EVALUATING GROUND SETTLEMENT ABOVE A MINED AREA

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ABSTRACT:

Many states allow construction of landfills over previously mined areas. However, mitigation of the underground mines by filling or removal is often required prior to landfill construction. A settlement analysis for the proposed vertical expansion of a residual waste landfill is presented in this paper. The primary purpose of the analysis was to evaluate the possibility of subsidence of an underground mined area underlying the landfill in response to the proposed 31 m high vertical expansion. The analysis was performed using the software FLAC (Fast Lagrangian Analysis of Continua) which is a two-dimensional explicit finite difference code. The results of the analysis show that the proposed vertical expansion would not cause mine subsidence but it would cause a small amount of elastic ground settlement. As a result, no negative impacts to the existing engineering components of the landfill liner system are anticipated after completion of the proposed vertical expansion. This settlement analysis provides an alternative to removal or filling of underground mines to obtain regulatory approval as demonstrated by this vertical expansion project.

INTRODUCTION:

This paper presents a ground settlement analysis for the proposed vertical expansion of a residual waste landfill at a coal fired power generation facility. The coal-fired power plant is located in Ohio and generates a substantial amount of coal combustion byproducts (CCB) that must be placed in a residual solid waste landfill to comply with the Ohio Environmental Protection Agency (OEPA) rules and regulations. The amount of Flue Gas Desulfurization (FGD) waste, a CCB, generated at this facility increased significantly with the promulgation of new Clean Air Act requirements. To accommodate disposal of the increased FGD volume, the existing residual solid waste landfill had to be expanded. Because of space constraints, it was decided to vertically expand the existing landfill by about 31 m.

Before approval would be granted by the OEPA, the owner had to demonstrate that the auger coal mines underlying the existing landfill would not be adversely impacted by the additional 31 m of CCB proposed for placement on top of the existing landfill. Many structures have been adversely impacted by mine subsidence such as roads and buildings (Holtz and Kovacs, 1981). To demonstrate the impact of the vertical expansion on the underlying coal mines, a ground settlement analysis was performed. The analysis shows that the small auger mined area did not pose a subsidence, instability, or negative threat to the existing engineering components of the landfill, and in particular the landfill liner system, after being subjected to the proposed vertical expansion. The analysis did show that the proposed vertical expansion would cause a tolerable amount of elastic ground settlement. This paper describes the investigation, laboratory testing, and analysis used to demonstrate that grouting of the mined area was not necessary to prevent subsidence of the mined area.

OEPA REGULATIONS:

Ohio Administrative Code 3745-30-06 (H)(3)(b) states "The residual solid waste landfill facility is not located within an area of potential subsidence due to an underground mine or within the angle of draw of an underground mine in existence on the date of receipt of the permit to install application by OEPA unless the potential impact to the facility due to subsidence is minimized."

The Rule includes a clarifying comment that states: "Removal or filling of the mines is an acceptable method for minimizing the potential for subsidence." The following analysis demonstrates that the vertical stress imposed by the 31 m vertical expansion would not induce mine subsidence. Detrimental mine subsidence is subsidence caused by movement and/or collapse of old mining works that adversely impacts the landfill facility and in particular the landfill liner system. In contrast, ground settlement means the compression of the existing rock above the mined area due to the 31 m vertical expansion.

SITE DESCRIPTION:

A small mined area measuring approximately 788 m^2 (8,475 square feet) in plan view is located along the mid-point of the existing landfill. The plan dimensions of the mined area are approximately 61.1 m long by 13.7 m wide. The mined coal seam is the Middle Kittanning No 6. Coal and mining operations were conducted in the 1960s by the Simco-Peabody Company.

