

Evaluation of Excavation-Induced Surface Settlement and Effectiveness of Cement Grouting in Mitigating Building Deformation

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One of potential issues during deep foundation excavation is surface settlement that could impact the safety of construction, and damage adjacent buildings and occupants. One of methods to mitigate excavation-induced surface settlement is the use of cement grouting or cement injecting. Cement grouting is a process of injecting liquid cement material in a soil or rock to change physical properties of the new formation. It is used to fill pores or voids in soils or rocks with mixed grouts. One of potential issues during deep foundation excavation is surface settlement that could impact the safety of construction, and damage adjacent buildings. Particularly with increasing population in many metropolitan areas, the land sources are very limited and buildings are close to each other, making deep foundation excavation a challenging task for construction contractors and crews. This paper presents a case study that shows how excavation project could possibly impact the safety of construction. Cement grouting method was used to mitigate excavation induced settlement of damaged building. After completion, a series of standard penetration tests (SPT) were performed to evaluate the effectiveness of cement grouting in soil improvements. It is concluded cement grouting has successfully demonstrated its effectiveness in mitigating settlement of damaged building due to deep foundation excavation.

Key words: cement grouting, foundation excavation, surface settlement, building deformation

Introduction

One of potential issues during deep foundation excavation is surface settlement that could influence the safety of construction, damage adjacent buildings, and interrupt daily life of occupants. Particularly with increasing populations in many metropolitan areas, the land sources are very limited and structures/buildings are built close to each other, making deep foundation excavation a challenging task for contractors and construction crews. Building damage due to excavation-induced ground movement has appeared to be a severe issue during foundation excavation (Son et al. 2005) and treatments must be taken to mitigate immediate building tilting and minimize the disturbance of excavation operations, surrounding buildings, structures, and local residents. One of methods to mitigate excavation-induced surface settlement is the use of cement grouting or cement injecting. Cement grouting is a process of injecting liquid cement material in a soil or rock to change physical properties of the new formation. It is used to fill pores or voids in soils or rocks with mixed grouts. The injecting pressure varies depending on a construction plan, soil properties, and site locations. More recent studies of cement grouting have been done in mitigating settlements due to tunneling process through existing foundation of structures (Mohammed et al. 2013, Xu et al. 2013), liquidation (Huang et al. 2008), and foundation excavation (Chepurnova 2014). To deal with surface settlements, a number of studies have been implemented using numerical analyses to predict surface settlements, lateral displacement, and strain and strength of the soil during deep foundation excavation (Ou et al. 1993, Wu et al. 2013, Heleh et al. 2012, Liu et al. 2011, Tan and Li 2011, Wang et al. 2005). A similar project done by Heieh et al. (2003) was compared. Their research indicated that grouting beneath adjacent buildings as the excavation is advanced to compensate for ground loss, but its operation is tedious and risky in nature. Local experience has shown that the effectiveness of grouting under adjacent buildings is uncertain (Heieh et al. 2003). The authors proposed that soil improvement in the form of jet grouting being implemented within the excavation zone (with a diameter of 0.6 m and spaced at 2 m intervals across the site) as a passive in order to minimize lateral displacement of diaphragms during excavation. Based on the paper (Heieh et al. 2003) the proposed design was able to reduce the estimated maximum wall displacement by more than 40% but the authors urged that any future design must be implemented in a case-by-case manner as the local soil properties vary and that would change the prediction of ground settlement. S. Coulter (2006) studied the effect of jet grouting on surface settlement for an Aeschertunnel in Switzerland. The jet-grout umbrella for the Aeschertunnel was formed with the installation 39 columns along the crown of the top of the tunnel with a diameter of 600 mm and a spacing of 450 mm between the boreholes at the tunnel face to ensure overlapping columns. S Coulter also indicated the installation of jet-grout columns as primary excavation support resulting in very low volume losses, in the range of 0.35% and a very narrow settlement trough. From the above research works, it is noticed a comprehensive review of job site condition plays a key that leads to a successful project implementation. A question here is: what if unexpected surface settlements occurred due to foundation excavation and adjacent buildings were in damage, what strategies can be immediately used and applied at job site in order to mitigate building tilting. Thus, this paper presents (1) a case study of building damage due to excavation induced surface settlements and (2) cement grouting technology in mitigating the impact of surface settlement on building safety and disturbance of occupants.

