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Effect of the chemical compounds of soil on the stability of excavation wall: a case study

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ABSTRACT

Chemical compounds of soils can remarkably affect the stability of the excavation wall. This is highlighted in soils with fine grain materials. Inter-particle chemical cementation (IPCC) increases soil cohesion and, in turn, provides more stable excavations. This study evaluates the effect of soil chemical compounds on the stability of an excavation excavated in the west of Iran, Kermanshah city. It adopted the 2D finite element method (2DFEM) to evaluate the physical stability of the excavation. In the excavation examined here, the maximum depth that could be excavated with no need for support was 36m. In contrast, according to simulation results, the maximum possible depth for an excavation with soil cohesion of 6kPa and friction angle of 33 degrees, derived from direct shear test, is 6m. As per the results of this investigation, iron oxide, aluminum oxide, and silicon oxide increase the soil's cohesion containing the clay mineral montmorillonite by 10 folds and increase its shear strength by 127%.

Keywords: *Excavation; Support; Chemical compounds; Cementation*

1. Introduction

The increased number of multistoried buildings and the demand for finding space for car parking, and other amenities in buildings, especially in city centers, has led to deep excavations. The type and material of the particles have a significant effect on the excavating depth. Soils with high friction angles can be excavated deeper. Conditions are better if the soil mass is composed of well-graded particles. When a particle's size reduces to 1 or 2μm, or even smaller, inter-plane forces affect the particle behavior. This is why the investigation of particles behavior requires the knowledge of colloid bonds and chemical planes. Most clay particles show colloid-like behavior with non-satisfied plane electric forces. Thus, isomorphous replacement is observable in their structure [1]. To this end, different tests have been conducted on different soil types. Some researchers [2-4] have discovered that the increased shear strength of the soil is associated with soil acidity and alkalinity. The electro-osmosis property of soil changes by the injection of chemical substances. Cementation occurs more in alkaline environments than acidic ones. Therefore, the shear strength of soil more increases in the vicinity of the cathode. Ozkan et al. [5] injected phosphate and aluminum into Kaolinite mineral-contained soil and found increasing shear strength by 500% to 600%. Alshawabkeh and Sheahan [6] injected acid phosphoric into Illite mineral-contained soil and concluded that it could increase shear strength by 160%. Asavadorndeja and Glawe [4] concluded that soil's undrained shear strength increases due to inter-particle cementation. They generated this cementation by the electrochemical injection of phosphate in the electric field of AC electricity. Otsuki et al. [7] injected magnesium into Kaolinite mineral-contained soil and concluded that shear strength increases by 300kPa near the cathode. Ou et al. [8] studies showed that the injection of $CaCl_2$ to clay (the best pH=10) increases soil strength remarkably as it generates some compounds activating inter-particle cementation. Chien and Ou [9] concluded that sodium chloride injection into the soil for 7 days increases shear strength by 4 to 5 folds. Abdullah and Al-Abadi [10] improved a swelled soil sample by injecting Ca^{2+} and K^{+} using the electro-kinetic method where PI and swelling potential reduced from 40 to 8 and from 14% to 0.4%, respectively in K^{+}-reinforced soil. K^{+} showed better performance than Ca^{2+}, so that it further increased shear strength. The injection of saline solution into the soil can activate the electro-osmosis behavior of soil and improve strengthening components because the water flows towards the cathode. This further compresses the soil and, in turn, increases the un-drained shear strength of soil [11]. Ou et al. [12] showed that the improvement of the electro-osmosis effect enhanced by injecting saline substances into the soil because the injection of saline substance-using electro-osmosis method separates ions, playing the main role in cementation, and causes them to bond to other substances of soil as individual ions. They concluded that injecting $CaCl_2$ into the soil by electro-osmosis method for 7 successive days increases mean un-drained shear strength by 5 folds. In contrast, electro-osmosis alone increases it only by 1.25 folds. Besides, the injection of $CaCl_2$ decreases effect time by 40%. Cementation effects on soil particles and their behaviors were studied by various researchers [13-16]. Stability and performance of excavations, investigated by various researchers [17-19].