The thickness of the coal seam mined in this small area is approximately 1.1 m and thus a 1.1 m thick opening is used in the settlement analysis even though the opening may be less than the full thickness of the coal seam. The small mined area consists of three (3) continuous auger mines with two fixed supports at each end and two intermediate columns or pillars that support and separate the three auger mines. The width of each of the three mine entries is 3.1, 2.7, and 3.1 m. Based on available drawings and profiles of adjacent mine cuts, it appears that mining was performed along the north-south axis, with mine entry located at the north end.

To minimize the potential impact of mine subsidence on the facility, and thus ensure compliance with OAC Rule 3745-30-06, the owner executed a mine grouting program, which was completed in 1996. The purpose of the mine grouting was to inject a fly ash/cement grout mix into the old coal mine works to prevent potential subsidence due to the planned expansion of the landfill. The project began in July, 1995 and was completed in June, 1996. Suspected voids from previous coal mining activities were identified from original mine maps. The mine maps indicated areas of continuous and auger mine works in two adjacent areas, partially under the existing landfill and partially under a presently undeveloped area. The grouting program included horizontal directional drilling under the landfill and conventional vertical drilling in the undeveloped area of the landfill. The work was accomplished by performing 608 vertical grout holes, totaling 8,169 linear meters of drilling. The vertical holes received 2,526 cubic meters of grout. Eight horizontal directional borings totaling 2,197 linear meters of drilling, and 4,773 cubic meters of grout, were also used. Unfortunately, the grouting records show that this small mined area, i.e., these three auger mines, was not grouted as part of the 1996 grouting program.

SUBSURFACE INVESTIGATION AND LABORATORY TESTING:

To determine site-specific engineering properties of the sandstone and shale above the mined area and below the liner system, a borehole was drilled in 2004 in close proximity to the mined area. The borehole was advanced using a drill rig, model CME-550X, equipped with hollow stem auger and NQ-2 rock core sampler. The boring was extended to approximately 52 m below the existing ground surface. Figure 1 presents a geologic profile in the vicinity of the small mined area. The three auger mines are overlain by 3.1 m thick gray clay shale, 9.1 m of intact sandstone, and the low-permeability recompacted soil liner and overlying PVC geomembrane. The low-permeability recompacted soil liner is modeled as sandy clay in the subsidence analysis.

After reviewing the rock quality designation data of the rock cores in the boring log and the physical characteristics of the rock cores, samples of sandstone and shale were selected for laboratory testing. The unconfined compression tests were performed in accordance with ASTM D-3148 to determine the stress-axial strain response of the rock. The test results were used to determine unit weight (γ), modulus of elasticity (E), strain at failure (ε_f), and unconfined compressive strength (q_u), and shear strength (c) of the rock. The results of these tests are summarized in Table 1. Because ASTM method D-3418 is an unconfined uniaxial test, the resulting modulus of elasticity corresponds to an unconfined stress state. Of course, at the

Table 1 – Unconfined Laboratory Tests Results

Elevation (ft)	**Rock Type**	**Specimen ID**	**γ (kN/m^3)**	**q_u (kPa)**	**C (kPa)**	**ε_f (%)**	**E (kPa)**
883.5-882.5	Sandstone	RS-1	22.96	56,516	28,258	1.6	5.03E+06
872.5-871.5	Sandstone	RS-2	22.50	34,688	17,344	1.38	3.92E+06
868.5-867.5	Sandstone	RS-3 (bottom)	21.61	33,874	16,937	1.25	4.93E+06
	Sandstone	RS-3 (top)	21.56	26,786	13,393	1.16	4.14E+06
853.5-852.5	Shale	RS-4 (bottom)	24.89	37,570	18,785	1.75	3.62E+06
	Shale	RS-4 (top)	24.95	55,848	27,924	1.93	4.68E+06
848.5-847.5	Shale	RS-5	24.61	36,956	18,478	2.13	3.29E+06