Construction Plan and Soil Properties of Excavation Site

An open-cut excavation was constructed in a densely populated area. Based on a construction layout, a braced-cut construction method was used and the job site was only 7.5 meters away from an existing 12-story building. Diaphragm walls (60 cm thick and 21m deep) were designed as a soil shoring structure to resist lateral earth pressure as well as high water pressure. Five levels of strut and wale were installed against both sides of diaphragm wall. The excavation finish surface was designed at a depth of 11.4 m below the ground surface. A cross sectional view of the entire site and the adjacent building is displayed in Figure 1. According to the soil boring report and soil logs (Table 1), the groundwater table was detected below ground surface between -2.0 m to -3.0 m. In addition, a 5-meter thick silty sand is located between 5.5m and 10.5 m beneath the surface, provided water pressure is significant against the diaphragm walls. Therefore, it was essential to operate dewatering during the excavation construction. Because the excavation surface had to be kept in a dry condition, the existing ground water table must be lowered at least 1 meter below the excavation surface (-12.5 m below the ground surface). Well points associated with multiple wells dewatering system were used. These wells were connected to pipes surrounding the excavation site. By using the dewatering system, ground water was pumped out of the job site to the nearby creeks. Based on Schroeder et al. (2004), lowing of the ground water table by 3 m (10 ft) is approximately equivalent to imposing a surface load on the soil of 30 MPa (624 psf). It was obvious that potential surface settlement might have been an issue that could significantly impact excavation safety.

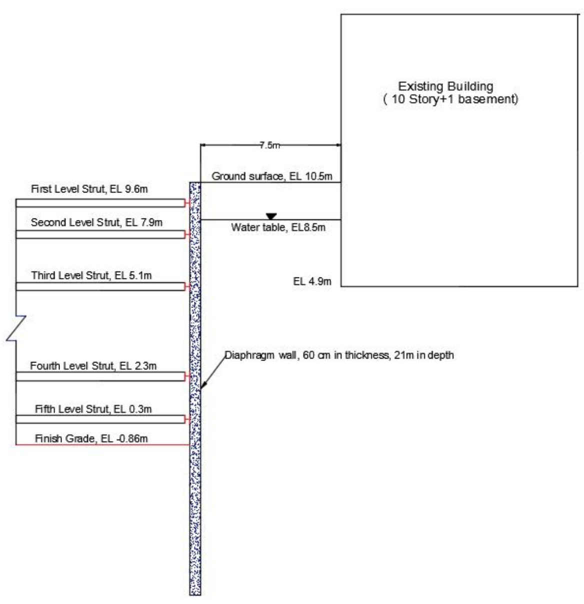

Figure 1: Cross sectional view of excavation site and the existing building

Table 1 Soil Properties and Boring report

Boring Data			Test Results									
			Soil	Gradation distribution (%)								
No.	SPT N	Depth (m)	Classification	Gravel	Sand	silt/ clay	Water content , %	Unit weight , t/m3	void ratio	LL, %	PL, %	Gs
S1	9	1.55-2.0	CL	0	6.9	93.1	30.1	2.01	0.82	35.6	22.7	2.74
S2	8	2.55-4.0	CL	0	7.2	92.8	30	2	0.82	34.6	22.1	2.74
S3	10	5.55-6.0	SM	0	66.6	33.4	21.9	2.04	0.59	-	NP	2.7
S4	11	7.55-8.0	SM	0	69.2	30.8	23	2.07	0.62	-	NP	2.71
S5	34	9.55-10.5	SM	0	69.5	30.5	22.2	2.07	0.6	-	NP	2.71
S6	9	11.55-12.0	CL	0	7.5	92.5	29.8	2.02	0.81	34.9	23	2.73
S7	6	13.55-14.0	CL	0	6.5	93.5	33.4	1.98	0.92	34.5	21.7	2.74
S8	9	15.55-16.0	CL	0	7.1	92.9	31.2	2.01	0.85	35.1	22.5	2.72