The settlement caused by dewatering is irreversible, so the ground settlement of a deep excavation caused by good dewatering cannot be ignored during the design and construction of excavation engineering [20]. Konai et al. [21] performed a series of shake-table tests on the excavation. Their research results indicate that in a post-seismic condition, when other factors were constant, lateral displacement, bending moment, strut forces, and maximum ground surface displacement increased with excavation depth and the amplitude of base acceleration. According to Bahrami et al. [22], the error rate in 2D

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analysis increases with decreasing excavation depth and increasing soil stiffness. Therefore, 2D analysis is not a suitable approach to analyze the behavior of retaining walls in excavations up to depths of 10m, and a 3D analysis is recommended for such excavations. It is found that the excavation in loose sand increases the ground movements induced by the excavation significantly [23].

In this study, the physical stability of the excavation wall is evaluated using a 2D finite element. The following facts have highlighted the importance of studying this 22m deep excavation with no support: (1) stability against high traffic load, (2) stability against inappropriate weather conditions including rain and snow and successive freezing-melting periods, (3) stability against earthquakes with the horizontal acceleration of 0.2 and (4) stability against surface water flows. Considering the depth of this excavation and its stability against different traffic and dynamic loads over a prolonged period, its grain size distribution and physicochemical properties could be used as a suitable model for excavations with sharp slopes.

2. Site identification and geotechnical properties

This section provides data associated with the site, geotechnical properties, and chemical test results.

2.1. Excavation size

The excavation site is located in the western part of Iran, Kermanshah city, and extends over a length of 110m and a width of 65m (Fig.1). This project has observed that the excavation wall has remained stable for the last 10 years. The groundwater level in the excavation site was reported 32m in summers [24].

Fig. 1. Investigated wall of excavation site (west-side wall).

2.2. Geographical location

The location and aerial maps of the excavation site are shown in Fig. 2 and Fig. 3, respectively.

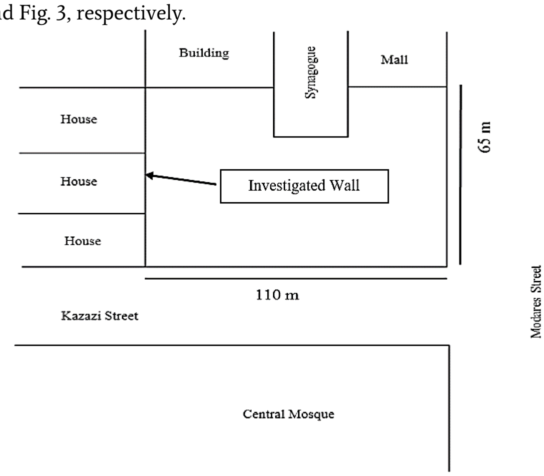

Fig. 2. Schematic view of the site.

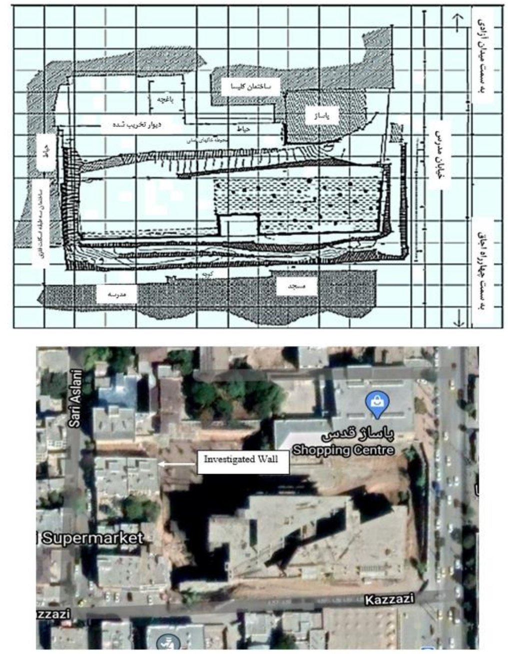

Fig. 3. Plan view of excavation site.

