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25 YEARS OF INNOVATION
APRIL 20–21, 2021

Lessons Learnt from 3D Soil-Structure Modeling of a Peanut-Shaped Cofferdam for Cut & Cover Tunnel

A.K.L. Kwong
Adjunct Professor, The University of Hong Kong

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This paper has been accepted and will be a part of the Rocscience International Conference 2021.

The paper will be published as a part of the conference proceedings by Taylor & Francis.

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ABSTRACT: The design and construction of infrastructures, whether it is in a recently reclaimed land or in a congested urban environment, are becoming more and more complex due to excavation of the deep grounds in soft and heterogeneous soils. To arriving a safe and economic design where the ground responses can be fully comprehended in a 3-dimensional configuration, 3D geotechnical modeling of soil-structures interaction has become popular and a tool that is indispensable.

The use of a peanut-shaped cofferdam for deep excavation of the cut-and-cover tunnel is gaining popularity. The cofferdam consisted of 3 numbers of truncated circular cells of 21 m long and 22 m wide for each of the cell connecting together. Each cell is formed by connecting perimeter D-wall panels in an arc shape which resists the lateral earth pressure by hoop forces. The hoop forces induced on the perimeter D-wall panels are then transferred at the junction of the cells to some heavy-duty D-walls designated as Y-Panels, which are transversely supported by some reinforced concrete struts and cross-walls.

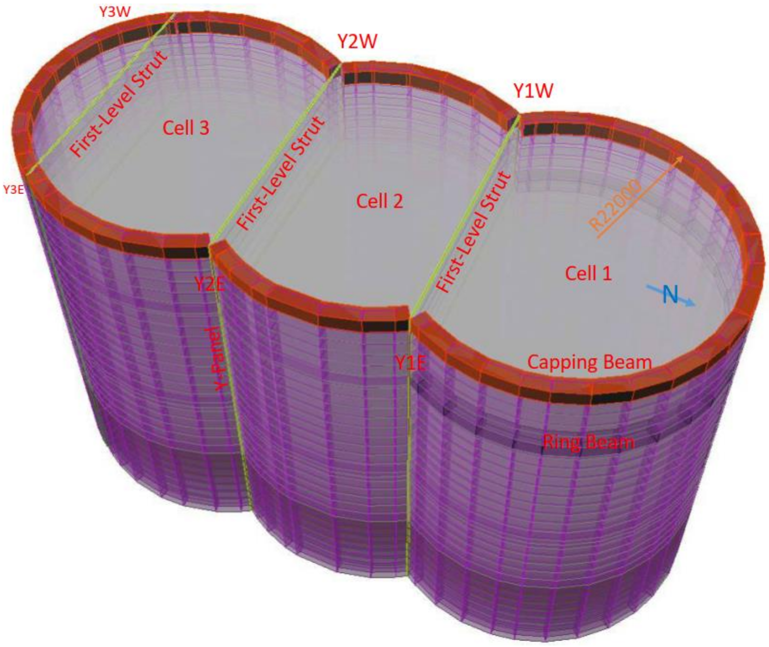
A 3D finite element computer program, RS3, is used in this paper to model the construction sequences with generic soil properties adopted to illustrate the key lessons learned from excavation involving 3-dimensional geometry. The bending moment and deformation of the D-wall panels, Y-Panels, and struts are presented in this paper to illustrate the mechanism developed in the composite structure.

In this study, it is found that the soil spring constant deduced from the simulation is variable at different unloading stages and will approach a relatively constant value which is higher than the prescribed value usually adopted in structural analysis.

1 INTRODUCTION

The design and construction of infrastructures, whether it is in a recently reclaimed land or in a congested urban environment, are becoming more and more complex due to excavation of the deep grounds in soft and heterogeneous soils. To arriving a safe and economic design where the ground responses can be fully comprehended in a 3-dimensional configuration, 3D geotechnical modeling of soil-structures interaction has become popular and a tool that is indispensable.

