Int. J. Electrochem. Sci., 16 **(2021)** Article ID: 210230, doi: 10.20964/2021.02.52

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Model Test of Soft Soil Consolidation Based on Surcharge Preloading Combined with Electro-Osmosis Methods

Gang Li[1], *Jia Liu*[2*], *Tao Luo*[1], *Ming Xie*[1], *Huanhuan Li*[1]

[1] Shaanxi Key Laboratory of Safety and Durability of Concrete Structures, Xijing University, Xi'an, Shaanxi 710123, China;
[2] School of Geological Engineering and Geomatics, Chang'an University, Xi'an, Shaanxi 710054, China.
[*]E-mail: 15929935077@163.com

Received: 13 October 2020/ *Accepted:* 8 December 2020 / *Published:* 31 December 2020

In this study, the experiments were carried out to determine the influence of surcharge preloading (SP) combined with electro-osmosis (EO) methods on soft soil consolidation, and the consolidation effect was improved by adding nano-SiO_2 particles or nano-Fe_3O_4 solution. We analyzed the variation laws of current (*I*), potential (*U*), water content (*w*), water discharge (*V*), pH, shear strength (*S*), and bearing capacity (*B*) in the process of EO. The results showed that as time (*t*) increased, the *I* and *U* in the soil dropped gradually, whereas the *V* went up. The *w* and pH of soil near the anode were lower than near the cathode, while the *S* and *B* were larger. Compared with the upper soil, the lower soil featured a higher *w*, lower *S*, and *B*, and without significantly pH changed. During the process of EO, transverse cracks were found in the soil in the anode region because of severe shrinkage. Under the action of SP combined with EO, the soil was compacted, thereby its strength was improved. Nanomaterials filled the pores between soil particles, and the nanoparticle aggregates reduced the soil pore size and number and thus made the soil more compact. At the concentration of 3‰ nano-SiO_2, SP combined with EO had the optimal consolidation effect on soft soil.

Keywords: Soft soil; Nanomaterial; Electro-osmosis; Surcharge preloading; Consolidation

1. INTRODUCTION

Electro-osmosis (EO) method is a ideal method to reinforce the soft soil foundation, which can quickly improve the bearing capacity of the foundation and will not cause instability.Li *et al*. [1] found that the consolidation of soft soil with EO combining with dynamic loading was superior than single EO method, and the optimal dynamic loading activation time was a function of maximum current ratio. Tang *et al*. [2] pointed out that the shear strength (*S*) of marine soil under EO treatment improved 60.90% at 35^{o}C, and water content (*w*) decreased 9.30% under 12 V. Liu *et al*. [3] carried out an experimental study on EO combined with intermittent or one-time grouting with the addition of $CaCl_2$

