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Comparative Optimization of Straight vs Curved Retaining Walls in Stiff Sandy Clay and Crushed Pebble Gravel using PLAXIS 3D

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Abstract: Based on Optimization of geometry of the deep excavation support system is essential in reducing horizontal displacements, bending moments, and costs of construction. Though previous studies have shown the need for curved retaining walls in expansive soils such as Black Cotton soil, this paper undertakes a 3D finite element parametric study to determine the performance of curved retaining walls which are non-circular against straight retaining walls in moderate to high strength soils. Using PLAXIS 3D software, models were constructed for a 10 meter deep excavation in two different soils that is, Stiff Sandy Clay and Crushed Pebble Gravel. Ultimately, it establishes when an arched geometry serves as an optimal structural choice versus when it becomes economically redundant.
Keywords: Curved Retaining Wall, Stiff Sandy Clay, Crushed Pebble Gravel, PLAXIS 3D, Finite Element Analysis, Arched Geometry, Diaphragm Wall, Straight Cantilever Retaining Wall, Plate Model, Mohr-Coulomb Model, Hardening Model.

I. INTRODUCTION

When digging deep into the ground, we have to make sure the surrounding soil and nearby buildings don't move or collapse. To do this, engineers usually build straight retaining walls. These walls rely entirely on their own bending strength to hold back the heavy soil. But for very deep excavations, these straight walls have to be extremely thick and packed with steel reinforcement, which is expensive and difficult to build.

To solve this problem, we can use Curved Retaining Walls instead. Just like curved water dams, these arched walls push the soil pressure sideways along the curve rather than just bending under the weight. In our first study, we showed straight and curved retaining walls using expansive soils like Black Cotton Soil. However, we still need to know if curved walls are actually necessary when the soil is stronger. A wall's stability depends entirely on the type of soil it is holding back. Weak clays need serious structural help, but stronger soils like Stiff Sandy Clay or Crushed Pebble Gravel not push against the wall nearly as hard. This paper builds on our previous work by using PLAXIS 3D software to test how these walls behave in stronger soils. We compared both straight and curved walls in Stiff Sandy Clay and Crushed Pebble Gravel.

II. LITERATURE REVIEW

1) Sandip M Chavan, Dr. Vijay Sharma (2017) used PLAXIS 2D to study how a standard 4m straight retaining wall behaves in Black Cotton soil. They found that because this soil shrinks and swells so much, a normal straight wall is highly unstable and moves around too much. They concluded that to make the wall safe, engineers have to use expensive deep pile foundations.
2) Jakub Stacho, Monika Sulovska (2019) also used PLAXIS, but they looked at how different types of gravel can improve the ground. They discovered that crushed pebble gravel has an incredibly high internal friction angle (around 52°) because of its rough, angular edges. This makes it extremely strong and great at holding weight without deforming. We are using their findings in our study to see if using such strong gravel makes curving the retaining wall unnecessary.
3) Daniel Gilmore, Dr. Raul Fuentes (2017) wanted to see if they could minimize wall movement simply by curving it. By applying a method usually used to design curved water dams, they proved that an arched shape naturally pushes the soil pressure outward toward the corners of the excavation. Their calculations showed that a curved wall can reduce horizontal movement by 15% to 25% compared to a straight wall, which means engineers wouldn't need to use as many internal steel props.

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4) Zhang, Y. P., & Zhang, T. Q. (2001) similarly looked into arched retaining walls as a smart, cost-effective alternative for deep foundation pits. They explained that curving the wall creates a much better structural shape that naturally leads to less bending and lower construction costs, simply by splitting the soil forces horizontally soil loads through horizontal arching action.
5) H. F. Schweiger, F. Scharinger, & R. Lüftenegger, (2009) compared 2D and 3D computer models of a deep excavation. They found that while a basic 2D model could somewhat guess how the wall would bend, it did a very poor job of predicting how the ground around it would actually settle. Because the excavation site was a complex 3D shape (roughly square), they proved that a full 3D analysis is absolutely required to get accurate results in these types of soils.

III. MODELLING METHODOLOGY AND ANALYSIS

A 3D Finite Element study of Straight and Curved retaining walls was conducted following a systematic methodology in PLAXIS 3D. A total of 4 numerical models were to be developed using Stiff sandy clay & Crushed Pebble Gravel:

A. Soil mode & Material properties:

The numerical model domain was established with dimensions of 100m x 100m. Contours were established as shown in Table 1.

TABLE 1: SET CONTOURS (IN M)

Contours (in m)	
X_{min}	-50m
X_{max}	50m
Y_{min}	-50m
Y_{max}	50m

It is done for mitigating boundary condition effects during the deep excavation analysis. A borehole is placed at 0,0,0, top elevation is set to 0m, whereas bottom elevation is set to -50m to get massive clay block created. Water table Head is set to -50 such that pore water pressure will not interfere with the wall. Now add materials for soil layers as per Table 2.