The use of a peanut-shaped cofferdam for deep excavation of the cut-and-cover tunnel is gaining popularity. The principle of the peanut-shaped cofferdam structure is that it makes use of the development of arching effect in the connecting perimeter D-walls which are more efficient in resisting compression than in bending. In this numerical study, the cofferdam consisted of 3 numbers of truncated circular cells of 21 m long and 22 m wide for each of the cell connecting together. Each cell is formed by connecting perimeter D-wall panels (1.5 m thick) in an arc shape which resists the lateral earth pressure by hoop forces. The hoop forces induced on the perimeter D-wall panels are then transferred at the junction of the cells to some heavy-duty D-walls designated as Y-Panels, which are transversely supported by some reinforced concrete struts (2 m wide by 2 m deep) and cross-walls (1.5 m thick). The cross-walls top level is 5 m to 8 m above the final excavation level (FEL) and is cut off to the FEL to make room for the permanent tunnel box construction. The perimeter D-walls are embedded into the stiff ground to ensure stability against base heave, piping, and uplift failures. Figure 1 shows the 3D view and the load path of the Peanut-shaped Cofferdam.



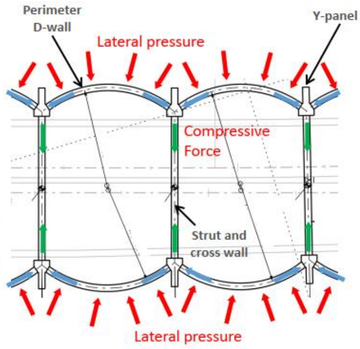


Figure 1. 3D view and load path of a Peanut-shaped Cofferdam.

During the excavation stage, the absence of heavy steel struts, king posts, and waler beams offer a drastic reduction in the construction program. It allows greater ease of machine plant movement and vertical lifting, leading to a much faster overall excavation cycle. The permanent structure can be cast in open space instead of confined by multiple strut layers that require the conventional re-propping sequence. It also reduces the amount of ground treatment below the excavation level due to toe stability.

A 3D finite element computer program, RS3, is used in this paper to model some typical construction sequences (Table 1) with generic soil properties (Table 2) adopted to illustrate the key lessons learned from excavation involving 3-dimensional geometry.

2 LOADING PATH

The modeling sequence closely follows the method and sequence to be adopted during the construction stages, and they are briefly summarized as follows:

1. The initial stage of the model consists of the forming of the capping beam, the 1st layer of struts at ground level, the perimeter D-walls, and the cross-walls.
2. Then followed by 1st stage – excavation to the bottom of the 2nd layer of struts.
3. 2nd stage – installation of the 2nd struts and also the ring beam at the 2nd strut level. Excavation to the bottom level of the 3rd layer of struts.

Table 1. Modeling sequences match with construction phases.

Stage	Modeling Activities	Stage	Modeling Activities	Stage	Modeling Activities
1	Assign elastic element to generate in-situ stresses	12	Install Strut in Fill and Ring Beam at -7 mPD (Second-Level Strut)	23	Excavate to -27 mPD
2	Change from elastic to plastic element	13	Excavate to -9 mPD	24	Excavate to -29 mPD
3	Install Y-Panel, D-wall, Capping Beam and Cross Wall	14	Excavate to -11 mPD	25	Excavate to -31 mPD
4	Install Top Strut at +5.5 mPD (First-Level Strut)	15	Excavate to -13 mPD	26	Excavate to -33 mPD
5	Excavate to +3.5 mPD	16	Excavate to -15 mPD	27	Excavate to -35 mPD
6	Excavate to +1.5 mPD	17	Excavate to -17 mPD	28	Excavate to -37 mPD
7	Excavate to -0.50 mPD	18	Install Strut in MD at -17 mPD (Third-Level Strut)	29	Excavate to Final Excavation Level (-37.5 mPD)
8	Excavate to -2.5 mPD	19	Excavate to -19 mPD	30	Install Strut in Alluvial Clay at -17 mPD (Fourth-Level Strut)
9	Excavate to -4.5 mPD	20	Excavate to -21 mPD	31	Demolish Cross Wall
10	Excavate to -6.5 mPD	21	Excavate to -23 mPD		
11	Excavate to -7 mPD	22	Excavate to -25 mPD		

4. 3rd stage – installation of the 3rd layer of struts and excavation to the final excavation level (FEL), but without the demolition of the cross-walls (keeping the cross-walls at 8 m above the FEL at the Y-Panels location.
5. 4th stage – installation of the bottom struts at FEL, adjoining the cross-walls supporting the Y-Panels. Demolition of all the cross-walls down to the FEL.