and Na_2SiO_3 solutions, concluding that intermittent grouting under anode-center joint grouting had the best reinforcement effect. Compared with one-time grouting, intermittent grouting yielded an increase of 4% in water discharge, a 9% reduction in cumulative energy consumption, and a significant improvement in bearing capacity (*B*). According to current research, they found that combining EO with other consolidation methods to give full play to their respective strengths and make up for each other's shortcomings was an effective approach for soft soil consolidation. Wang *et al*. [4-5] investigated the consolidation of dredged slurry used EO combining with vacuum preloading (VP) methods, and proved that the *S* decreased linearly with increasing of distance from anode (*D*), whereas increased sharply near the cathode. Meanwhile, they indicated that $FeCl_3$ was better than $Al_2(SO_4)_3$ for EO consolidation combined with VP, and the drainage (*V*), *S* and soil uniformity were improved by the flocculant. Hu *et al*. [6] investigated the effect of chemical reagents on the consolidation with VP combined with EO, and found that $FeCl_3$ solution was most energy-saving, and $Ca(OH)_2$ solution was the most economical and practical addition. Fu *et al*. [7] conducted the EO combined variable spacing VP tests on the soft ground, and found that the combined method was superior in consolidation effects, and the energy consumption for large spacing EO was less than small spacing EO. Wang *et al*. [8] noted that the combined method of surcharge-vacuum-EO can improved the consolidation effect and shorten the consolidation time, and the final ground settlement will reduced with decreasing of additional stress. Kang *et al*. [9] investigated the EO effect on marine clays with preloading, and found that the settlement, *V*, and *S* increased with increasing of potential (*U*), while the *w* decreased. Sun *et al*. [10] found that the alternate time between VP and EO method don't need too long or too short, and the alternate time should be adjusting to the drainage rate. Zhou *et al*. [11] reported that the combination of EO and VP had an obviously better consolidation effect than EO or VP alone. The different combinations of EO and VP were similar in the final average settlement of soil, and the lag condition of EO effectively reduced energy consumption. Therefore, in engineering, the consolidation degree of VP combined with EO should be controlled to within 80%. Liu *et al*. [12-13] concluded that stepped VP combined with intermittent EO in stepped voltage modes outperformed VP combined with EO in consolidating the soil and significantly reduced electrode corrosion and the average energy consumption coefficient of intermittent EO. The distribution range of soluble salts significantly affected the EO effect, which was better when the saline soil was distributed near the anode instead of the cathode. Sun *et al*. [14] found that VP combined with EO achieved a better asynchronous reinforcement effect, while the alternating consolidation time of VP combined with EO also exerted an apparent influence on the reinforcement effect. If the alternating time was too short, VP and EO could not be achieve full drainage; if the alternating time was too long, the energy provided by VP and EO was not fully utilized. Li *et al*. [15] studied the effects of voltage and hydraulic permeability coefficient on the degree of radial consolidation and the dissipation of average pore pressure, concluding that for the combination of surcharge preloading (SP) and EO, a higher power supply voltage yielded better performance, and 10^2-10^3 was a suitable range for the ratio of the EO permeability coefficient to the hydraulic permeability coefficient. Jiang *et al*. [16] pointed out that EO combined with VP could realize the rapid dehydration and settlement of soft soil, and soft soil consolidation could be completed within 30 days with great improvements in various indices of the consolidated soft soil. Hu *et al*. [17] proposed that pneumatic fracturing was somewhat effective in promoting EO drainage, and EO combined with loading and pneumatic fracturing could well process the deep soil. Fu *et al*. [18] reported that low-energy dynamic compaction improved the drainage path, so that the outflow performance of soil was stronger than that when EO was single applied. Low-energy dynamic compaction not only enhanced the circuit *I* and soil compactness to make up for soil cracks but also facilitated the development of soil surface settlement, improved the uneven treatment of circumferential soil, and slowed down anodic corrosion. Wu *et al*. [19] found that when VP and EO were coupled for consolidation, the negative excess pore pressure reached its maximum, i.e., -90 kPa, while the differential settlement was minimized at 0.01 cm. Under the combined action of VP and EO, a larger negative excess pore pressure was formed in the foundation, which achieved a better preloading effect and effectively reduced the differential settlement of the surface.

To effectively solve the problem of slow consolidation of soft soil, studies have been carried out on soft soil foundations with the combination of SP and EO, and they have achieved promising results [20]. However, there are few studies on the use of nanomaterials to improve the consolidation effect of SP combined with EO method. In this paper, we investigated the influence of SP combined with EO on soft soil consolidation, and the influence of consolidation effect by adding nanomaterials were analyzed. Based on the macro characteristics and micro structure of soft soils, the mechanism of electro-osmotic consolidation was analyzed, which provides a reference for popularizing the practical application of EO method.

2. EXPERIMENTAL

2.1 Materials

Silt soil obtained from Huai'an in Jiangsu Province was used in this study. Table 1 lists the physical index of the soft soils. In order to reduce the error, the soil was dried and crushed firstly. Subsequently, the soil and water were accurately weighed and poured into the mixing bucket, and fully mixed with mixer until fully uniform with a water content of 70%.

Table 1. Physical index of soft soil

Water content/%	Liquid limit/%	Plastic limit/%	Plasticity index	Density/(g/cm^3)
6.75	43.6	21.7	21.9	1.82

Due to the positively charged of nano-materials, the nano-particles forced the surrounding water molecules to move to the cathode together under EO effect, which further improved the drainage rate and the shear strength of soils. Therefore, nano-SiO_2 and nano-Fe_3O_4 were used in this study. The nano-SiO_2 particles were purchased from Nanjing Paukert Advanced Material Co., Ltd. The particles had a size of 20 nm, a purity of greater than 99.8%, a specific surface area of 280 m^2/g, and a pH ranging from 5 to 7. The nano-Fe_3O_4 solution was purchased from Hangzhou Zhitai Purification

Technology Co., Ltd. The solution had a particle size of 20-30 nm, a purity of greater than 99.9%, and a particle content higher than 20%. During the experimental process, a certain amount of nano-materials were added into the appropriate amount of water and stirred evenly, then the water and soil were mixed evenly to prepare the soil samples.

