



# Experimental Study on the Vacuum Drainage Model of Slope Terrain Based on Manganese Tailings

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**Abstract.** The increasing development of mineral resources have posed a significant challenge in the safe disposal of large volumes of tailings with high water content. This study aims to investigate the engineering properties and drainage consolidation characteristics of manganese tailings and assess the feasibility of vacuum drainage technology in enhancing the strength of manganese tailings with high water content and improving the stability of manganese tailings dam slope. To this end, an indoor model test apparatus was developed to separate mud and water in manganese tailings soil and a scaled model was established for indoor vacuum drainage consolidation. By varying parameters such as the number of drainage channels and the site slope ratio during the application of vacuum pressure, the study examined the drainage volume and rate consolidation patterns of manganese tailings soil. Settlement deformation data at various distances and depths from the drainage body were monitored to identify the impact range of the drainage consolidation process on the surrounding soil. Penetration tests were conducted before and after consolidation to clarify the role of vacuum drainage consolidation in improving the mechanical properties of manganese tailings soil.

**Keywords:** manganese tailings pond; model test; vacuum drainage; settlement

## 1 Introduction

Tailings dams, as important facilities for storing mining waste, play a crucial role in environmental protection and resource recovery. However, the stability and safety of tailing dams remain critical issues in mining engineering because the strength of dams are strongly affected by water content and density. In recent years, various methods on vacuum preloading have emerged, evolving from basic methods to more advanced techniques for reinforcing soft soil foundations. However, the engineering application and disposal effect of vacuum preloading technology in tailing dams still need to be further studied.

Lei compared traditional and improved vacuum preloading methods, finding that the intermittent ventilation method for injecting gas yielded the highest drainage rate<sup>[1]</sup>.

Bhosle designed large 3D units to investigate the smear effect on Mumbai marine clay<sup>[2]</sup>. Liu significantly improved the bearing capacity of ultra-soft foundations by improving the vacuum preloading method, increasing drainage rate by 8.4% and 27.9%<sup>[3]</sup>. Cai tested conventional and novel PVC drainage boards, finding that the new drainage boards exhibited superior improvement effects on dredged soil.<sup>[4]</sup> Li tested three types of drainage boards, concluding that double-sided connected drainage boards had the best anti-clogging effect<sup>[5]</sup>. Field tests of vacuum preloading method were carried out to solve the problems of poor dam stability caused by low strength fine tailings<sup>[6]</sup>.

A self-developed indoor slurry-water separation model test apparatus was developed to study the effectiveness of vacuum dewatering on the reinforcement of tailings dams. The vacuum load application process is controlled by setting one or more drainage channels and adjusting the slope ratio. Real-time monitoring is conducted to measure the water discharge weight and the settlement displacement of the tailings at different locations under the action of vacuum pressure. This helps to understand the slurry-water separation law of manganese tailings under vacuum pressure and the drainage consolidation characteristics and deformation behavior during consolidation.

## 2 Physical Properties of Manganese Tailings Sample

The tailings soil used in this study was obtained from a tailings site in Hubei Province, with basic physical properties shown in Table 1.

The table shows that the Liquid Limit is less than 50 % with Plasticity Index of 16.8. It can be seen that this is a kind of soil that is susceptible to water content. Characterized by more than 50% fine particle content, the soil properties are more complex.

**Table 1.** Basic physical properties of the manganese tailings.

Sample	Maximum Dry Density g/cm <sup>3</sup>	Water Content/%	Plastic Limit/%	Liquid Limit/%	Plasticity Index/%	Sand	Silt	Clay
Manganese Tailings	1.59	50	22.4	39.2	16.8	1.16	47.77	51.07

## 3 Model Apparatus and Experimental Procedure

### 3.1 Test Apparatus

The test apparatus comprises a vacuum pump, a collection barrel, custom-made mini drainage wells, and a model box. The model box, made of 10 mm thick acrylic plates, is sealed at the bottom, with dimensions of 300 × 400 × 450 mm. The drainage system comprises drainage pipes and connectors. The drainage pipe is perforated at 10 cm from the front end, wrapped in geotextile fabric, and connected through cross connectors to form a vacuum mini drainage well structure. Wet manganese tailings are

used to wrap the outgoing pipe to ensure airtightness. The collection barrel is connected to the vacuum pump and drainage pipes, with a vacuum gauge to monitor the pressure.

### 3.2 Experimental Scheme

To investigate the influence of the number and slope of vacuum mini drainage wells on vacuum drainage, experiments were designed with different numbers of drainage wells and different slope ratios. The experimental code is designated as MT, and Table 2 provides simplified codes for the experimental conditions. The wells are arranged in a plum blossom pattern, with a depth of 10 cm and a row spacing of 10 cm.

### 3.3 Experimental Procedure

A tracer mesh is placed on the sidewall, and the soil is layered compacted according to the mesh spacing. Initial strength and moisture content of the test soil are measured, and the mini drainage wells are inserted. The piping system is connected, and a sealing membrane is placed on the surface, with edges compacted with wet manganese tailings to ensure airtightness. Vacuum pressure is increased from 0 to -80 kPa with each increase of 20 kPa every 12 hours. And drainage volume is recorded during the test. Model test is considered complete when the water volume remains unchanged within 1 hours.