Table 2. Soil and structure material properties.

Soil	Cohesion	Friction Angle	Young's Modulus	Poisson's Ratio	Unit Weight	
	kPa	Degrees	kPa		kN/m^3	
Fill	0	33	22500	0.25	20	
Marine Deposit	40	0	10400	0.25	16	
Alluvial Clay	60	0	20000	0.25	19	
Alluvial Sand	0	35	30000	0.25	19	
Completely Decomposed Granite	5	32	60000	0.25	19	
Structural Member	Thickness	Area	Young's Modulus	Poisson's Ratio	Moment of Inertia Max-axis	Moment of Inertia Min-axis
	m	m^2	kPa			
Y-Panel (Cells 1 and 2)		14.05	3E+07	0.2	49.98	8.36
Y-Panel (Cell 3)		13.63	3E+07	0.2	47.31	7.577
D-wall	1.5		2.9E+07	0.2		
Capping Beam	2.0		3.0E+07	0.2		
Ring Beam	2.0		2.9E+07	0.2		
First-Level Strut	Width 2m Depth 2 m	4	2.9E+07	0.2	1.333	1.333
Second-Level Strut	Width 2m Depth 2 m	4	2.9E+07	0.2	1.333	1.333
Third-Level Strut	Width 2.5m Depth 2.5 m	6.25	2.9E+07	0.2	3.255	3.255
Fourth-Level Strut	Width 1.0m Depth 1.5 m 2 no.	3.0	2.9E+07	0.2	0.5625	0.25
Cross Wall	Width 1.0m Depth 1.5 m	1.5	3.0E+07	0.2	0.28125	0.125

Results of the analysis are presented in Figures 2 to 6.

Figure 2 shows the sectional view of the structural arrangement of the Y-Panel with the struts and the cross-walls. Very high bending moment and the high compressive force of about 117,000 kN-m and 160,000 kN are experienced by the Y-Panel and the struts respectively.

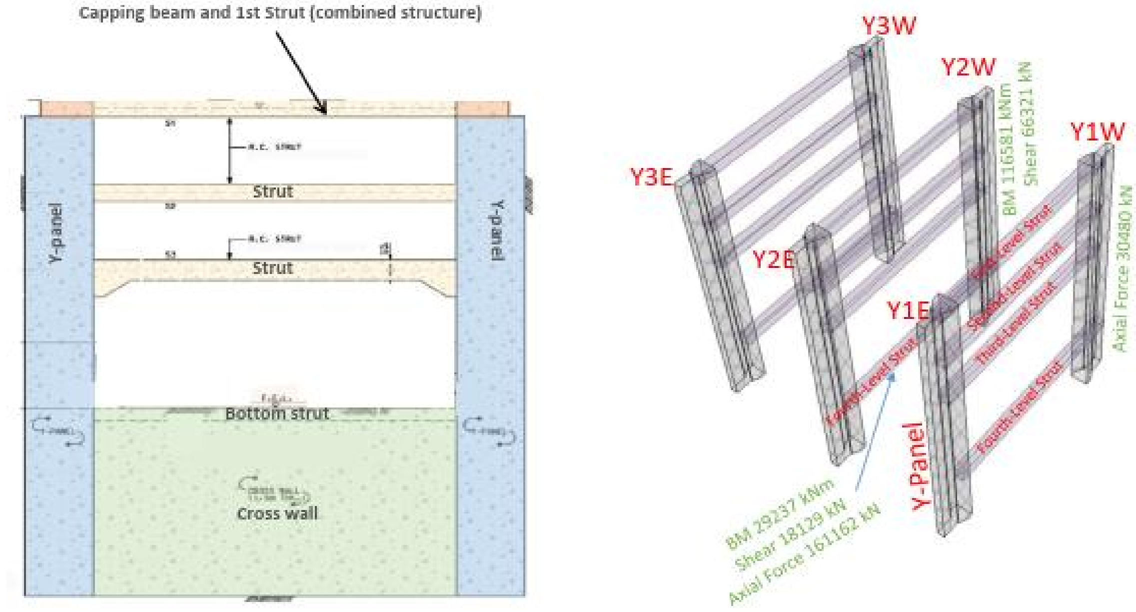


Figure 2. Sectional View of a Y-Panel.