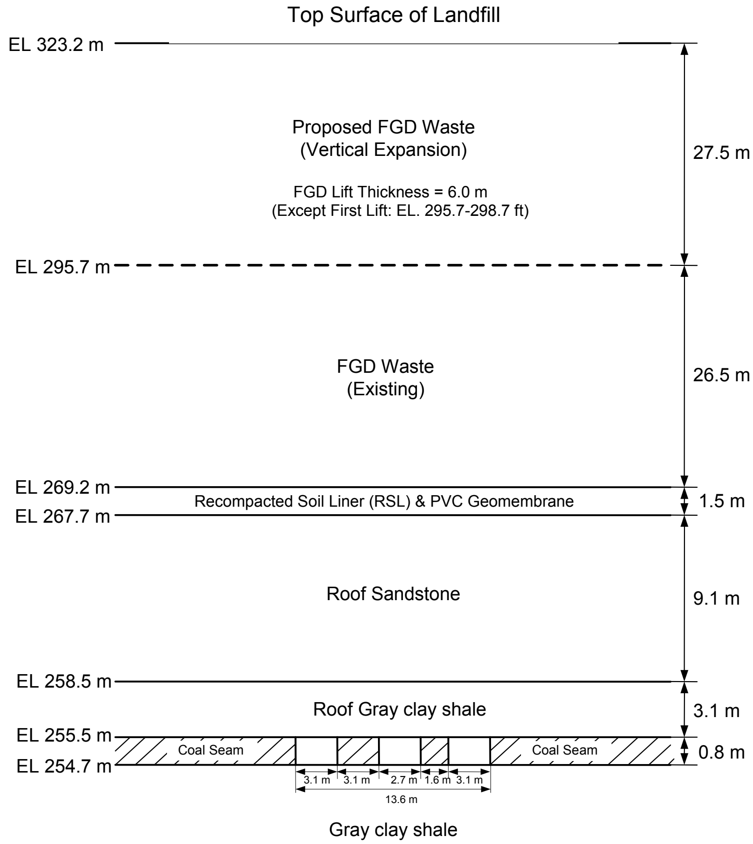

Fig. 1 Typical geologic profile

depth of the mine the rock is confined and thus these results were used to estimate the corresponding confined modulus. Table 2 presents estimated values of confined modulus using data in Table 1 and the method presented in Abel (1988).

Table 2 – Estimated Values of Confined Modulus Using Abel (1988).

Elevation (ft)	**Rock Type**	**Specimen ID**	**q_C (kPa)**	**c (kPa)**	**Ratio E/q_u**	**E (kPa)**
883.5-882.5	Sandstone	RS-1	1.69E+05	8.47E+04	88.69	1.50E+07
872.5-871.5	Sandstone	RS-2	1.04E+05	5.22E+04	112.9	1.17E+07
	Sandstone	RS-3 (bottom)	1.02E+05	5.08E+04	145.74	1.48E+07
868.5-867.5	Sandstone	RS-3 (top)	8.04E+04	4.02E+04	154.44	1.24E+07
	Shale	RS-4 (bottom)	1.13E+05	5.65E+04	96.35	1.09E+07
853.5-852.5	Shale	RS-4 (top)	1.68E+05	8.38E+04	83.83	1.40E+07
848.5-847.5	Shale	RS-5	1.11E+05	5.55E+04	88.99	9.86E+06

The minimum, maximum, and average values of Young's modulus of elasticity from the following sources: (i) unconfined laboratory tests, (ii) estimated values for a confined condition to simulate actual subsurface stress condition, and (iii) literature values are presented in Table 3. Comparing the modulus of elasticity values obtained for the confined stress condition and the literature values show good agreement. Based on the review of various data and the range of values in Table 3, design values of Young's modulus for the sandstone and shale shown in Table 3 were used in the ground settlement analysis. These design values essentially correspond to the average confined values (see Table 3). The average of the cohesion values shown in Table 2 for the sandstone and shale, i.e., $57.0x10^3$ and $65.1x10^3$ kPa, respectively, were also used in the mine subsidence analysis.

Table 3 – Summary of Young's Modulus of Elasticity (E) Data.