**Table 2.** Model test plan for different numbers of vacuum mini wells.

Number of tests	MT1	MT2	MT3	MT4	MT5
Number of vacuum wells	One Rows	Two Rows	Three Rows	Three Rows	Three Rows
Slope ratio	1:10	1:10	1:10	1:5	0

## 4 Changes in the Physical Properties of Manganese Tailings

### 4.1 Impact of Different Experimental Conditions on Soil Drainage Volume and Drainage Rate

The drainage volume and drainage rate are important indicators for evaluating the effectiveness of vacuum drainage in treating manganese tailings. The curves of drainage volume and drainage rate versus time are shown in Figure 1 and Figure 2.

Analysis of the drainage volume and rate in the five model tests reveals three distinct stages: initial, stable, and deceleration. In the initial stage (0-48 hours), the drainage volume increased rapidly as vacuum pressure rose. This is mainly the flow of free water from the soil to the drainage structure under vacuum pressure. During the stable stage (after 48 hours), the volume increased steadily. In the deceleration stage, drainage slowed, leading to stabilization of the volume. The water content in the soil gradually decreases with the compression and consolidation process, resulting in a gradual de-

crease in drainage rate. The number of vacuum mini wells significantly affected the drainage volume. As the number of wells increased, the final drainage volume increased, reaching 4486.2 g with three rows, compared to 1497.7 g with one row, highlighting the enhanced drainage capacity as more wells were provided.

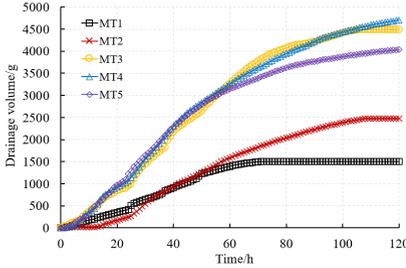


Fig. 1. Drainage volume curve of vs. time.

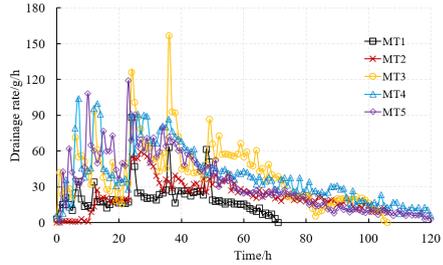


Fig. 2. Drainage rate vs. time curve.

The drainage rate rose initially with the vacuum pressure, then fluctuated. During the stable stage, the rate stabilized, but the steady rate and duration varied depending on the number of wells. For tests with different slope ratios, a higher slope ratio gave rise to greater drainage volume and drainage rate per unit mass of manganese tailings, indicating that a higher slope ratio improves drainage and prolongs the stable stage.

### 4.2 Impact of Different Experimental Conditions on the Overall Deformation of the Soil Body

To visually observe the settlement of soil at various depths due to the influence of vacuum mini well pipes, tracer strips were placed on the sidewall before pouring the manganese tailings into the model box. The deformation analysis results are shown in Figure 3 to Figure 7.

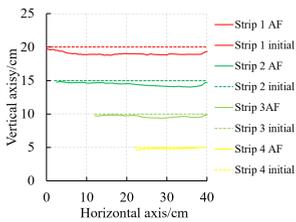


Fig. 3. Displacement of tracer strip at MT1.

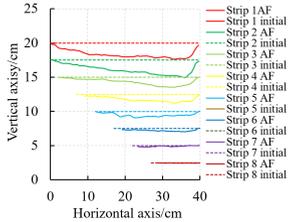


Fig. 4. Displacement of tracer strip at MT2.

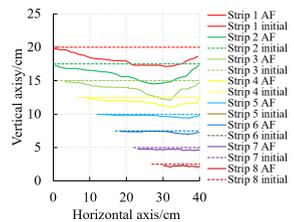
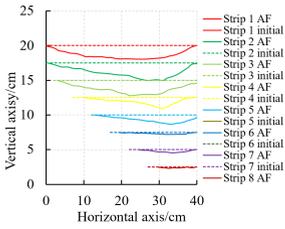
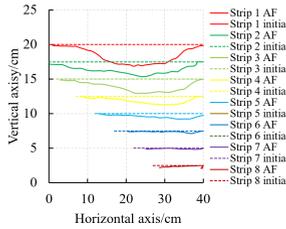


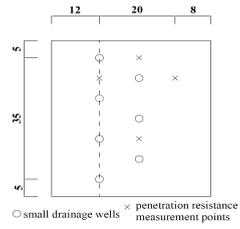
Fig. 5. Displacement of tracer Strip at MT3



**Fig. 6.** Displacement of tracer Strip at MT4.



**Fig. 7.** Displacement of tracer Strip at MT5.



**Fig. 8.** Penetration resistance measuring point diagram.

Experimental results show that vacuum drainage of manganese tailings using one, two, and three rows of mini drainage wells induce settlement across all soil depths, though limited by model box walls and the initial dam. In the test with on row of wells, the maximum surface settlement was 1.21 cm, decreasing to 0.33 cm at minimum at deeper depths. The test with two rows of wells showed a maximum surface settlement of 2.54 cm, decreasing to 0.09 cm at minimum in deeper layers. In the test with three rows of wells, surface settlement reached 2.89 cm, with deeper layers settling by a minimum of 0.39 cm. Surface and shallow layers experienced greater vacuum loads, leading to larger settlements due to pore water expulsion. In contrast, deeper layers experienced lesser settlement due to bottom surface constraints and reduced vacuum pressure. Adding drainage well rows increased settlement, especially at the surface and shallow depths.