Figure 3 shows the deformation pattern of the Y-Panel and the D-wall. It is noted that with the very high bending moment in the Y-Panel, the lateral deformation of the Y-Panel and the D-wall is moderate of about 80 mm which is considered to be within the serviceability limit.

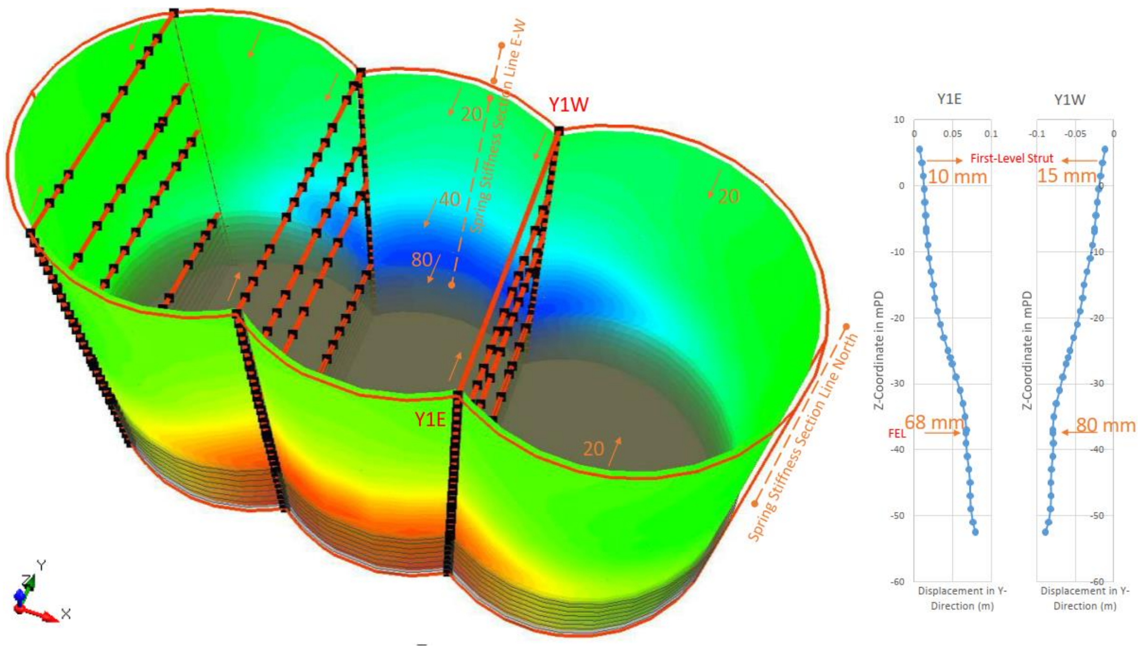


Figure 3. Deformation of the Y-Panel and the D-wall.

3 SOIL STRESS PATH

From the assessment of the deformation pattern and magnitude of the D-wall panel, it would appear that the structural system is very rigid. The element stresses at the excavation side are extracted from the model below the third strut level (-20 mPD) and the FEL (-37.5 mPD) for examination (Figure 4). As the excavation of the soil increases with depth, the reduction of the vertical stresses is not constant during the unloading because of the stress redistribution, and interaction with the deformation of the D-wall panel.