There are three galleries excavated in the west wall to conduct in-situ tests in each stratum and record the obtained results (Fig. 4). The latitude and longitude of the site are 34°19'11.6"N; 47°04'14.2"E, respectively.

Fig. 4. Excavation galleries in west side wall [24].

2.3. Physical properties of soil

The specifications of each stratum displaying the soil strata are shown in Fig. 5. Soil cohesion and friction angle were obtained from the direct shear test and were reported 6kPa and 33 degrees, respectively. Conducting numerical analyses using these values shows that the excavation wall's stability height should be shorter than 22m.

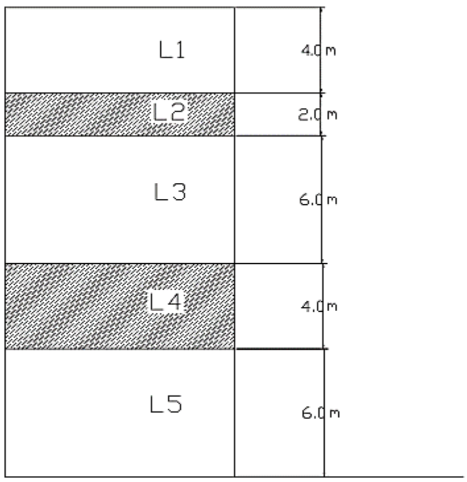

Fig. 5. Soil layers of excavation wall [24].

This difference may be attributed to eliminating the chemical cementation effect during sampling and handling the sample in a lab. Fig. 6 shows the soil grain size distribution curve, and Table 2 shows its physical properties.

Fig. 6. Soil particle distribution of investigated wall.

Table 2. Physical characteristics of soil.

Parameter	Amount
D_{10}	0.0015
D_{30}	0.055
D_{60}	3
C_u	2000
C_c	0.67
Soil Type	Sandy Clay (SC)
LL	45.35
PL	20.41
PI	24.94
γ_{field}	2.14 gr/cm^3
γ_d	1.83 gr/cm^3
$\gamma_{d\,max}$	1.88 gr/cm^3
ω	17.10 %
ω_{opt}	12.13 %
C (Large Direct Shear Test)	6 kPa
φ (Large Direct Shear Test)	33 °

Fig. 7 and Fig. 8 show shear stress against displacement for small scale and large scale in the direct shear test.

2.3.1. Direct shear test

A series of direct shear tests were performed to find the soil cohesion and internal friction angle. A large direct shear test was used for samples with a lateral displacement rate of 0.05mm/min.

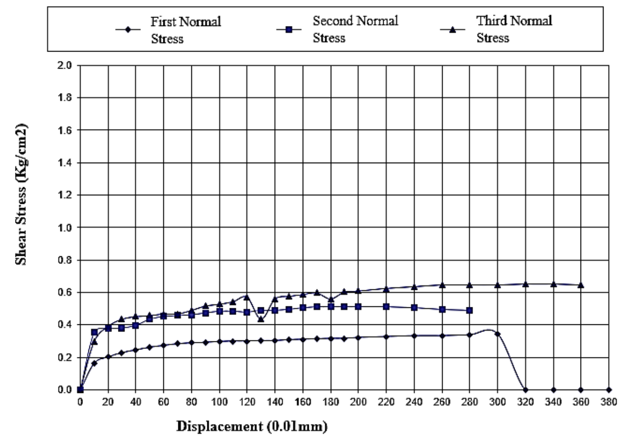

Fig 7. Shear stress against displacement in small scale.

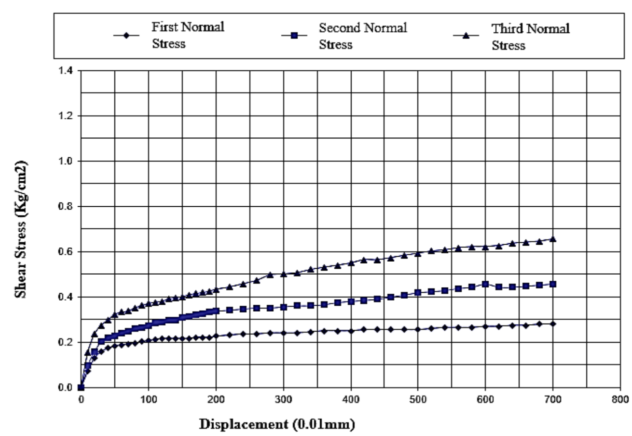

Fig. 8. Shear stress against displacement in large scale.