Rock Type	Young's Modulus (E) (kPa)							
	Minimum		Maximum		Average		Publi-shed Value	Design Value
	Unconfined	Confined	Unconfined	Confined	Unconfined	Confined		
Sand stone	3.92E+06	1.17E+07	5.03E+06	1.50E+07	4.50E+06	1.35E+07	1.92E+07	1.34E+07
Shale	3.29E+06	9.86E+06	4.68E+06	1.40E+07	3.86E+06	1.16E+07	1.10E+07	1.15E+07

FLAC MODEL FOR UNDERGROUND MINE:

The small mined area is approximately located at elevation of 255.5 m (838 ft) as shown in Figure 1. The auger mines are underlain by shale and are overlain by stratums of shale and sandstone that serve as a mine roof and a dissipater of the vertical stresses applied at the ground surface by the landfill, respectively. The sandstone is overlain by at least 2.4 m of a low-permeability recompacted soil liner (LPSL), which is overlain by waste. The state regulations require a 1.5 m thick layer of LPSL to meet the geologic isolation zone criterion. At this site, the bedrock is lined with at least 2.4 m thick layer of low-permeability recompacted soil that satisfies the OEPA geologic isolation zone criterion. Construction records indicate that the thickness of the LPSL placed over the sandstone ranges from 2.4 to 4.6 m in thickness, but definitely exceeds 1.5 m. To be conservative, only a 1.5 m thickness for the LPSL is used in the analysis as shown in Figure 1.

A finite element mesh was developed to model the generalized geologic profile and the small underground mined area shown in Figure 1. Near the middle of the mesh, three openings are used to represent the three auger mines. The mesh is shown in Figure 2 and is drawn to-scale so the three mine openings are barely visible/extremely small (see small white rectangles) in comparison with the overlying bedrock and landfill. Because of the small appearance of the mines in the full mesh, it is not surprising that placement of 27.5 m of FGD (unit weight = 13.1 kN/m^3) to simulate the vertical expansion, did not significantly impact the deep auger mines.

Figure 1 shows that the low-permeability soil layer is overlain by approximately 26.4 m of existing waste, which is applied in the ground settlement analysis in four lifts, i.e., 5.1, 6.1, 6.1, and 9.1 m. The waste for the vertical expansion is applied in 6.1 m lifts with the exception of the first lift elevation 295.9 m (970 ft) to 298.9 m (980 ft)), which is 3.1 m thick. Thus, the vertical expansion of the existing landfill from elevation 205.9 m is applied in five lifts. Even though the proposed vertical expansion is only to an elevation of 327.3 m, the ground settlement analysis continued to a waste elevation of 335.5 m using a lift thickness of 3.1 m each. Therefore, four more lifts were placed so the landfill could reach elevation 335.5 m. Extending the settlement analysis to elevation 335.5 m is a worst-case scenario, i.e., waste over-filling, to ensure that there is no detrimental impact to the LPSL even if the landfill height was inadvertently extended an additional 12.2 m.