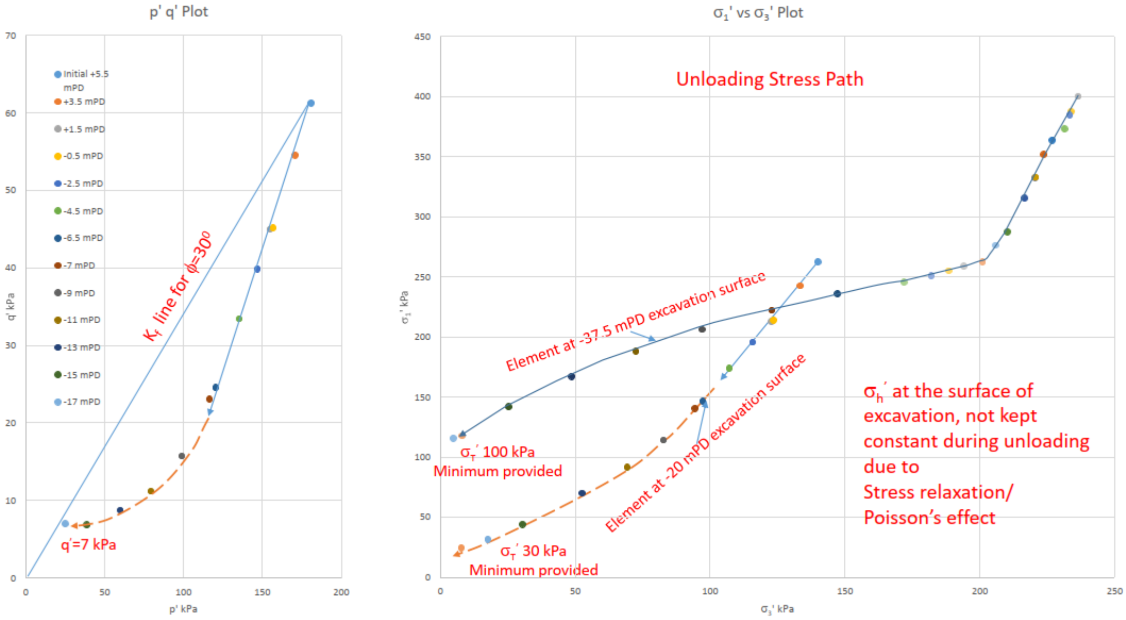


Figure 4. Unloading stress path.

A detailed examination of the deformation pattern along the depth profile of the D-wall at the major axis of the 3-cells is presented in Figure 5, which shows that the upper part of the D-wall panel deflects away from the excavation side whereas the lower part deflects in the opposite direction in the form of a bi-axial mode.

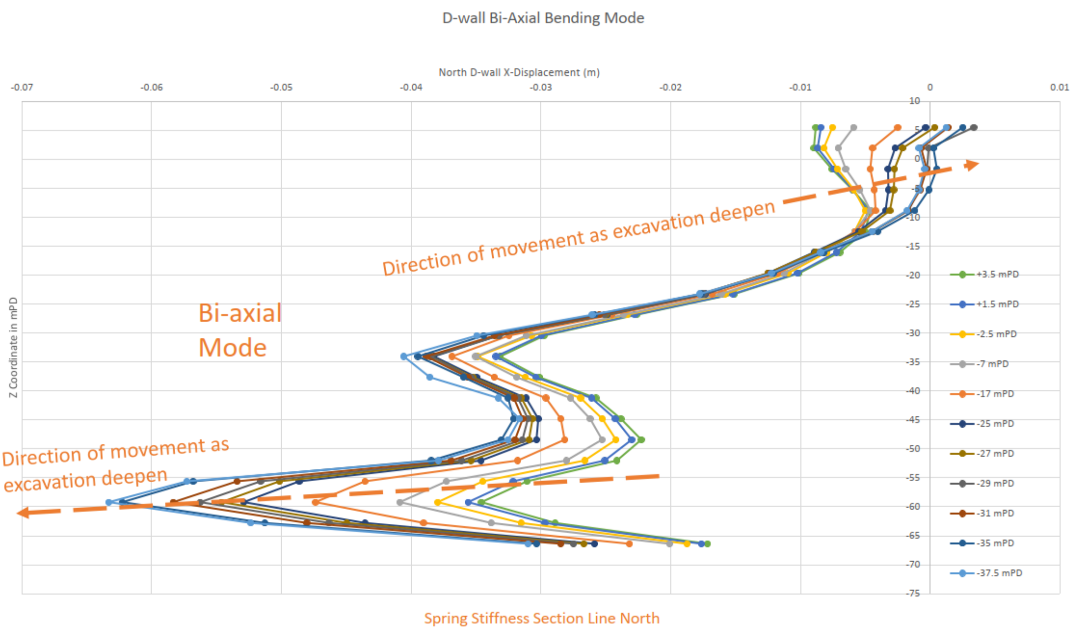


Figure 5. Bi-axial mode of deformation.