2.2 Model box

The model experiment was carried out in a customized cylindrical plexiglass box, and Figure 1 shows a sketch diagram of the model test. The box was 400 mm in diameter, 280 mm in height, and 10 mm in thickness. Four anode tubes were fixed with 10 mm away from the inner boundary, and one cathode tube was fixed in the center of model box. Under the cathode tube, the drain hole was connect with the collecting vessel. The iron electrodes were used in this study, and the anode was a hollow pipe with 8 mm in diameter, 240 mm in height and 1 mm in thickness. A plexiglass tube with 18 mm in diameter, 290 mm in height and 1 mm in thickness wrapped with iron wire served as the cathode. Furthermore, the cathode was wrapped with a geotextile to prevent blocked. In order to simulate the effect of SP, the fine sands with thickness of 10 cm were put on the surface of soft soils, and the geotextile with thickness of 1 mm was put between soils and sands.

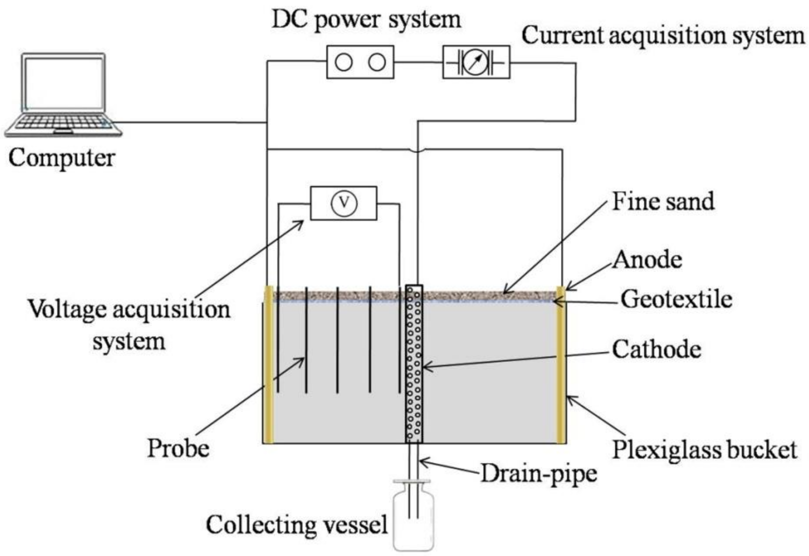

Figure 1. Sketch diagram of model test

2.3 Methods

Table 2 shows the test scheme, the experiments were carried out to investigate the effect of SP combined with EO on soft soil consolidation, and nanomaterials were added to the soils to strengthen the EO effect. Based on previous research results, the effect of EO consolidation can be significantly improved when 3‰ nano-SiO_2 particles or 2‰ nano-Fe_3O_4 solution is added. Thereby, the optimal concentration of nanomaterial was directly applied in this study. As shown in Table 2, six groups of experiments were carried out, and the parallel experiments were conducted at the same time. The experimental *U* and *t* were set at 30 V and 72 hours, respectively, and the initial *w* of the soil sample was set as 70.0%. The measurement indices mainly included the *I*, *U*, *w*, *V*, pH, *S*, and *B*. According to the standard for soil test method (GBT 50123-2019), the initial *w* of the soil sample was measured before the experiments. During the experimental process, the *V* and *I* were recorded every hour firstly, and recorded every 2 hours after 24 hours. Meantime, the *U* was measured every 12 hours. When the experiment ended, the pH, *S*, and *B* of soil samples at different distances from the anode were measured, and the *w* and scanning electron microscopy (SEM) were performed on the representative samples.

Table 2. Test scheme

Test No.	Time/h	Potential/V	Methods	Nanomaterials	Concentration/‰
T1	72	30	EO	--	--
T2	72	30	EO	nano-SiO_2	3
T3	72	30	EO	nano-Fe_3O_4	2
T4	72	30	SP+EO	--	--
T5	72	30	SP+EO	nano-SiO_2	3
T6	72	30	SP+EO	nano-Fe_3O_4	2

3. RESULTS AND DISCUSSION

3.1 Effect on current and potential

Energy consumption is one of the problems limiting the practical application of EO consolidation, which is closely related to *I* and *U*. Figure 2 shows the change in *I* with *t*. On the whole, the *I* decreased with *t*. When the *t* ranged from 0 to 15 hours, the *I* first declined rapidly and then decreased gradually before leveling off, which was consistent with the conclusion reached by Wang *et al*. [21]. The main reason was that during the process of EO, the electrode material was gradually corroded over time, which increased the interface resistance. At a specific *U*, the *I* decreased as the *t* increased. The *I* under different test conditions were changed, and the largest is T5. Liu *et al*. [3] reported that the injection of chemical solution improved the electrical conductivity of soil, thus increasing the *I*. Nevertheless, the *I* was not significantly increased after the addition of nanomaterials in this study, indicating that the nanomaterials did not increase the electrical conductivity of soil.