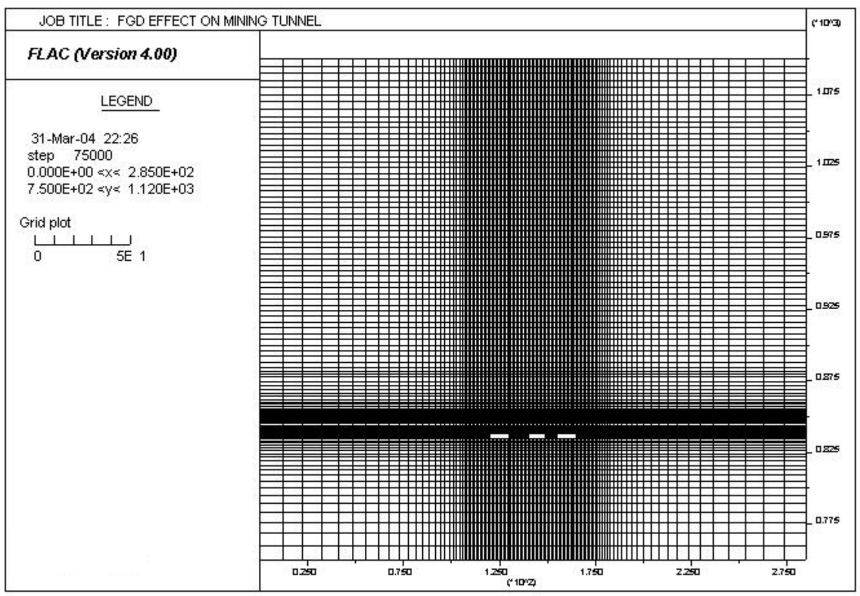

Fig. 2 Finite element mesh in the vicinity of the auger mines

A second finite element mesh was created to model the worst-case scenario which assumes that the intermediate pillars separating the three auger mines (see Figure 1) have been removed or compromised over time and thus provide no support. This worst-case is modeled using one opening that spans from the left side of the left mine to the right side of the right mine or a distance of 13.6 m. It is doubtful that the two intermediate pillars have been completely removed but it will be shown that the LPSL will not be subjected to any detrimental settlement and the mines will not undergo mine subsidence even if the pillars have been removed or compromised. The settlement analysis also used a conservative final waste height of elevation 335.5 m using 3.1 m thick lifts. Thus, a waste elevation of 335.5 m and no mine pillars represents two worst-case scenarios, i.e., waste over filling and lose of the mine supports.

The ground settlement analysis was conducted using the finite difference program FLAC. FLAC (Fast Lagrangian Analysis of Continua) is a two-dimensional explicit finite difference code that simulates the behavior of structures built of soil, rock, or other materials that undergo plastic flow when their yield limit is reached. The basic formulation used in FLAC for the analysis of tunnels assumes a two-dimensional plane strain condition. This condition is associated with long structures or excavations with constant cross-sectional area and subjected to loads in the plane of the cross-section. There is also a three-dimensional version of FLAC (Flac3D) but it was not used because the plane-strain analysis was deemed sufficient for the three abandoned auger mines beneath this landfill. FLAC also allows the inclusion of holes or excavations, e.g., a tunnel, in a finite element mesh using the built-in "null" model. Thus, the "null" model is used in the analysis to represent the three auger mines in the analysis with mine pillars and to represent one larger mine opening in the analysis without mine pillars. For the ground settlement analysis presented herein, the elasto-plastic, Mohr-Coulomb constitutive model was used to model all of the materials shown in Table 4.

Table 4: Material Properties used in FLAC Settlement/Mine Subsidence Analysis

Material Type	Unit Weight, γ (kN/m^3)	E (kPa)	Poisson's Ratio, ν	c' (kPa)	ϕ' (deg.)	Source or Reference for Material Properties
FGD (aged)	13.1	4.6×10^6	0.4	191.5	0	Cemented sand E and ν from Baig et al. (1997) and c' and ϕ' from Ohio State University (OSU)
FGD (new)	13.1	3.5×10^6	0.4	0	38.0	
Low-Permeability Soil layer	20.4	2.0×10^5	0.25	0	25.0	Bardet (1997) Sandy clay
Roof Sandstone	22.2	1.3×10^7	0.38	5.7x 10^4	0	Tests performed by OSU
Roof Gray clay shale	24.5	1.1×10^7	0.29	6.51x 10^4	0	Tests performed by OSU
Coal seam/Mined Area	18.9	3.6×10^6	0.3	7182	10.0	Hoek and Brown (1980)
Bottom Gray clay shale	24.5	1.1×10^7	0.29	6.51x 10^4	0	Tests performed by OSU

DISCUSSION OF FLAC RESULTS:

FLAC was used to estimate the subsidence or vertical displacement (Δ) at the top of the three auger mines and the settlement at the top of the sandstone layer, i.e., bottom of the LPSL (see Figure 1). The subsidence at the top of the mines is of interest to determine the impact of the proposed vertical expansion on these abandoned mines but the ground settlement at the top of the sandstone is probably more relevant for determining the impact of the proposed vertical expansion on the existing LPSL. Because the sandstone underlies the LPSL, settlement of the sandstone could have a detrimental impact on the LPSL. For example, if the sandstone settles substantially it would undermine the LPSL over the mined area and induce tensile stresses and strains in this layer which could result in an increase in hydraulic conductivity. Thus, the FLAC vertical displacement at the LPSL/sandstone interface is discussed below.

The vertical displacement at the LPSL/sandstone interface above each of the three auger mines is essentially the same and is 1.9 mm (Δ_{max}) for a maximum waste elevation of 335.5 m. The vertical displacement at the LPSL/sandstone interface is primarily due to elastic ground settlement, not mine subsidence or mine collapse. The FLAC results also show that displacement at the LPSL/sandstone interface due to the proposed vertical expansion would be about the same as the settlement induced by placement of the current waste height (~1.0 mm).

LaGatta et al. (1997) present a database of the failure tensile strain for laboratory compacted clay specimens. These specimens are significantly thinner than the 2.4 – 4.6 m thick LPSL present at this landfill. Thus, the allowable tensile strains for this LPSL are expected to be greater than the failure tensile strains reported by LaGatta et al. (1997). LaGatta et al. (1997) suggest that a tensile strain of 0.2% for a Plasticity Index (PI) of 11 to a tensile strain of 4.4% for a PI of 32 is allowable for a low plasticity compacted clay. The calculated distortion (Δ/L) at the soil/sandstone interface across the middle 2.7 m wide mine opening (see Figure 1) is calculated to be 0.0014 using Δ_{max} of 1.9 mm divided by 1.35 m or one-half of the middle mine opening. The distortion is calculated by dividing the maximum differential settlement, i.e., settlement at the center of the mined area minus the settlement outside the mined area, over the length that the differential settlement is occurring, which is one-half of the mine width (Δ_{max}/L).

The average tensile strain caused by distortion can be computed by integrating over the deflected shape to determine the arc length of the deformed section. LaGatta et al. (1997) present a chart that relates distortion to tensile strain. Using this chart and the distortion of 0.0014 calculated above, the tensile strain induced at the bottom of the LPSL due to elastic ground settlement, not mine subsidence, of 1.9 mm which is less than the recommended 0.1% based on a mine width of 2.7 m. This tensile strain is also in agreement with the tensile strain calculated for the relevant elements using FLAC. The calculated tensile strains are below the allowable tensile strain of 0.2 to 4.4% suggested by LaGatta et al. (1997). Therefore, the analyses indicate no detrimental impact.

Figure 3 presents the settlement profile based on the results of the FLAC analyses at the top of the LPSL/sandstone interface for the cases of "with" and "without" intermediate support pillars in the mined area and a waste elevation of 335.5 m. The profiles represent the calculated pattern of distortion. The pattern of distortion provides a more reliable method for calculating strains because it can be evaluated over the actual length over which the differential settlement is calculated using FLAC and not only over the width of the mined area. For example, for the case of "with" support pillars, the maximum vertical displacement (Δ_{max}) of 1.9 mm is dissipated over 16.8 m instead of 1.35 m. The distance of 16.8 m corresponds to the distance from zero vertical displacement to Δ_{max} as shown in Figure 3 and the distance of 1.35 m corresponds to one-half of the mine opening. The resulting distortion is 1.9 mm divided by 16.8 m or 0.00011. This distortion is an order of magnitude less than the distortion of 0.0014 calculated using 1.9 mm divided by 1.35 m and also results in negligible tensile strain in the LPSL. For the no support pillars case, the maximum vertical displacement of 2.8 mm is dissipated over 16.8 m instead of 6.8 m which is one-half of the mined area without pillars or 13.6 m. The resulting distortion is 2.8 mm divided by 16.8 m or 0.00016. This distortion is significantly less than the distortion of 0.0006 calculated using 2.8 mm divided by 4.5 m. This distortion also will not result in any detrimental tensile strains to the LPSL even if the mine pillars are lost or removed.