Fig. 9 indicates the shear stress-normal stress curve. Based on these curves, cohesion and friction angle are 6kPa and 33 degrees (Table 2).

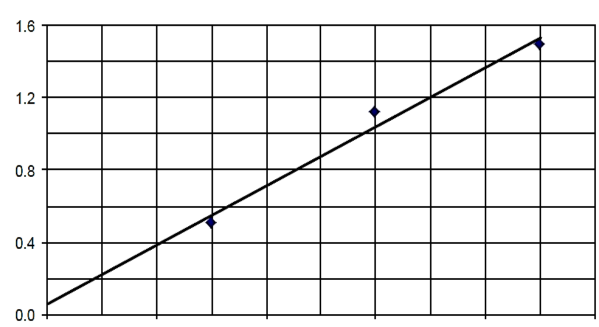

Fig. 9. Results of direct shear tests.

2.4. Chemical properties of soil

2.4.1. pH

The pH affects the surface charge of clay particles and, in turn, the repulsion force between particles. Positive charge-edges could be created in solutions with a lower pH. They are essential, less important, and almost unimportant in Kaolinite minerals, Illite minerals, and

Smectite minerals. It is the most important factor in Kaolinite minerals as it controls the texture of substances depositing from suspension [1] and accelerates weathering in acidic environments [25]. This study reported pH to be 9.3, indicating a completely alkaline environment. Since this soil is strongly alkaline, it has experienced little weathering.

2.4.2 X-Ray Diffraction (XRD) test

No two minerals have the same distance between their atomic layers in three dimensions. Therefore, the refraction angle and atomic distance could be used to differentiate a mineral. XRD is a proper technique to identify clay minerals because each clay mineral's plane distance could be identified by Miller's index (001). Basal planes generally show the severest refraction among crystal planes as they have been laid out near atoms. XRD could differentiate non-clay minerals that are available in the soil. The complete pattern of XRD includes a series of refractions with different severities and different 2θ values where each refraction should be attributed to some components of the studied sample [1]. The XRF results approved the existence of iron compounds in the studied soil. In the studied soil, the peak value was registered for an angle<35 degrees. On the other hand, the obtained XRF curve agrees with that of Fe^{+3}. This confirms the existence of iron in soil (Fig. 10). Furthermore, XRF results approved the existence of Fe^{+2} dioxide and Al^{+2} dioxide in soil. Other compounds of soil with different percentages were obtained by the titration method.

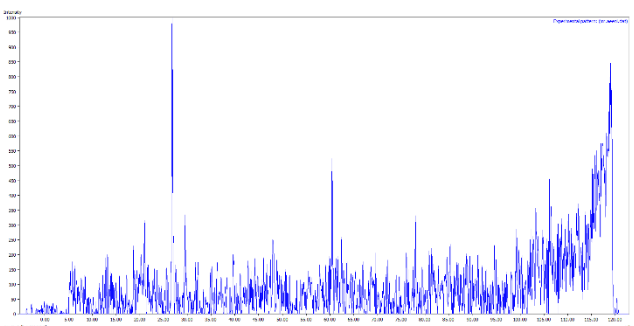

Fig. 10. XRF result of investigated soil.

Table 3 shows the results. Fe^{+2} and Al^{+2} oxides and higher percentages of silicon oxide are the most important chemical compounds available in the studied soil. Table 3 compares the higher percentage of iron of the studied soil with that of other soil types. Comparing chemical analysis results with available compounds of the studied soil indicates that this soil belongs to the Montmorillonite mineral category of the Nontronite sub-category. Other physical properties mentioned for this category and sub-category completely agree with the obtained results. Relying on different studies on different soil types and their frequency in nature [1], the studied soil is categorized in the "rare soil" category.