Analysis of Lateral Displacement and Surface Settlement

The competence and success of a geotechnical engineering is measured by how comparable the predicted behavior of the soil-structure system is with the measured performance (Sayed, 1987). In the tool box of a geotechnical engineering, problem-solving methods may include analytical closed-form, empirical, and numerical solutions. The enormous complexities encountered in natural states of geological media can make analytical closed-form approaches very difficult. A large number of simplifying assumptions were necessary to obtain the closed-form solutions. Therefore, in the past, geotechnical engineering was considered an essentially empirical discipline (Desai and Christian, 1977). Among numerical methods, finite element method (FEM) is the most promising and has obtained tremendous advancement since the 1940s when modern development of the FEM began in the field of structural engineering. Since the 1970s FEM has been successfully applied to many problems in geotechnical engineering involving such complexities as nonhomogeneous media, nonlinear material behavior, spatial and temporal variations in materials properties, arbitrary geometries, etc. (Zienkiewicz et al., 1999). Plaxis, 2-D finite element method software, was employed to analyze the lateral displacement, surface settlement, and heave on the bottom of the excavation. The constitutive model used in the FEM analysis is Mohr-Coulomb Criterion (Desai and Siriwardane, 1984). By taking advantage of the geometric symmetry of the site, a cross section was taken along the longer dimension at the middle point of the shorter dimension (see Figure 2). To avoid any effects due to the boundary of the FEM model, the distance between the boundary and the diaphragm wall was 11.5 m, which is the excavation depth (see Figure 2). Based on the results of the FEM analysis, the ground surface settlement was 0.08 m, which occurred soon after the groundwater was lowered to 12.5 m below the ground surface, the largest lateral displacement of the diaphragm walls was 0.03 m near the bottom of the excavation (see Figure 3), as well as the largest heave was found near the center of the excavation and its amount was 0.14 m (see Figure 4).