Based on an allowable tensile strain of 0.2 to 4.4% suggested by LaGatta et al. (1997) for a low plastic soils and the presence of support pillars, the LPSL should not be adversely impacted by the increase in vertical stress caused by the proposed vertical expansion. Even if the support pillars have been removed or compromised over time, the soil layer should not be adversely impacted by the increase in vertical stress caused by the proposed vertical expansion. Thus, the potential impact to the facility due to ground settlement and/or mine subsidence is negligible because the vertical expansion is not inducing a vertical stress that is sufficient to cause detrimental tensile strains in the existing soil layer or subsidence of the abandoned mines. The calculated vertical displacement at the LPSL/sandstone interface is primarily due to elastic ground settlement, not mine subsidence or mine collapse. The calculated vertical stresses were verified using Boussinesq's stress distribution theory using charts in Holtz and Kovacs (1981).

CONCLUSIONS:

Mine subsidence is an important design issue for the expansion or development of landfills overlying abandoned coal mines because regulations usually prohibit a landfill in an area of potential mine subsidence. To comply with state regulation, the abandoned mines usually have to filled/grouted to prevent subsidence. This paper presents a ground settlement/mine subsidence analysis that was used to demonstrate that the vertical expansion of an existing landfill facility would not apply sufficient vertical stress to the three underground auger mine to induce detrimental mine subsidence so the open mines did not have to be grouted. The vertical expansion may induce some minor elastic deformation of the layers overlying the mines but not mine subsidence.

Based on the results of the FLAC analyses, the subsurface geological setting, the engineering properties of the materials encountered, and long-term monitoring and stability of the existing landfill, it is concluded that subsidence of the three underground auger mines would not occur due to the proposed vertical expansion. It appears that this type of analysis can be used for other sites to evaluate the potential for mine subsidence and ground settlement and the impact, if any, on the engineered components of the overlying landfill.

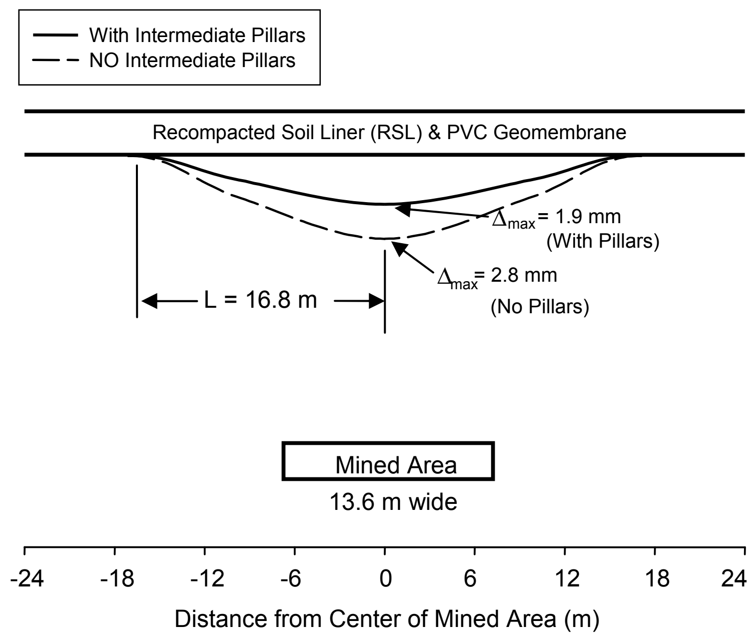

Fig. 3 :Subsidence profile at LPSL/sandstone interface with and without pillars in mined area.

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