Table 3. Chemical composition of investigated soil (Based on chemical tests).

Chemical Composition	(Mass) Percent Available in Sample
$CaSO_4$	0.38
$CaSO_3$	0.22
SiO_2	37.67
Fe_2O_3	16.90
Al_2O_3	9.65
CaO	7.0
MgO	0.4
Aluminum & Iron Oxide	26.55
CO_2 (Based on Volume Percent)	6.3

3. Numerical analysis

To determine the effect of chemical compounds on the stability of the studied excavation wall, numerical analysis was conducted on the wall using 2D finite elements. The excavation modeled with the physical properties obtained in the laboratory is expected to be stable at height=22m otherwise; the effect of chemical compounds will be undeniable. This modeling was performed using 15 node plane strain elements. To take the load of the building located above the excavation into account, the uniform load was considered to be 700kg/m^2, and Poison's ratio was considered to be 0.35. Dexter et al. [26] relation was used to apply variations of the modulus of elasticity versus excavation depth:

$$q_c = 328 + 37.39(1/_S) + 1.615\sigma' \qquad (1)$$

Where q_c is the cone resistance, σ' is the effective stress of soil in kPa and S is a dimensionless parameter. The suggested value for S is nearly 0.03. The proposed relations 2 and 3 are used to obtain a relation between depth and the modulus of elasticity [27].

$$E = \alpha q_c \quad : \alpha = 3.8{\sim}5.7 \qquad (2)$$

$$E = {}^5/_3\,(q_c + 1600) \quad : PI < 15\% \qquad (3)$$

In this study, PI is >15%. Therefore, we used relation 2. Besides, we considered α to be 4.75. Table 4 shows variations of E in each stratum.

Table 4. Variation of modulus of elasticity with depth.

Depth	$\sigma' = \gamma' \times h$	q_c	ΔE	E (kPa)
0~2	11	1635.07	7766.6	357766
2~4	33	1670.06	7935.37	357935
4~6	55	1706.13	8104.14	308104
6~8	77	1741.66	8272.91	428272
8~10	99	1777.19	8441.67	428441
10~12	121	1812.72	8610.44	428610
12~14	143	1848.25	8779.21	358779
14~16	165	1883.78	8947.98	358947
16~18	187	1919.31	9116.74	409116
18~20	209	1954.84	9285.51	409285
20~22	231	1990.37	9454.28	409454
22~24	253	2025.9	9623.05	409623

The relation suggested by Duncan et al. [28] was used to take the variations of friction angle versus depth into account.

$$= A + B(D_r) - [C + D(D_r)0]\log_{10}({\sigma'}/_P) \qquad (4)$$

Where σ' is the effective stress of soil, D_r is relative density, and P is air pressure, which is considered 1 atm. A, B, C, and D are coefficients that are extracted from Dexter et al. [26] (Table 5).

Table 5. Amount of parameters A, B, C, D for excavation site (Based on Dexter et al. [26]).

Parameter	A	B	C	D
Amount	39	10	3	2

Also, relative density is calculated from relation (5).

$$D_r = \left(\frac{\gamma_{d_{Max}}}{\gamma_d}\right)\left(\frac{\gamma_d - \gamma_{d_{min}}}{\gamma_{d_{Max}} - \gamma_{d_{min}}}\right) \qquad (5)$$

Where $\gamma_{d_{Max}}$ the maximum dry unit weight, γ_d is the dry unit weight, $\gamma_{d_{min}}$ is the minimum dry unit weight. The value of relative density was obtained at 77%. Table 6 shows variations of friction angle versus depth.

Table 6. Variation of friction angle with depth.