Figure 3 shows the variation laws of *U* with *t*, and the results consistent to Wang *et al*. [22]. With longer *t*, the *U* fell progressively, though the decrease was relatively fast within the first 25 hours. Based on the observed *I* and *U* variation, the *I* and *U* under the action of SP combined with EO were greater than those under EO only. The *I* and *U* further increased as a result of the addition of nanomaterials, resulting in a further growth in EO energy consumption.

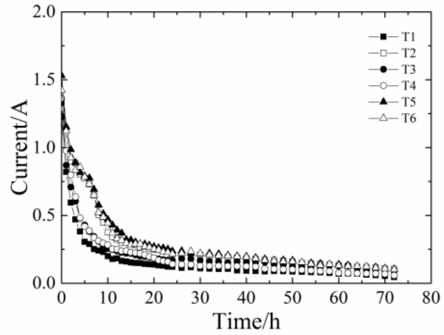

Figure 2. Relationship between current and time

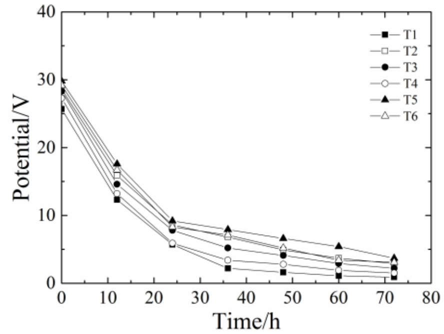

Figure 3. Relationship between potential and time

3.2 Effect on water content and water discharge

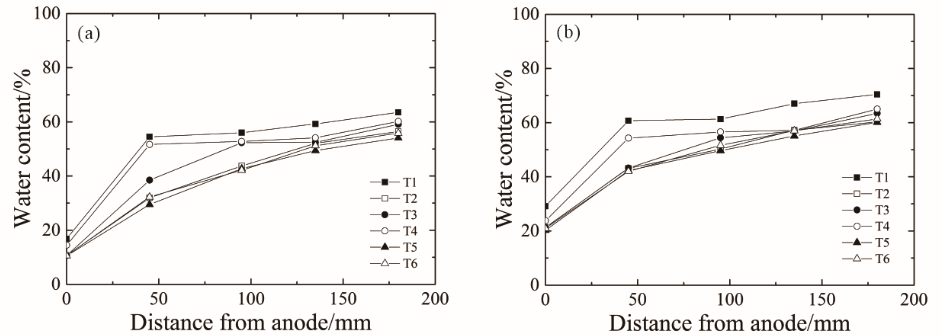

Figure 4. Relationship between water content and distance from anode (a) upper layer, (b) lower layer

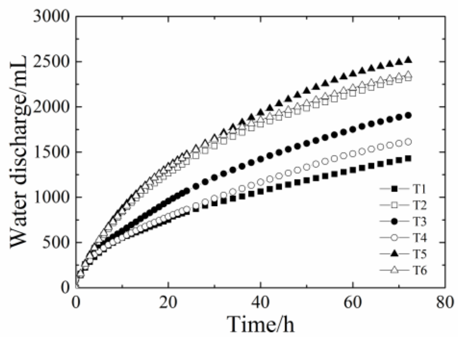

Figure 5. Relationship between water discharge and time

During the EO process, as *V* increased, the settlement and *S* of soil increased, while the *w* of the soil declined significantly. Figure 4 shows the distribution of *w* in the upper (100 mm depth) and lower (200 mm depth) soil with respect to *D*. The *w* of soil near the anode region was lower than the *w* near the cathode region, and the *w* in the upper soil was significantly lower than that in the lower soil. The main reason was that, because of the EO, the cations in the soil moved to the cathode while the anions moved to the anode, and the ions dragged the nearby water molecules with them, thus forming a directional seepage from the anode to the cathode and from top to bottom [23]. Figure 5 shows the variation of *V* with *t*. As shown in the Figure 5, the *V* increased with *t*, and as the *w* decreased, the curve's slope in the initial phase of drainage was significantly higher than that in the later stage. On the whole, the above results indicated that the *V* of soil under SP combined with EO exceeded that under the action of EO alone. Furthermore, the *V* was further increased by the addition of nanomaterials. When 3‰ nano-SiO_2 was added, the *V* was the largest (T5), followed by when 2‰ nano-Fe_3O_4 added (T6), which confirmed the results of the *w* of the soil. Based on the above analyses, nanomaterials improved the effect of EO drainage, and 3‰ nano-SiO_2 was the best concentration of the best nanomaterial in this study.