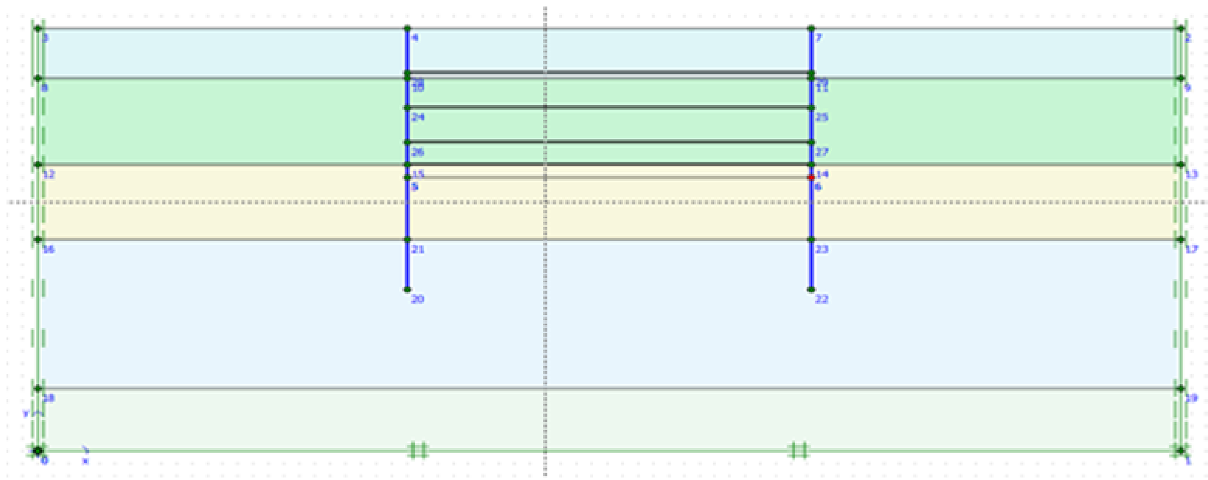

Figure 2: Two-dimensional FEM model

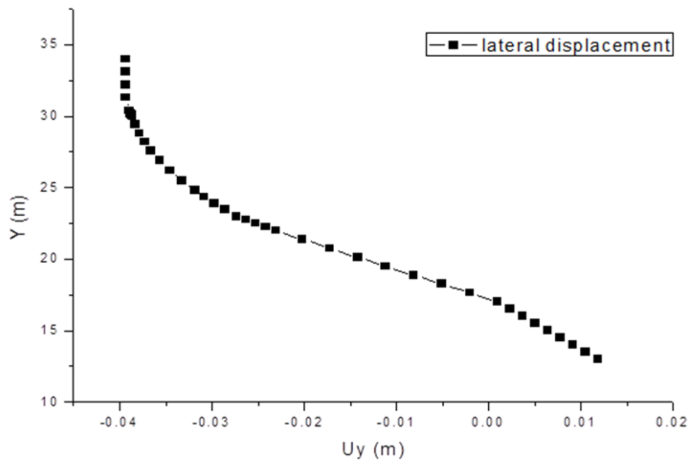

Figure 3: Lateral displacement of the diaphragm wall

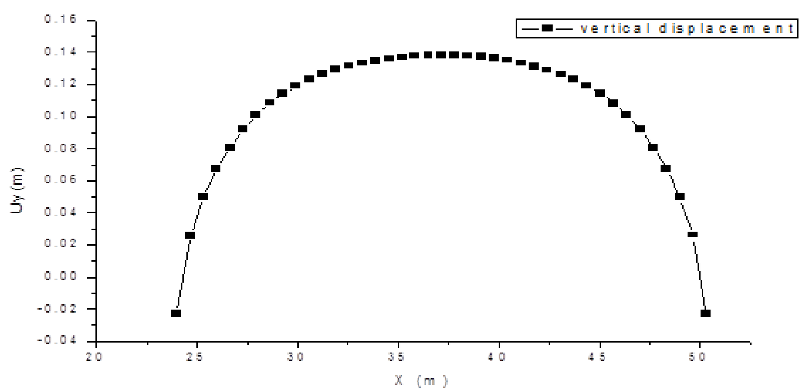

Figure 4: Heave on the bottom of the excavation

Uplifting Analysis of Excavation

Based on a numerical analysis of lateral displacement and surface settlement, adjacent buildings needed to be monitored closely to minimize the inconvenience of daily life of building occupants and safety of construction. As shown in Figure 1, there is a 10-story building nearby the excavation site that might have potential damage due to excavation induced settlement. As mentioned previously the diaphragm wall (60cm in thickness, 21 m in depth) connected with five levels of struts (Figure 1) were designed as excavation shoring support. Given the soil report in Table 1, these are two layers of the soil located between -5.5 m to -16m where soil properties were expressed as follows:

- A layer of soil was located at a depth of between 5.5m to 10.0 m below the ground surface where the soil was classified as silty sand (SM). The standard penetration test (SPT) N value was tested at 10, indicating the soil was soft.
- A layer of soil located at a depth of between 10 m to 16 m below the surface was classified as sandy clay (CL) where the moisture content (w) was tested at 34.9% and the liquid limit (LL) was tested at 34.5%, suggesting that the soil was nearly in a liquid state. When an impermeable soil is below the finish grade, a potential uplifting event might have caused the bottom of excavated surface to move upward (heaving). Thus, a hydrostatic uplift analysis was performed to determine if the factor of safety is below the standard 1.5:

Hydrostatic uplift analysis (Factor of Safety, FS) can be expressed in Eq. 1:

$$FS = \frac{\gamma_{L*}\ H_L}{\gamma_w * H_P} \geq 1.5 \qquad \text{Eq. 1}$$

where
γ_L= field density of clay
γ_w= density of water
H_L=thickness of clay
H_p= piezometric level (head)

A mathematical relationship between a depth of excavation and a FS is shown in Figure 5. Obviously, a critical excavation depth for foundation operation is found at 8 meters below the surface. According to the soil logs in conjunction with geotechnical engineering analysis, when the foundation is excavated at a depth of 11.57 m, a FS is determined as 0.34 which is significantly less than 1.5. The analysis result indicated that uplifting would be more likely occurred during excavation.