Depth	$\sigma' = \gamma' h$ (kN/m^2)	Effective Friction Angle Reduction*	Effective Friction Angle (°)
0~2	11	0	30
2~4	33	-2	28
4~6	55	-3	7
6~8	77	-4	28
8~10	99	-4	28
10~12	121	-4	28
12~14	143	-5	5
14~16	165	-5	5
16~18	187	-5	28
18~20	209	-5	28
20~22	231	-5	28

The studied excavation was excavated in two stages in the saturated state. The specifications of each stratum with a thickness of 2m were allocated separately. Fig. 11 shows changes to the model after 2DFE analysis conducted on the studied 22m excavation. These changes are negligible.

Table 7 shows the maximum height for the excavation stability for different C/6 ratios, where 6 is the cohesion value derived from the direct shear test. This table shows that the required cohesion for the excavation's stability at the height of 22m should be 10 times higher than the cohesion measured in a laboratory. Indeed, the chemical compounds of soil could raise soil cohesion by 10 folds.

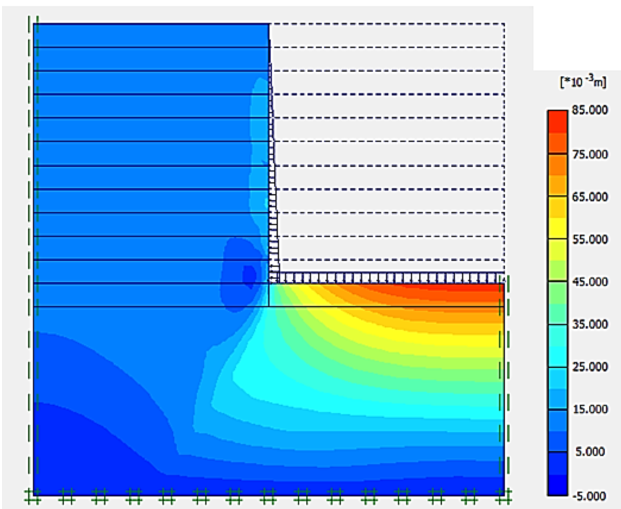

Fig. 11. 22 Meters excavation in 11 steps with 2 meter depth in F.E. numerical analysis.

Table 7. Results of F.E. numerical analysis for excavation site.

Ratio of Cohesion Amount to the Base Cohesion (C/6)	Depth of Stable Excavation
1	Collapse in 6 m
4	Collapse in 10 m
8	Collapse in 20 m
9	Collapse in 22 m
9.5	Collapse in 22 m
9.75	Collapse in 18 m
10	Collapse in 18 m
10.1	Stable up to 22 meter of Excavation

Fig. 12 shows the C/6 ratio versus the stability height of the excavation. According to numerical results, for the cohesion of 60kPa and friction angle of 33 degrees, the safety factor for heights 22m and 36m should be 1.786 and 1.102, respectively.

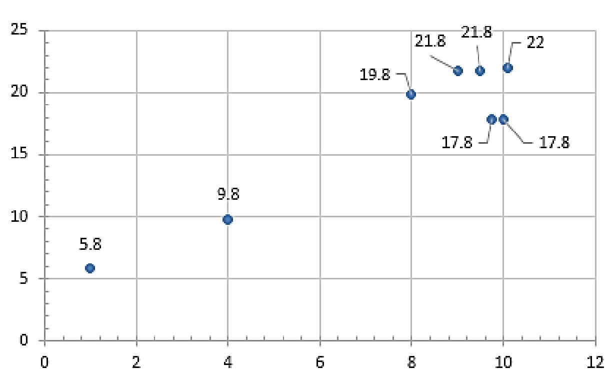

Fig. 12. Graph obtained in F.E. numerical analysis.

This indicates that the excavation wall remains stable at a depth of 36m, and it will be unstable beyond this depth. Therefore, it can be argued that chemical compounds could serve as a safe, low-cost, and executable support in closed spaces and small civil spaces. The use of meshless methods [29] for the numerical analysis of excavated walls may be useful for more accuracy of future studies' results.