TABLE 2: THE PROPERTIES USED FOR STIFF SANDY CLAY & CRUSHED PEBBLE GRAVEL

General	Material set	Identification	Stiff Sandy Clay	Crushed Pebble Gravel
		Material model	Mohr-Coulomb	Hardening Soil
		Drainage type	Drained	Drained
	General properties	γ_{unsat} (Unsaturated unit weight)	15 KN/m^3	17.36 KN/m^3
		γ_{sat} (Saturated unit weight)	20 KN/m^3	19.55 KN/m^3
Parameters	Stiffness	E' (Young's modulus)	50*10^3 KN/m^2	-
		E_{50}ref = E_{oed} ref	-	65.8*10^3 KN/m^2
		E_{ur} ref	-	197.4*10^3 KN/m^2
		ν' (Poisson's ratio)	0.3	0.5
	Strength	c'_{ref} (Cohesion)	15 KN/m^2	1 KN/m^2
		φ' (phi – friction angle)	30^o	51.8^o
		ψ (psi - Dilatancy angle)	0^0	21.8^0
	Advanced	K_0^{nc}	-	0.3
Groundwater	Flow parameters	$K_x = K_y$	-	864 m/day
Interfaces	Strength	Strength	Rigid	Rigid
Initial	K_0 settings	K_0 determination	Automatic	Automatic

B. Structures mode:

Draw line for making Straight and Curved retaining walls. Dimensions of the wall are given in Table 3:

TABLE 3: DIMENSIONS OF THE WALL

Length of the wall (L)	30m
Retained Height (H)	10m

Embedded depth (D)	10m
Arch Rise	2m

For Straight retaining wall use the following in command window:

_line (-15 -15 0) (15 -15 0)

Whereas for Curved retaining wall, make a parabolic arch of span 30m. From x = -15m to x = 15m and bulges outward by 2m at the centre. Use the following in command window:
_line (-15 -15 0) (-12 -15.72 0) (-9 -16.28 0) (-6 -16.68 0) (-3 -16.92 0) (0 -17 0) (3 -16.92 0) (6 -16.68 0) (9 -16.28 0) (12 -15.72 0) (15 -15 0)
Turn the created lines into 20m deep plate by Extruding them and hence create them Plate according to Table 4:

TABLE 4: EXTRUDE THE LINES

Extrusion Vector	
X	0
Y	0
Z	-20m

Create material as Diaphragm wall and Assign to the above created plates as per the properties used in Table 5:

TABLE 5: THE PROPERTIES USED FOR DIAPHRAGM WALL

Material set	Identification	Diaphragm Wall
	Material type	Elastic
Properties	d (Thickness)	1m
	γ (Unit weight)	25 KN/m^3
	Isotropic	No
	E_1 (Vertical Stiffness)	$28*10^6$ KN/m^2
	E_2 (Horizontal Stiffness)	$2.8*10^6$ KN/m^2 [10% of vertical]
	ν_{12} (Poisson's ratio)	0.2
	G_{12} (Shear Moduli)	$11.67*10^6$ KN/m^2
	G_{13}	$11.67*10^6$ KN/m^2
	G_{23}	$1.167*10^6$ KN/m^2

Create material as Capping beam and Assign to the created lines as per the properties used in Table 6:

TABLE 6: THE PROPERTIES USED FOR CAPPING BEAM

Material set	Identification	Capping Beam
	Material type	Elastic
Properties	E	$15*10^6$ KN/m^2
	γ (Unit weight)	25 KN/m^3
	Beam type	User-defined
	A (Cross section area)	2m^2
	I_2 (Moment of Inertia)	0.667m^4
	I_3	0.167m^4

Create line and material as Steel prop in PLAXIS 3D it is beam as per properties shown in Table 7, which will connect straight side walls across the centre of excavation by entering the following command:

_line (-15 0 0) (15 0 0)

TABLE 7: THE PROPERTIES USED FOR STEEL PROP

Material set	Identification	Steel Prop
	Material type	Elastic
Properties	E	$210*10^6$ KN/m^2
	γ (Unit weight)	76.5 KN/m^3
	Beam type	User-defined
	A (Cross section area)	1m^2
	I_2 (Moment of Inertia)	0.12m^4
	I_3	0.12m^4

For Defining the Soil Excavation volume that is the 30m*30m chunk block of soil that will dug out. Create the surfaces using following commands and extrude it as pe Table 8:
_surface (-15 -15 0) (15 -15 0) (15 15 0) (-15 15 0)

TABLE 8: EXTRUDE THE SURFACE

Extrusion Vector	
X	0
Y	0
Z	-10m

For creating soil volumes in Straight and Curved retaining walls, create Surfaces by using the following commands and further assign the diaphragm walls to these created surfaces:

Left surface wall:
_surface (-15 15 0) (-15 -15 0) (-15 -15 -20) (-15 15 -20)

Right surface wall:
_surface (15 -15 0) (15 15 0) (15 15 -20) (15 -15 -20)

Back surface wall:
_surface (-15 -15 0) (15 -15 0) (15 -15 -20) (-15 -15 -20) [Do not do this for Straight Retaining wall].