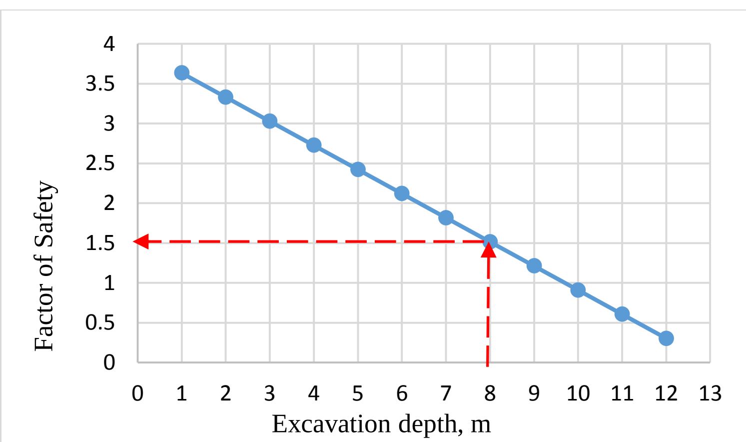

Figure 5: Mathematical relationship between FS and excavation depth

Cement Grouting

After completion of excavation, groundwater flooding was observed on the finished surface as shown in Figure 6. This observation was evident to an uplifting event. When uplifting occurred, soil particles at the excavated and its surrounding areas would be reoriented, resulting in a surface settlement and subsequently causing an adjacent building to tilt. After the building started leaning, the contractor installed a tiltmeter mounted on the basement wall of the existing building to monitor the deformation of building due to excavation-induced surface settlement. The angular distortion of tiltmeter was recorded at a radian of 1/480 exceeding the tolerable settlement of buildings (1/500, for safe limit for no cracking of buildings) as recommended by (Bjerrum, 1963). This measure indicated the existing building has leaned towards the excavation site and cracking of building might has been occurred. On the following day, cracks were noticed on the wall of the basement of the adjacent building as shown in Figure 7. It was believed that the foundation of building settled due to excavation-induced settlement and soil uplifting. To prevent the building from being further tilted, cement grouting was immediately scheduled and used to fill underground voids and in an attempt to lift up the settled building foundation. The cement grouting was set at a pressure rate of 5-10 kg/cm^2 and the grouting rate was set at 30 liter/min. The decision to grouting pressure was made based on the concern that a higher grouting rate could have undermined the confining effect of soil, diaphragm walls, and the existing foundation. Cement paste was injected into the soil and penetrated slowly to fill voids. The target improvement areas were determined at a layer of silty sand and a part of clay ranging from -5 m to -12 m. The mix design of cement grouting was determined at a ratio of 1:1:0.6 (cement: water: nature sand) with a designed unconfined compressive strength (q_u) of 30-40 kg/cm^2 (285-430 psi). The cement grouting was injected at an interval of 4 meters along the sidewalks in front of the damaged building. Figure 8 illustrates the arrangement of cement grouting work.

Figure 6: Groundwater flooding on finished surface

Figure 7: Water leaking due to horizontal crack in a basement wall (left) and a column (right)

Effectiveness of Cement Grouting in Mitigating Surface Settlement

To evaluate the effectiveness of cement grouting in mitigating excavation induced surface settlement and tilting building, a series of standard penetration test (SPT) were performed. SPT samples were collected from the range of -2 m to -22 m. Based on boring data, depths between -8 to -12 m were specifically monitored as this range was identified as critical area for uplifting event. Figure 8 shows the improvement of soil properties before and after cement grouting. It is noticed that SPT N values increased from 11 to 22 at a depth of 8 m, and from 9 to 27 at a depth of 12 m. SPT N value was not significantly improved at a depth of 10 m. However, the soil properties between 9-10 meters shows the SPT N value was 33 and 34 before and after grouting meaning that the soil was stiff and consolidated at this range. Apparently, shear strength of the soil between depths of 2 m to 22 m increased. Four control points were also installed in front of the damaged building before cement grouting and were used to monitor the progress of surface settlement as well as building tilting. Table 2 depicts the effectiveness of cement grouting in mitigating excavation induced settlement. All surface settlements measured from the four control points indicated the surface was lifted up ranging from 1 mm to 6mm. Furthermore, angular distortion was recorded on October 22 at 1/403 (radian) as compared with the initial 1/481 (radian) measured on September 24. The tilting situation of building seemed to be under control and did not show significant angular distortions. Field observations were implemented during cement grouting to closely monitor building deformation. Until completion of cement grouting, no further settlement was observed and the tilting of building had been terminated. The effectiveness of cement grouting in mitigating surface settlement and building deformation was significant. It should be noted that due to information sensitivity, the exact location and date of the event must be remained anonymous. Due to the limited information of field measurement, lateral displacements were not measured to compare the difference between analysis results and actual data.

