2021) to predict the future settlements. Table 5 summarizes the soil properties used in this study. Field settlement curves were used to determine values for $C_{\alpha\varepsilon}$ and C_v as discussed in Section 3.2. Values for Young's modulus (E_s) and compression index ($C_{c\varepsilon}$) were evaluated by back-calculating to match the actual settlement that occurred.

Table 5. Settle3 Geotechnical Parameters

Immediate Settlement	E_s = 167,580 kPa
Primary Consolidation	$C_{c\varepsilon}$=0.038 (non-linear, strain-based) OCR=1.0 (normally consolidated) C_v= 94.4 m²/year
Secondary Compression	$C_{\alpha\varepsilon}$=0.0122 (strain-based)

4.2. Building Load

The development at this site is proposed to be a commercial building structure utilized as a warehouse/distribution centre. The building will be on the order of 40,190 m² (40 m by 95 m) surrounded by asphalt parking and pavement for vehicle access. Typically loading pressure for this type of building structure is approximately 9.58 kPa (California Buildings Standards Commission 2022).

4.3. Numerical Modelling

Table 6 summarizes the numerical modeling settings used in Settle3.

Table 6. Settle3 Modeling Summary

Project Settings	Stress Computation Method: Boussinesq Soil Profile: Non Horizontal Layers Interpolation Method: Inverse Distance Groundwater Analysis: Piezometric Lines Secondary Compression: 15% of primary (reset time when load changes)
Loads	Fill to El. 134m: 230 kPa (Bottom El. 123m) Fill to El. 148m: 230 kPa (Bottom El. 134m) Fill to El. 161.5m: 260 kPa (Bottom El. 148m) Fill to El. 175m: 260 kPa (Bottom El. 161.5m) Building Load: 9.5 kPa (Bottom El. 175)
Soil	Borehole Editor: 38 Boreholes Rockfill (Af) placed over Quaternary Alluvium (Qal)
Query	SM 106 (SM12), SM 108 (SM11), SM 110 (SM15)

Staging allows the model to simulate time-dependent consolidation analysis, during which the first portion of the model is used to represent fill loading and the remaining stages are used to represent the secondary compression in the next 50 years as shown in Table 7. During the staging, initial settlement, primary consolidation, and secondary compression were considered in the model. Based on this model, the total settlement in the next 50 years was predicted to be 113.5 cm due to the self-weight of the rockfill. A building load was applied at stage 2033 which corresponds to the year from today that the building is assumed to be constructed. Based on this model, the total settlement in the next 50 years is predicted to be 117.1 cm.

Table 7. Summary of Critical Staging and Loadings

	Settle3 Time (Years)	**Stage Name**
Bottom of Excavation	0	2005
Load A Applied	8	2013
Load B Applied	9.5-10.9	2014-2015
Load C Applied	10.3-11.5	2015-2016
Load D Applied	10.5-12.5	2015-2017
Today	18	2023
Building Load	28	2033
50-Year Settlement	68	2073

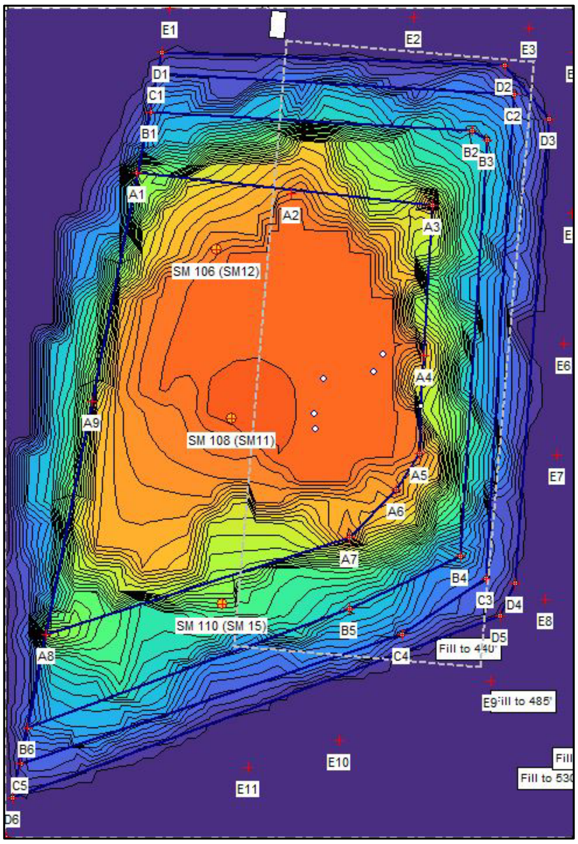

Figure 9. Settle3 Contour Plots

Three query points were used within the model to interpret this analysis based on the locations of the settlement monuments. The settlement contours representing the highest deformation within the quarry and approximate locations of the settlement monuments are presented in Fig. 9. In addition, total settlement graphs created from the query points are presented on three separate plots to compare with the actual survey data measured from the field as shown in Fig. 10 through Fig. 12.