C. Mesh mode:
In this mode, Select all the Beams and Plates one by one, and change the coarseness factor (which is by default 0.5) to 0.2. Then Generate Mesh, which will display the number of elements and nodes generated in command line. Verify this by viewing the mesh.

D. Staged construction:
This process will move Stage by Stage or Phases by Phases. Check whether during initial phase the calculation type is set to K_0 Procedure.
In Straight retaining wall,
Add Phase 1 and only Activate Plates
Add Phase 2 and only Activate Beams, and keep everything checked from Phase 1.
Add Phase 3 and Deactivate the 30m*30m top surface with 10m deep, and keep everything checked from previous phases.

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In Curved retaining wall:
Add Phase, Phase 1 expand Plates and only Activate Plate_1, Plate_4, Plate_7, Plate_10, Plate_11, Plate_12, Plate_13.
Add Phase 2 and Activate Plate_2, Plate_5, Plate_8 and keep everything checked from Phase 1.
Add Phase 3 and Activate Plate_3, Plate_6, Plate_9 and keep everything checked from previous phases.
Add phase 4 and Activate all Beams, and keep everything checked from previous phases.
Add phase 5 and and Deactivate the 30m*30m top surface with 10m deep, and keep everything checked from previous phases.
Finally, Calculate and process of all phases. The phases will turn green with checkmarks indicates PASS. And further View calculation results and generate a report.

IV. RESULTS AND DISCUSSION

1) *Horizontal Displacement:* To evaluate the performance of retaining walls, the maximum horizontal displacement (U_y) is extracted and compared in Figure 1. The conventional straight retaining wall exhibited a critical maximum displacement of 7mm (or 0.007m) in Stiff Sandy Clay, And 5.984mm (or 0.005984m) in Crushed Pebble Gravel . But by altering the geometry to a curve, the maximum displacement reduced to 5.927mm (or 0.005927 m) in Stiff Sandy Clay, And 3.305mm (or 0.003305m) in Crushed Pebble Gravel.
2) *Bending Moment:* The maximum Bending moment (M_{22}) observed and compared in Figure 2 in straight retaining wall is 79.38 KN-m in Stiff Sandy Clay, And 72.12 KN-m in Crushed Pebble Gravel. But for curved retaining wall it got reduced to 77.40 KN-m in Stiff Sandy Clay, And 71.15 KN-m in Crushed Pebble Gravel. This reduction proves that curved geometries not only limit physical soil movement but also actively relive structural stress from concrete panels.

Types of Soil	Stiff Sandy Clay		Crushed Pebble Gravel	
Parameters	Straight Retaining Wall	Curved Retaining Wall	Straight Retaining Wall	Curved Retaining Wall
U_y	0.007 m	0.005927 m	0.005984 m	0.003305 m
M_{22}	79.38 KN-m	77.40 KN-m	72.12 KN-m	71.15 KN-m

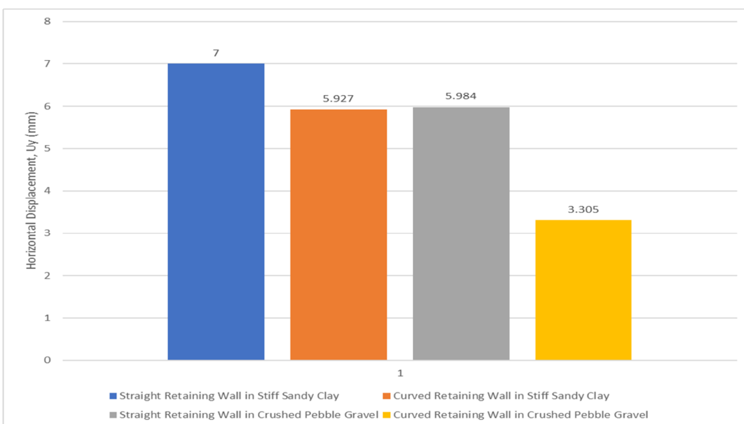


Figure 1: Horizontal Displacement Uy (mm)

Figure 2: Horizontal Bending Moments M22 (KN-m)