Steeper slopes increased the more settlement in tests with different slope ratios. The maximum settlement was 3.14 cm for a 1:5 slope ratio, compared to 2.51 cm for a zero slope ratio. This indicates that higher slope ratios lead to more significant settlement, likely due to higher vacuum loads and more pronounced pore volume compression.

In conclusion, the number of mini drainage wells and slope ratio significantly affect settlement, with more wells and steeper slopes resulting in more substantial settlement, particularly at the surface and shallow layers. These findings are crucial for optimizing drainage and consolidation strategies in engineering applications to control settlement and enhance soil reinforcement.

### 4.3 Shear Strength Distribution at Different Depths and Locations in the Soil after the Experiment

As shown in Figure 8, penetration resistance was measured at each point to obtain the undrained shear strength distribution at various depths and measurement points.

Figure 9 shows that after treatment with the mini drainage well vacuum drainage method, the undrained shear strength of the manganese tailings samples significantly increased. The shear strength variation showed spatial differences depending on the number of drainage wells.

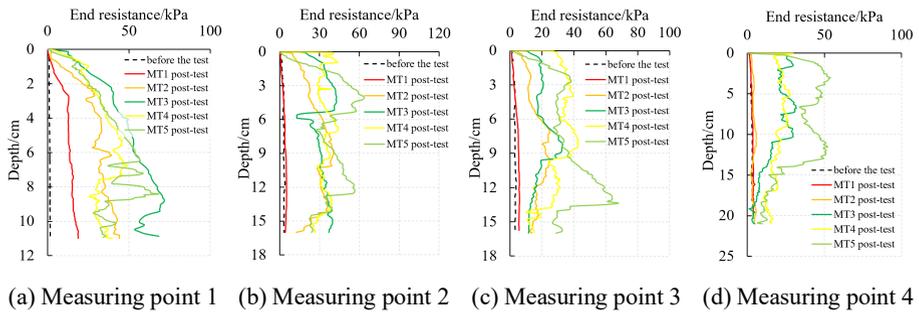


Fig. 9. Shear strength variation with depth at different measuring points.

For the first three experimental groups, as the number of wells increased, shear strength at various depths also increased, peaking at 10–15 cm, with an average increase exceeding 10 times. However, at 20 cm, the increase in shear strength was limited as the effective range of the mini drainage wells is approximately 15 cm. In the last two groups, shear strength showed noticeable enhancement from the slope toe to the middle and then the top. For example, in the MT3 test, shear strength at 5 cm increased by 12.6 times and at 10 cm by 6.28 times. In the MT4 test, shear strength at 5 cm increased by 14.73 times and at 10 cm by 5.94 times. The MT5 test showed the most potent effect, with a 15.43 times increase at 5 cm and 12.83 times at 10 cm. However, at 20 cm, the increase was more limited, e.g. at measuring point 1 in the MT5 test, where it increased by only 2.05 times. Shear strength variation in both horizontal and vertical directions followed specific patterns. Horizontally, the strength increased more near the drainage wells due to higher vacuum pressure. Vertically, the strength was more significant in the upper layers than in the deeper layers, as vacuum pressure attenuates with depth, limiting the drainage and consolidation effect in the deeper soil.

The research results show that vacuum pre-compression technology has obvious effects in tailings dam reinforcement. And vacuum preloading has a broad application in in-situ dewatering and reinforcement of tailing dams.

## 5 Conclusion

This study evaluates the effectiveness of the mini drainage well vacuum drainage consolidation technique for treating manganese tailings through five experimental groups. By varying the number of drainage channels and slope of the manganese tailings, the study compares observed phenomena with treatment parameters to analyze the impact of slope on the treatment. The following conclusions are as follows:

(1) After treatment, the manganese tailings underwent successful consolidation and drainage under vacuum negative pressure. Pore water pressure significantly decreased, accompanied by a decline in water content and an increase in soil density. Furthermore, cohesion among particles improved, forming a stable structure. This confirms the effectiveness of the mini drainage well vacuum drainage technique.

(2) Increasing the slope ratio enhances both the drainage rate and volume, leading to more significant settlement.

(3) The pocket penetrometer tests show that horizontally, the closer to the drainage wells, the greater the strength of the manganese tailings; and vertically, the strength was higher in the upper layers and exhibited a decreasing trend with depth.

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