In a typical structural analysis, a ground spring stiffness of the geotechnical materials was usually assumed from a handbook (e.g., Geoguide 1, 2020) for carrying out the detailed reinforcement design of the major structural system consisting of the perimeter D-wall panels, Y-Panels, struts, cross-walls, ring beams, capping beam and corbels, with each modeling sequence follows closely to the stages of construction. The perimeter D-walls, cross-walls, struts, and Y-panels were represented by a series of thin-shell elements. The ground medium surrounding the perimeter D-walls was represented by a series of area springs perpendicular to the shells. Figure 6 extracts the spring stiffness (horizontal force divided by horizontal deflection) along the major and minor axes of the 3-cells along the D-wall panels.

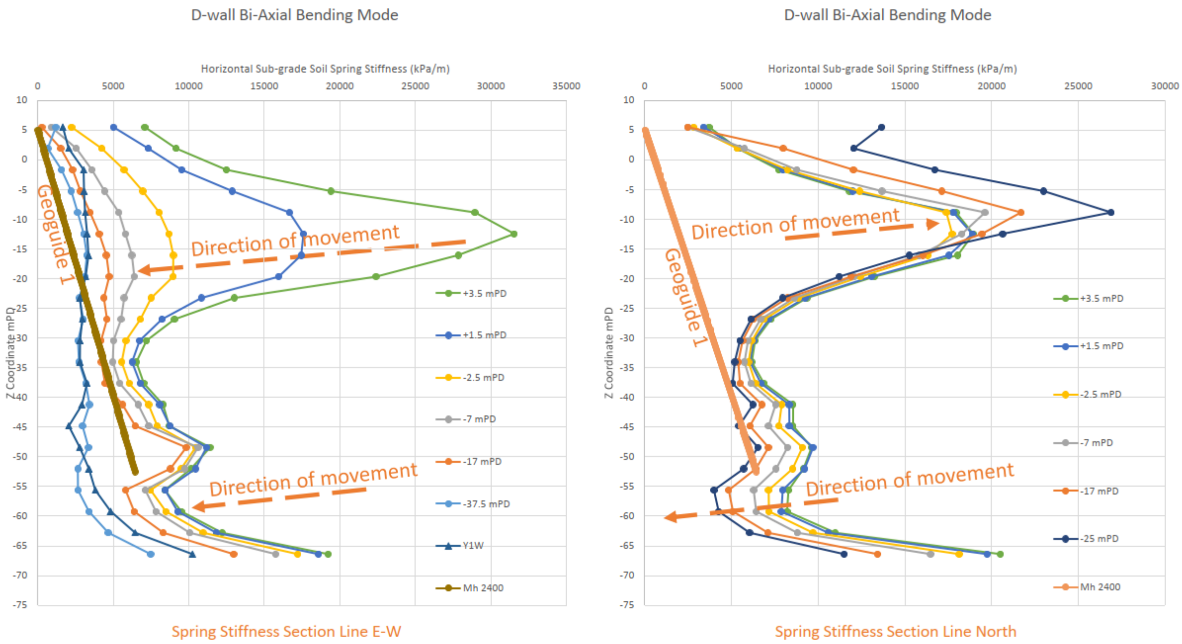


Figure 6. Distribution of the horizontal subgrade soil spring stiffness.

It can be seen that the soil spring stiffness is variable at different unloading stages and not linearly increases with depth.

4 CONCLUSIONS

A 3D finite element computer program, RS3, is used in this paper to model the construction sequences with generic soil properties adopted to illustrate the key lessons learned from excavation involving 3-dimensional geometry. It is found that the soil spring stiffness is variable at different unloading stages and not linearly increases with depth and is higher than the prescribed value usually adopted in structural analysis.

5 REFERENCE

Geoguide 1 (2020). Guide to retaining wall design. Geotechnical Engineering Office, CEDD, The Government of the Hong Kong SAR. 245 pages.

RS3. https://www.rocscience.com/software/rs3