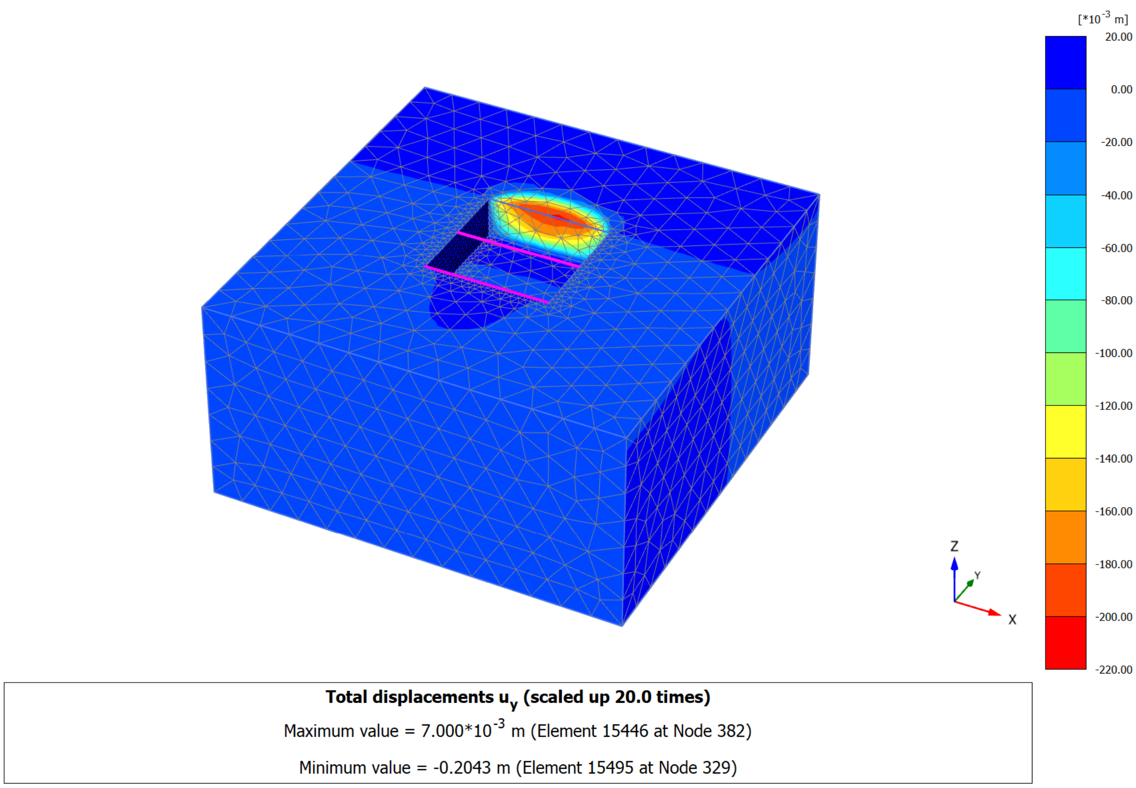
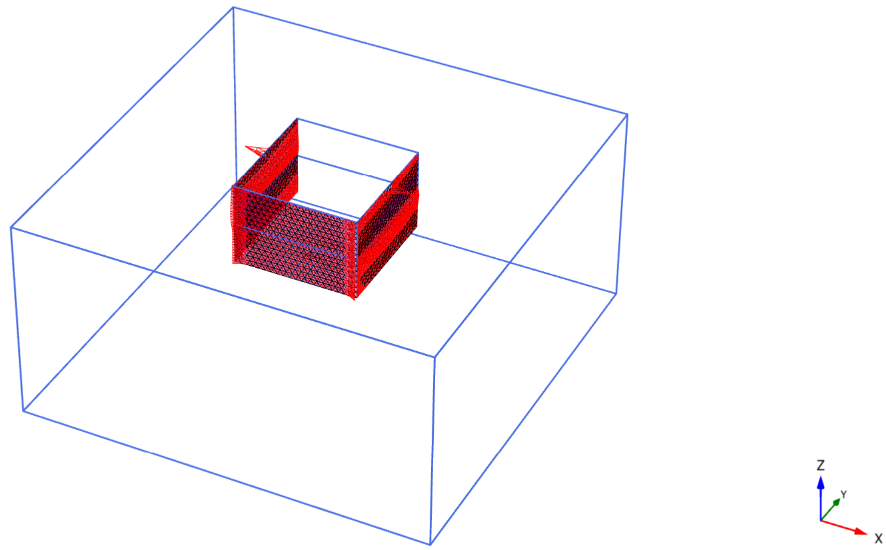


Figure 3: Horizontal displacement profile of Straight Retaining wall using Stiff Sandy Clay in PLAXIS 3D