3.3 Effect on pH

During the EO process, the pH of the soil will change as the electrochemical reaction. Figure 6 shows the distribution of the pH of soil with respect to *D*. The soil near the anode region was acidic (low pH), whereas the soil near the cathode region was alkaline (high pH), which was consistent with the results of Fu *et al*. [18]. The primary reason was that during the EO, the reaction in the anode region generated H^+, while the reaction in the cathode region formed OH^-. Therefore, the soil near the anode region was acidic, while the soil near the cathode region was alkaline [3]. In general, the pH of soil under different testing conditions basically followed the same distribution laws. Since the electrodes ran through the soil layers and the reaction mainly affected the region around the electrodes, there was a slight difference between the pH of the upper and lower soil.

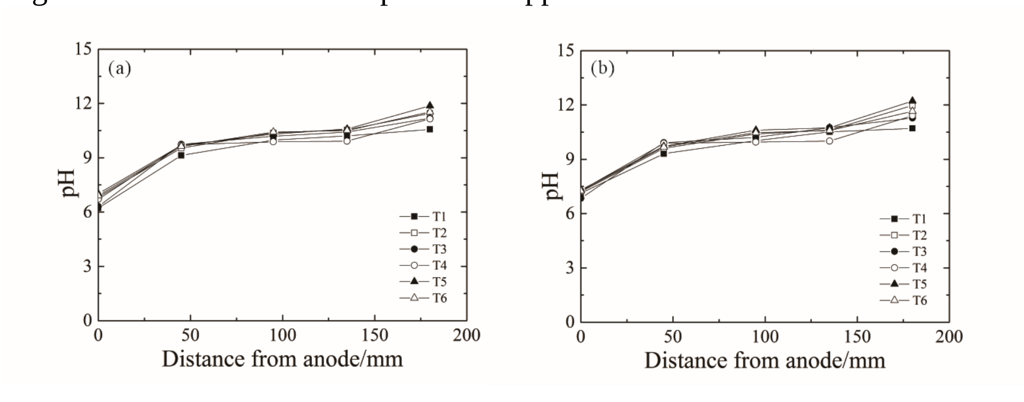

Figure 6. Relationship between pH and distance from anode (a) upper layer, (b) lower layer

3.4 Effect on shear strength and bearing capacity

As an important index of soil strength, *S* is usually determined from direct shear testing or triaxial testing. Our experimental scheme made it difficult to conduct sampling and indoor tests after the experiment. Therefore, the *S* was measured by a portable filling instrument. Figure 7 shows the distribution of *S* with *D*. The soil near the anode region had a high *S*. However, as the distance from the soil to the anode increased, the *S* of the soil gradually decreased, with the *S* of the upper soil being significantly higher than that of the lower soil, which was consistent with the findings of Hu *et al*. [17, 22]. Under the action of the electric field, a directional top-to-bottom seepage from anode to cathode was formed [23]. As a result, the soil near the anode region had a low *w* but high *S*, while the soil near the cathode region featured a high *w* but a low *S*. On the whole, under SP combined with EO, the soil had a higher *S* than under EO alone, which became more obvious with greater soil depth. In addition, the *S* of soil was markedly improved by the addition of nanomaterials.

Bearing capacity is an important index to reflect the bearing performance and stability of soil. Figure 8 shows the distribution of *B* of the soil with *D*. Consistent with the distribution law of the *S*, the *B* of the soil near the anode region was significantly larger than that of the soil in the cathode region, and the *B* of the upper soil was drastically greater than that of the lower soil. Both results are in good agreement with the results of Liu *et al*. [3]. In general, the *S* and *B* of soil were larger under SP combined with EO, and the two indices were further increased after the addition of nanomaterials. When 3‰ nano-SiO_2 was added, the soil had its highest *S* and *B*, indicating 3‰ was the optimal concentration of this nanomaterial.