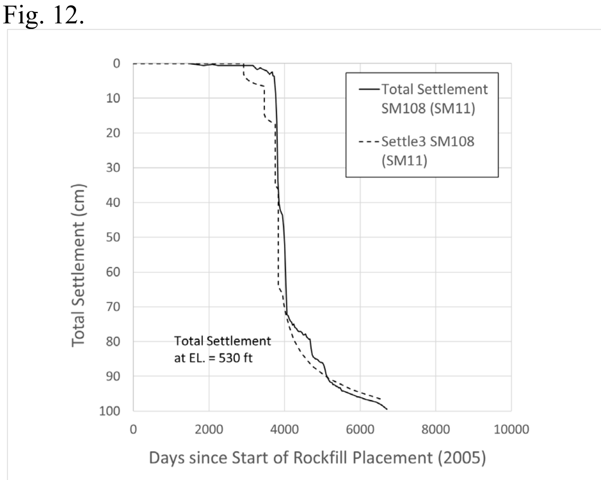

Figure 10. SM11 Settle3 Comparison

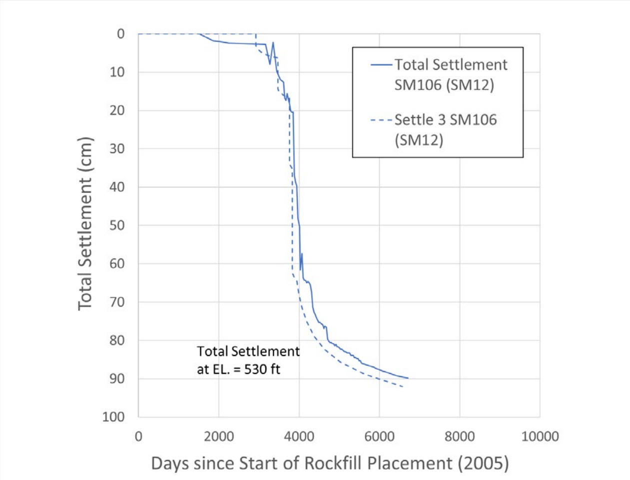

Figure 11. SM12 Settle3 Comparison

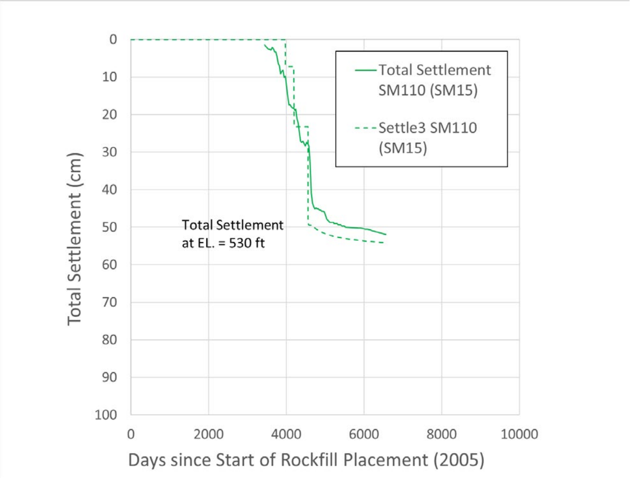

Figure 12. SM15 Settle3 Comparison

5. Interpretation

5.1. Static Settlement (Self-Weight)

The maximum total settlement measured to date at SM11, SM12, and SM15 is approximately 99.3, 89.9, and 51.8 cm, respectively. As shown in Fig. 10 through Fig.12, the maximum settlement to date based on the Settle3 back-calculated analysis is 96.8, 91.9, 54.1 cm, respectively. This means that the settlement at SM11 is slightly under-predicted and the settlement at SM12 is slightly over-predicted for the deepest fills placed in the quarry. At SM 15, the analysis is also slightly over-predicting settlement, but overall, the values are conservative with an average error of approximately 3%.

The analysed data in Settle3 resulted in a total settlement in the next 50 years at a minimum of 57.9 cm and a maximum of 113.5 cm. Therefore, the total remaining settlement from today ranges from 3.8 to 16.8 cm. The highest settlement of 16.8 cm is predicted to occur in the deepest portion of the rockfill and is predicted to reduce to a minimum settlement of 3.8 cm in the shallower portions of the rockfill.

5.2. Static Settlement (Building Load)

The total settlement based on the Settle3 model is approximately 117.1 cm due to the self-weight of the fill and a building load. This means that the building will add approximately 3.6 cm of additional settlement in the next 50 years if it is constructed in 10 years from today. The longer the building takes to be constructed the less additional settlement will likely occur due to the strain hardening occurring in the soil.

6. Conclusions

Future settlement of backfill made up of mostly Silty Sand (SM) and Silty Gravel (GM) at an aggregate mining quarry site using numerical method and settlement monitoring data was predicted to be approximately 16.8 cm. Future building loads are predicted to induce an additional 3.6 cm of settlement in approximately 10 years from today.

The most influential parameters within the model were the modified compression index ($C_{c\varepsilon}$) and the secondary compression index ($C_{\alpha\varepsilon}$). The modified compression index was back calculated to be 0.038 until an average total settlement was approximately the same as the surveyed total settlement. The secondary compression index was estimated to be 0.0122 using survey data and can vary due to human error in estimating the slope of the semi-log curve and determining the end of primary consolidation (d_{100}).

Differential settlement should be considered as an additional topic of study for this project. Due to the massive size of the proposed building, differential settlement should also be considered due to the potential 20.4 cm of settlement in the centre of the building and smaller settlements towards the shallower portions of the fill.

Acknowledgements

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