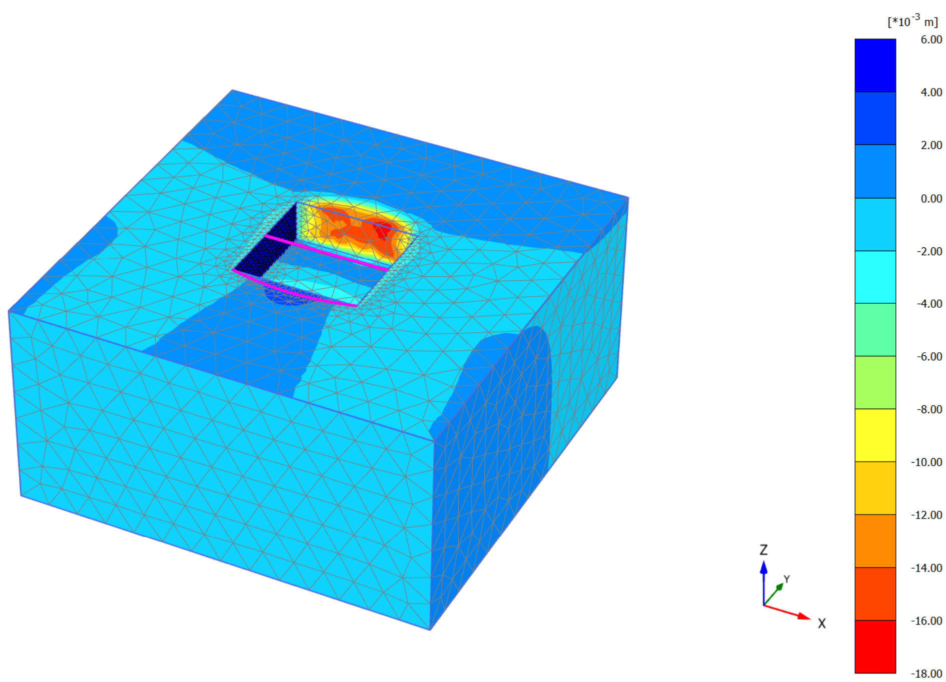


Bending moments M_{22} (scaled up $5.00*10^{-3}$ times)

Maximum value = 79.38 kN m/m (Element 810 at Node 5862)

Minimum value = -1046 kN m/m (Element 665 at Node 13)

Figure 4: Horizontal Bending moment of Straight Retaining wall using Stiff Sandy Clay in PLAXIS 3D



Total displacements u_y (scaled up 200 times)

Maximum value = $5.927*10^{-3}$ m (Element 9379 at Node 25021)

Minimum value = -0.01749 m (Element 17723 at Node 346)

Figure 5: Horizontal displacement profile of Curved Retaining wall using Stiff Sandy Clay in PLAXIS 3D

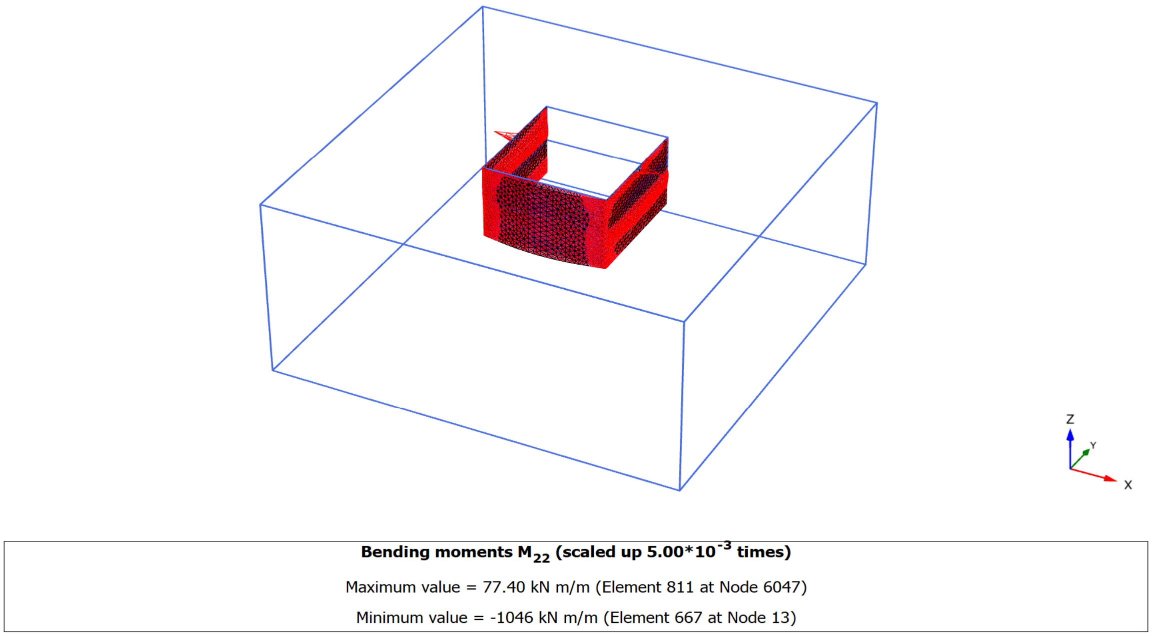


Figure 6: Horizontal Bending moment of Curved Retaining wall using Stiff Sandy Clay in PLAXIS 3D