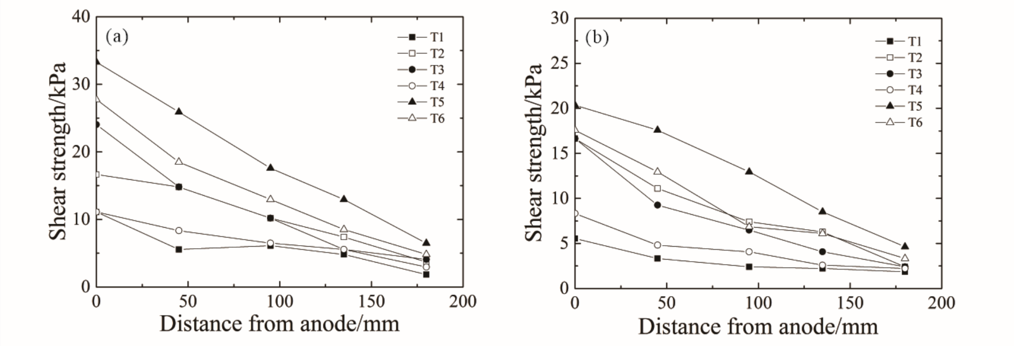

Figure 7. Relationship between shear strength and distance from anode (a) upper layer, (b) lower layer

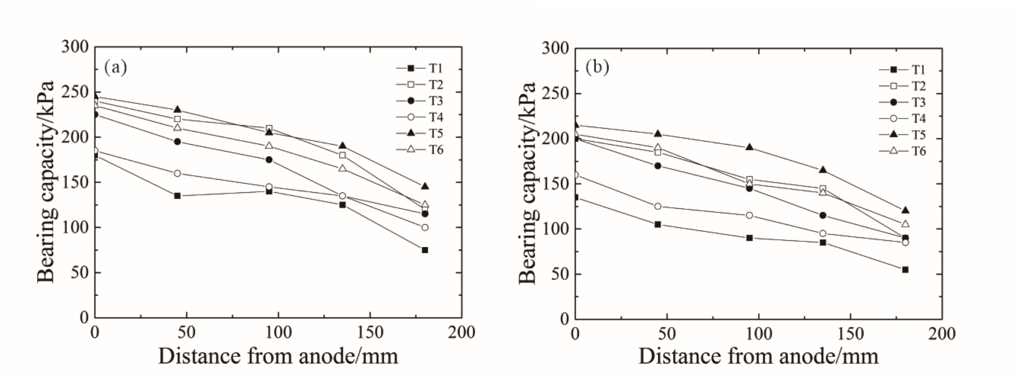

Figure 8. Relationship between bearing capacity and distance from anode (a) upper layer, (b) lower layer

3.5 Microscopic structure of soft soil

The microstructure and macro characteristics of the soil are correlated. Following the experiment, soil samples in the anode region were selected for SEM imaging. Firstly, liquid nitrogen was used to freeze and sublimate the samples, which were then put into a freeze dryer for low-temperature vacuum drying. The water contained in the samples was pumped at a high speed to keep the microstructure of the soil samples constant. Before SEM scanning, the samples were cut into thin slices, and the relatively flatter slices were selected for SEM testing in order to maintain the original structural shape of the soil surface. After spraying with gold and vacuuming, the samples were scanned and photographed by the FEI Q45 field-emission SEM to obtain the microstructure of the soil samples [24].