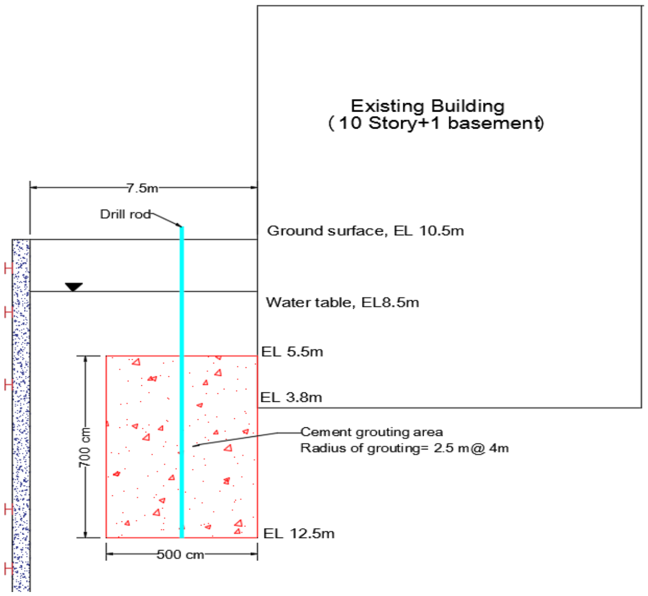

Figure 8: Cement grouting arrangement and layout

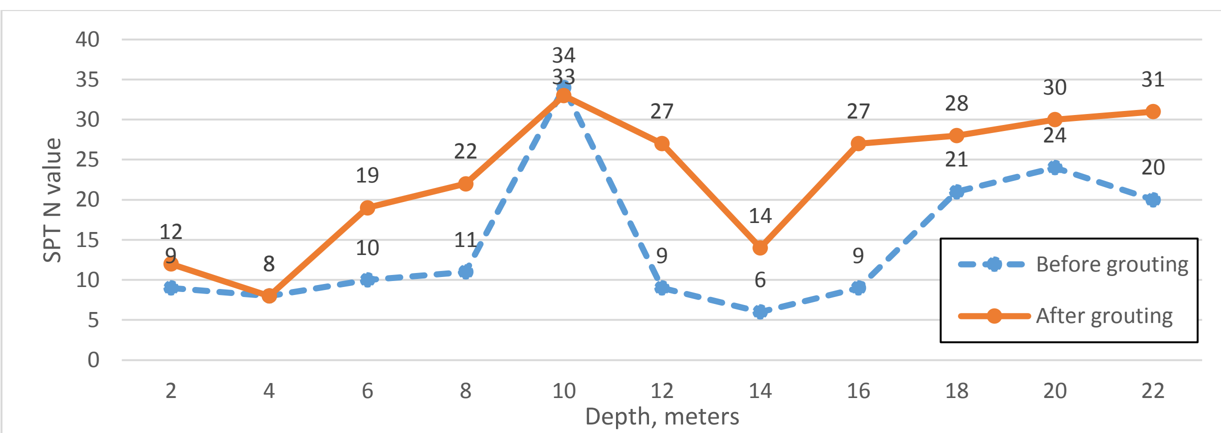

Figure 9: Effectiveness of cement grouting

Table 2: surface settlement before and after cement grouting

Point No.	Initial reading (mm)/Sep. 24	Reading (mm)/ Oct. 27	Settlement(mm)
P1	-491	-490	+1
P2	-424	-421	+3
P3	-518	-515	+3
P4	-444	-438	+6

Conclusions

Cement grouting has successfully demonstrated its effectiveness in mitigating surface settlement and building deformation due to deep foundation excavation. This paper presents a case study that shows how excavation project could possibly impact the safety of construction and cause adjacent buildings to tilt. Normally, such failure can be prevented by thorough reviewing soil boring report and performing geotechnical analysis to identify potential excavation induced settlements. A comprehensive preparation and construction plan could be implemented to avoid any potential excavation-induced settlement and loss of buildings and properties, even human life. Lessons learned from the construction can be used for contractors to better prepare for excavation to prevent surface settlements and building tilting, particularly with the site near to adjacent buildings. Future direction of the research will be focused on collecting field data to reflect and calibrate the numerical analysis as well as providing information of settlements to contractors so as to mitigate potential risks for building damaging and excavation issues.

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