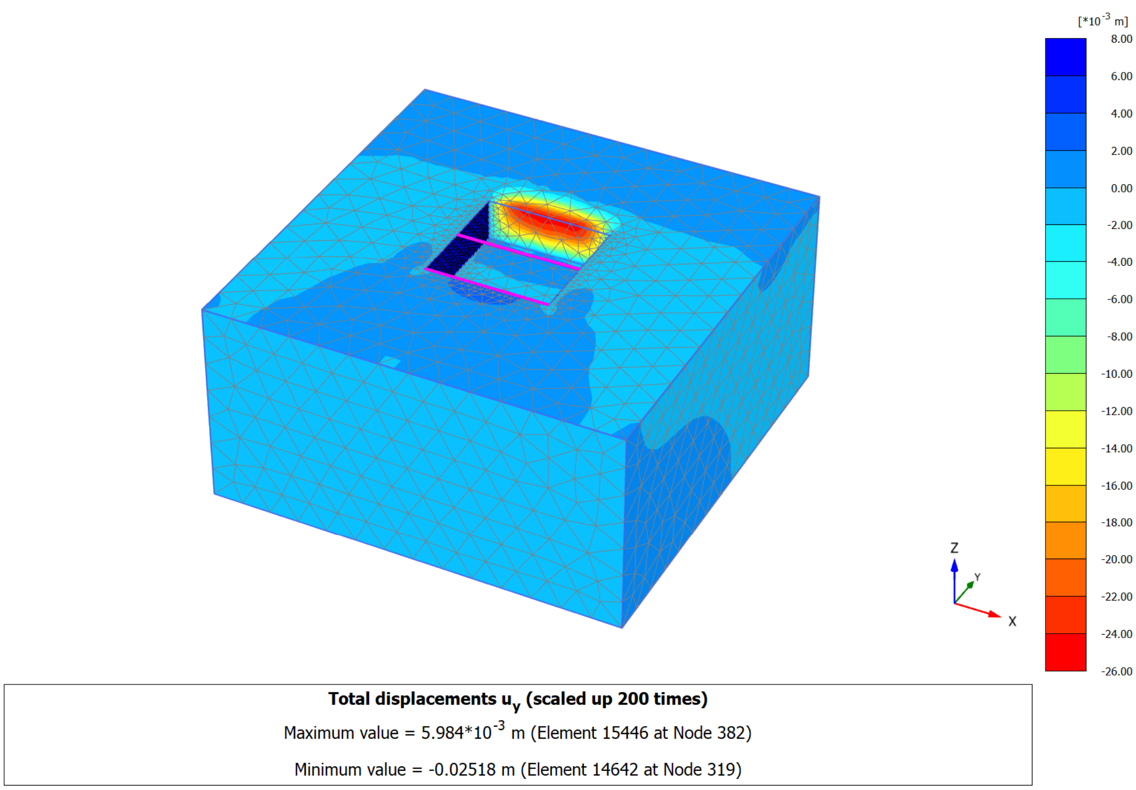


Figure 7: Horizontal displacement profile of Straight Retaining wall using Crushed Pebble Gravel in PLAXIS 3D