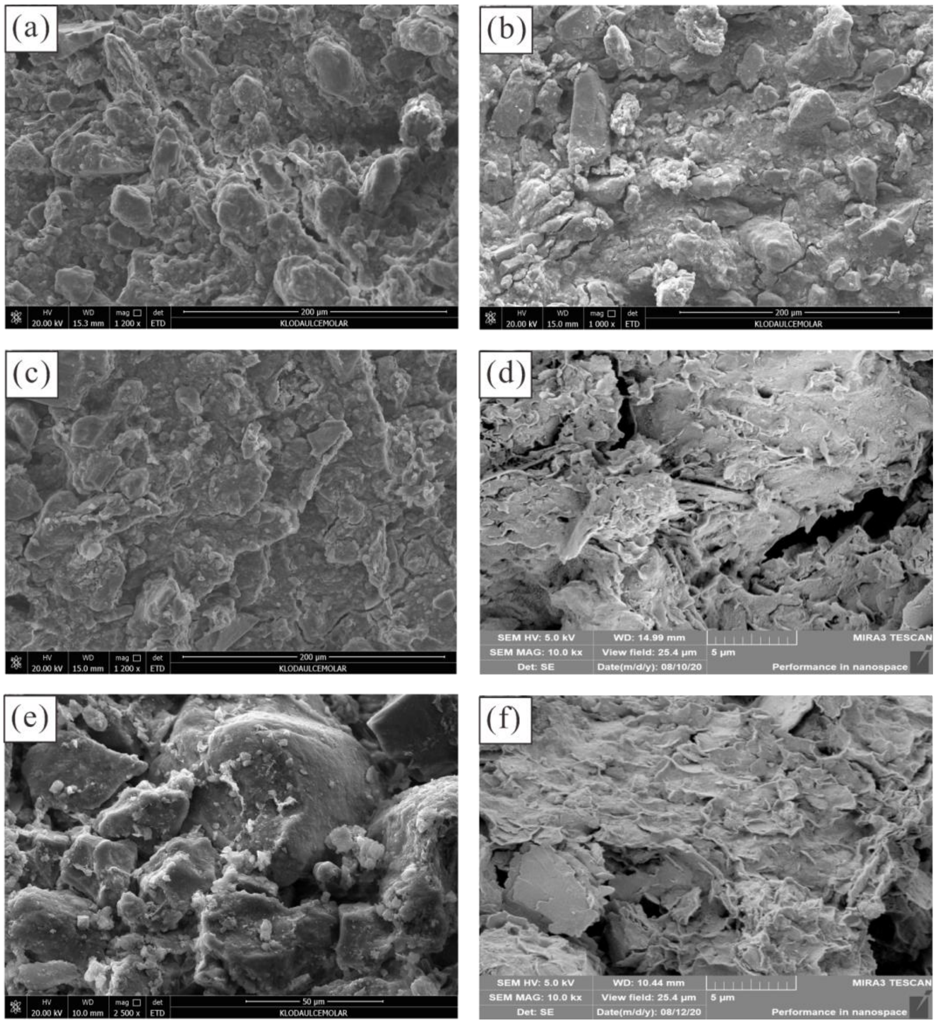

Figure 9. SEM image of soft soils

Figure 9 shows the microstructure of the soil samples scanned by the SEM. After EO consolidation, the soil was basically in a flocculated-agglomerated structure, with a high content of clay in the particles. The soil particles were obviously aggregated, with relatively few pores, showing a compact structure. Transverse cracks were found in T1 group mainly because under the action of the electric field, the water in the soil seeped from the anode to the cathode, so the soil in the anode region had varying *w* and severe shrinkage, causing the formation of transverse cracks. The soil processed by SP combined with EO had a more compact structure. In addition, some fine particles migrated to fill the macropores, gradually reducing the macropores in the soil to small pores or eliminating them, resulting in higher soil compactness [25]. These results show that compared with EO alone, SP combined with EO was more conducive to reducing soil pore number and size, improving soil compactness and promoting the discharge of free water and pore water. The added nanomaterials played a role in filling the pores between soil particles, and the generated nanoparticle aggregates reduced pore size and made the soil compact [26]. Under SP combined with EO, the nanoparticles surrounded the soil particles to turn the smaller soil particles into larger soil particles, resulting in more cemented material and fewer pores between the soil particles, forming a more stable and compact soil structure.

Based on the above results, the *S* and *B* of soils were higher under SP combined with EO, and the two indices were further increased after the addition of nanomaterials. The microstructure of soil formed under such conditions was consistent with the macro mechanical properties of the soil.

4. CONCLUSIONS

In this study, we investigated the influence of surcharge preloading combined with electro-osmosis on soft soil consolidation, and the electro-osmotic consolidation effect was improved by adding nano-SiO_2 particles or nano-Fe_3O_4 solution. The following conclusions were drawn:

(1) With longer time, the current and potential in the soil gradually dropped, whereas the water discharge increased. The soil near the anode had a smaller water content and pH yet a larger shear strength and bearing capacity.

(2) By comparing the surcharge preloading coupled with electro-osmosis with electro-osmotic method alone, we found that the former had the optimal consolidation effect when 3‰ nano-SiO_2 was added.

(3) During electro-osmosis process, the water content of soil near the anode varied greatly, and transverse cracks were found in the soil as a result of severe shrinkage. The nanomaterials filled the pores between soil particles, and the generated nanoparticle aggregates reduced pore size and made the soil more compact.

(4) The microstructure of soil reflects its macro mechanical properties to some extent.

ACKNOWLEDGEMENTS
This study was supported by the Special Fund for Scientific Research by Shaanxi Provincial Education Department (18JK1199), Special Fund for Scientific Research by Xijing University (XJ18T01), and Special Fund for Basic Scientific Research of Central Universities-The Project of Cultivating Excellent Doctoral Dissertation of Chang'an University.

CONFLICT OF INTEREST
On behalf of all authors, the corresponding author states that there is no conflict of interest.