4. Results and Discussion

With a height of 22m, the support-free excavation of the project has remained stable for 10 years. However, it has experienced light and heavy traffic loads, surface water flows, and earthquakes with a horizontal acceleration of 0.2. According to numerical analyses, however, the excavation's stability height should be 6m considering the strength parameters measured in the laboratory. This indicates that chemical compounds can significantly affect the excavation stability, and in the conducted direct shear test, this effect was eliminated. According to the direct shear test results on a disturbing sample of the excavation with the same in-situ and laboratory unit weights, soil cohesion and friction angle should be 6kPa and 33 degrees, respectively. However, measured Lab. cohesion is very low. The reason may be the neutralization of chemical cementation during sampling and handling the sample in the laboratory. The measured pH is 9.3, indicating a completely alkaline environment. The soil alkalinity is very high. It can be argued, therefore, that it has experienced little weathering. XRF tests confirmed the existence of iron compounds in the soil. On the one hand, the peak value was registered for a friction angle<35, and on the other hand, the XRF curve agreed with that of iron (iii) (Fe^{+3}). This confirms the existence of iron in the studied soil. Also, the existence of Fe^{+2} oxide and Al^{+2} oxide was confirmed. Fe^{+2} oxide, Al^{+2} oxide, and higher percentages of silicon oxide are the most important soil compounds. The first notable fact is higher percentages of iron in the studied soil than other soil types. By comparing the soil's chemical composition analysis with its chemical compounds, it was revealed that the soil belongs to the Montmorillonite mineral category of the Nontronite sub-category and is categorized in the "rare mineral" category.

The studied excavation site was analyzed in a saturated condition. It was excavated in multiple stages. The specifications of soil in each stratum with a thickness of 2m were allocated separately. The required cohesion for the excavation's stability at the height of 22m should be 10 times higher than the laboratory's cohesion. This indicates that the chemical compounds of soil could raise soil cohesion by 10 folds. According to 2D finite element results, the maximum stability height is 36m. The safety factor for a height of 22m and 36m should be 1.786 and 1.102, respectively. This indicates that the excavation wall remains stable at these depths. Seismic and explosion loading [30-31] near the excavated walls can be considered for future studies.

4.1. Increasing soil shear strength

Excavation bottom was considered at depth=22m, which is the most critical point in terms of stability. The increased shear strength of this point was derived from relation 6:

$$\tau = \sigma \tan \varphi + c \quad (6)$$

Shear strength obtained 306 and 390kN/m^2 for disturbed samples, as pre-cementation results, and in-situ results, as post-cementation results, respectively. This indicates that shear strength raised by 127.45%. This means that the chemical compounds of soil raise shear strength by 127.45%.

5. Conclusion

Following conclusions can be drawn from the present investigation:

1. The chemical compositions of soil, especially aluminum oxide (ii), iron oxide (ii), silicon, and calcium oxide, can remarkably increase the shear strength and stability of excavation walls.
2. The effect of chemical compounds on shear strength depends on the severity of the dominant mineral of soil and other

chemical specifications. For Kaolinite minerals, this effect has been reported up to 6 times. This study showed that the effect of chemical compounds on Montmorillonite mineral is about 1.3.

3. The effect of the chemical compounds of soil is manifested as cohesion. This is originated from inter-particle cementation. Chemically, this is a one-way irreversible effect. If the inter-particle cementation-induced bond is broken, this bond will be irreversible, and soil cohesion should be measured in the laboratory without the effect of chemical compounds.
4. The alkalinity of the soil environment affects inter-particle cementation (the best pH =10). This means that an acidic environment has an inverse effect. Higher pH values and alkalinity provide the ideal condition for cementation.
5. Experiencing little weathering due to soil alkalinity has positively impacted excavation wall stability over the past 10 years.
6. Conducting in-situ tests in the excavation site is strongly recommended to obtain the actual cohesion of the excavation.
7. The existence of iron dioxide, aluminum dioxide, and silicon dioxide compounds in Montmorillonite mineral-contained soil has raised cohesion by 10 folds and has increased shear strength by 127%.
8. Seismic and explosion loading near the excavated walls can be considered in future studies.
9. Also, meshless methods for numerical analysis of excavated walls may be useful for the accuracy of future studies' results.

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