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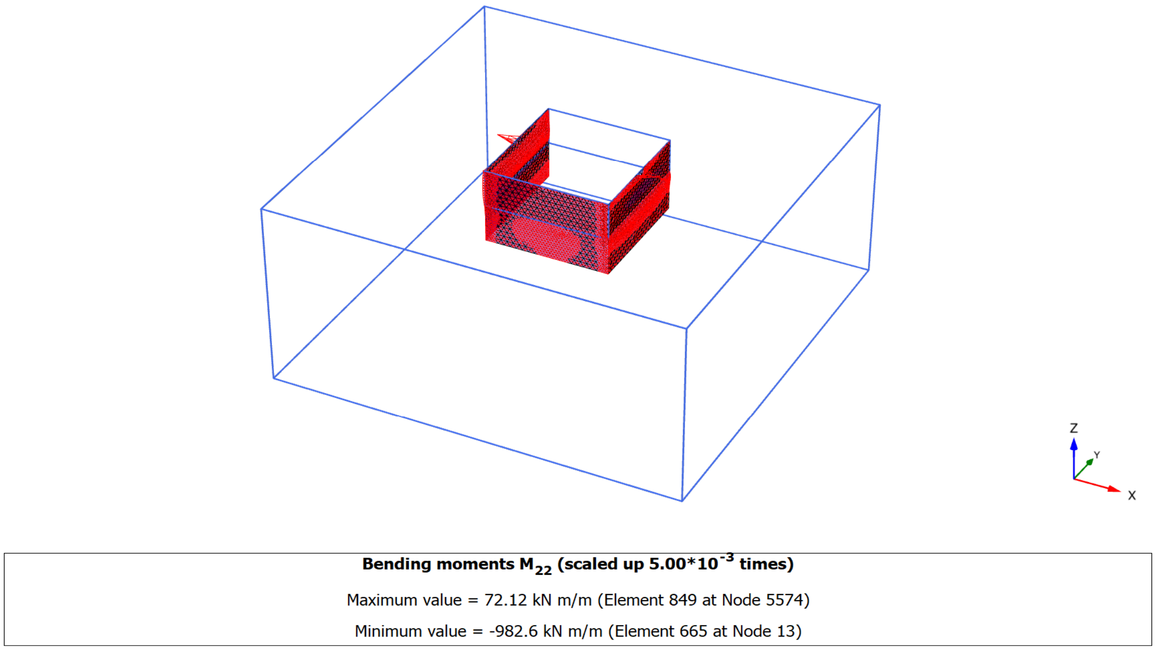

Figure 8: Horizontal Bending moment of Straight Retaining wall using Crushed Pebble Gravel in PLAXIS 3D

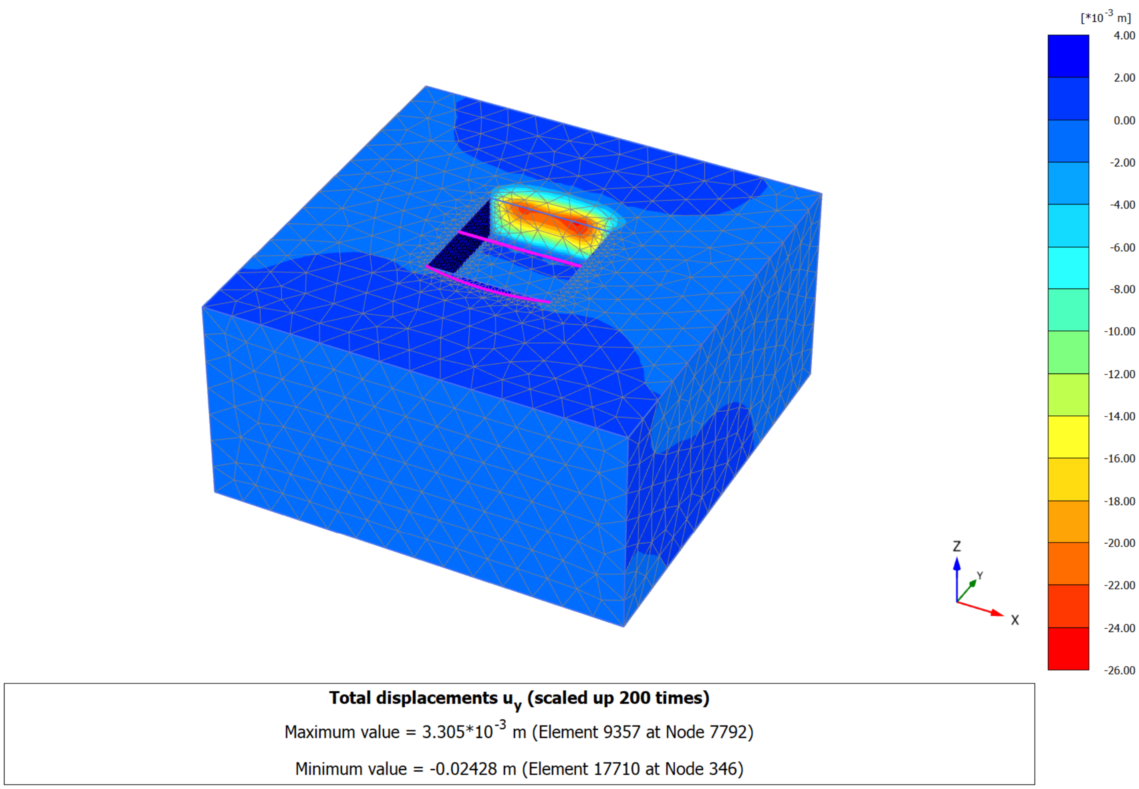

Figure 9: Horizontal displacement profile of Curved Retaining wall using Crushed Pebble Gravel in PLAXIS 3D