DATA AVAILABILITY
The data used to support the findings of this study are available from the corresponding author upon request.

References

1. X. B. Li, J. Y. Shu, J. Wang, H. T. Fu, P. Wang and X. Q. Hu. *KSCE J. Civ. Eng*., 23 (2019) 4687.
2. X. W. Tang, Z. J. Xue, Q. Yang, T. Li and M. VanSeveren. *Dry. Technol*., 35 (2017) 1696.
3. Y. X. Liu, X. Y. Xie, L. W. Zheng, C. T. Xu, H. Y. Wang and W. J. Wang. *Bull. Sci. Technol*., 35 (2019) 142.
4. J. Wang, H. T. Fu, F. Y. Liu, Y. Q. Cai and J. Zhou. *Can. Geotech. J*., 55 (2018) 147.
5. J. Wang, R. Zhao, Y. Q. Cai, H. T. Fu, X. B. Li and X. Q. Hu. *Eng. Geol*., 246 (2018) 123.
6. J. L. Hu, X. B. Li, D. K. Zhang, J. Wang, X. Q. Hu and Y. Q. Cai. *KSCE J. Civ. Eng*., 24 (2020) 2599.
7. H. Fu, Y. Cai, J. Wang and P. Wang. *Geosynth. Int*., 24 (2017) 72.
8. L. J. Wang, Y. M. Wang, S. H. Liu and C. Y. Xue. *Environ. Geotech*., (2019) 1.
9. H. Kang and K. Ahn, *Journal of the Korean Geo-Environmental Society*, 16 (2015) 53.
10. Z. H. Sun, M. J. Gao and X. J. Yu. *Dry. Technol*., 35 (2017) 38.
11. Y. D. Zhou, J. Y. Fu, A. Deng and S. X. Chai. *Chin. J. Rock Mech. Eng*., 38 (2019) 1677.
12. F. Y. Liu, Z. Li, G. H. Yuan and J. Wang. *J. Civ. Environ. Eng*., (2020). DOI: 10.11835/j.issn.2096-6717. 2020. 064.
13. F. Y. Liu, Y. J. Wang and J. Wang. *China J. Highw. Transp*., 29 (2016) 19.
14. Z. H. Sun, X. J. Yu, M. J. Gao and K. Wu. *Chin. J. Geotech. Eng*., 39 (2017) 250.
15. Y. Li, X. N. Gong, M. M. Lu and B. Guo. *Chin. J. Geotech. Eng*, 32 (2010) 77.
16. C. S. Jiang, W. M. Si, X. Zeng, X. Y. Zhao, H. Y. Liu and C. Zou. *Journal of Railway Engineering Society*, (2019) 28.
17. P. C. Hu, J. Zhou, X. G. Wen, Y. X. Chen and Y. W. Li. *J. Zhejiang Univ (Eng. Sci.)*, 49 (2015) 1434.
18. H. T. Fu, J. Wang, Y. Q. Cai, L. Zhang and Y. Cai. *Chin. J. Rock Mech. Eng*., 34 (2015) 612.
19. H. Wu and L. M. Hu. *J. Tsinghua Univ. (Sci. Technol.)*, 52 (2012) 182.
20. F. Y. Liu, H. T. Fu, J. Zhou, J. Wang, R. Zhao, W. X. Yuan, X. M. Lou, Y. W. Jin and Y. Q. Cai. *Geotech. Test. J*., 43 (2019) 20180234.
21. J. Wang, Y. J. Wang, F. Y. Liu, H. T. Fu and X. Q. Hu. *China J. Highw. Transp*., 29 (2016) 37.
22. J. Wang, L. Zhang, F. Y. Liu and H. T. Fu. *Chin. J. Rock Mech. Eng*., 33 (2014) 4181.
23. L. W. Zheng, X. Y. Xie, K. H. Xie, J. Z. Li and Y. M. Liu. *J. Zhejiang Univ (Eng. Sci.)*, 51 (2017) 1064.
24. T. Jiang, X. C. Wang and J. R. Zhang. Journal of North China University of Water Resources and Electric Power (Natural Science Edition), 41 (2020) 90.
25. F. Y. Liu, Z. P. Zhang, J. Wang, G. H. Yuan and H. T. Fu. *Chin. J. Rock Mech. Eng*., 39 (2020) 1893.
26. Y. M. Zhang, D. Ma, G. X. Li and J. X. Bi. *J. Eng. Geol*., (2020). DOI: 10.13544/j.cnki.jeg. 2019-128.