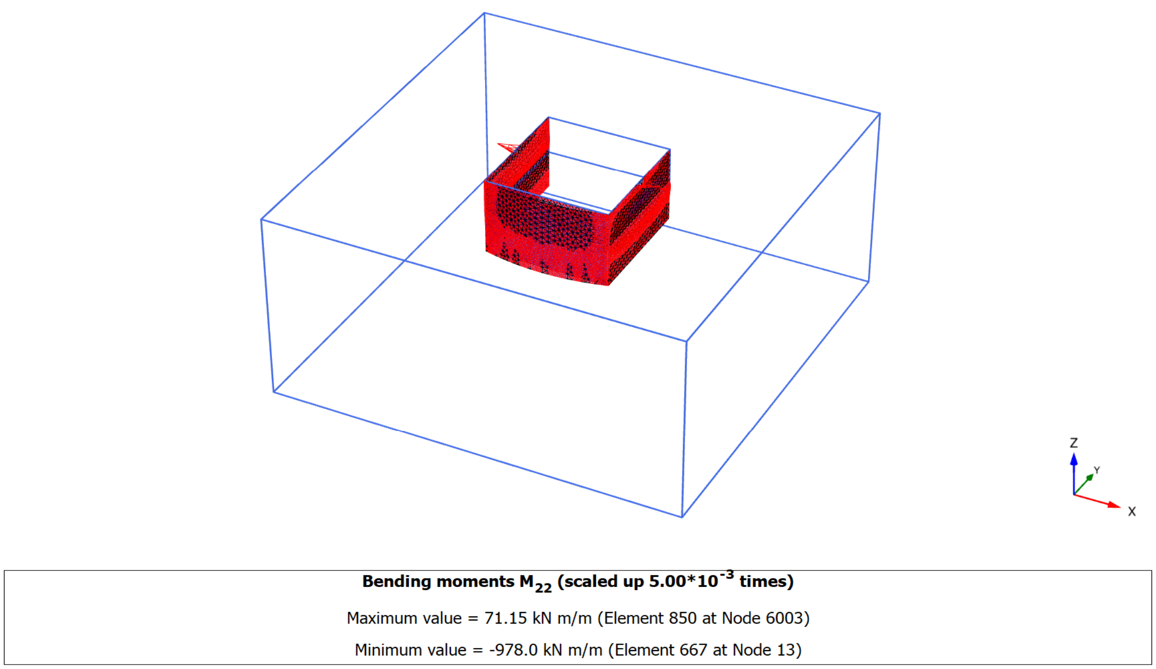

Figure 10: Horizontal Bending moment of Curved Retaining wall using Crushed Pebble Gravel in PLAXIS 3D

V. CONCLUSIONS

Based on 3D finite element analysis conducted in PLAXIS 3D, the following conclusion are found:

1) *Software Models (Mohr-Coulomb vs. Hardening Soil):* An important finding from our study is how the wall shape interacts with different soil models in the software. For the Stiff Sandy Clay, the simpler Mohr-Coulomb model worked perfectly, showing a well-controlled wall deflection of 7.00 mm. But for the Crushed Pebble Gravel, we used the more advanced Hardening Soil model. This model proved that the gravel's massive friction angle 51.8^0 and interlocking rocks naturally push back against the wall, resulting in an even smaller deflection of just 5.98 mm for a standard straight wall.
2) *Superiority of Curved Geometry:* After modifying the wall geometry to a non-circular curved or arch drastically improves structural stability and also capitalizes on 3D spatial soil structure interactions.
3) *Displacement Reduction:* The arched geometry successfully reduced the maximum lateral displacement by 15.3% (from 7mm to 5.927mm) in Stiff Sandy Clay and by 44.76% (from 5.984mm to 3.305mm) in Crushed Pebble Gravel. Additionally, it reduced the maximum horizontal bending moments, actively relieving flexural stress on the concrete panels.
4) *Bending Moments:* The arched geometry also successfully reduced the Bending Moments by 2.49% (from 79.38 KN-m to 77.40 KN-m) in Stiff Sandy Clay. And 1.34% (from 72.12 KN-m to 71.15 KN-m) in Crushed Pebble Gravel.
5) *Economic Optimization:* While the curved wall performs exceptionally well, the magnitudes of displacement in these highly competent soils are inherently minimal. Therefore, while the arch serves as an optimal tool for reducing concrete thickness in moderate soils Stiff Sandy Clay, the added construction complexity of an arched wall may be economically redundant in extremely high-friction environments like Crushed Pebble Gravel.

VI. ACKNOWLEDGMENT

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