Geomechanics and Engineering, *Vol. 15, No. 6 (2018) 1143-1151*
DOI: https://doi.org/10.12989/gae.2018.15.6.1143

Compaction techniques and construction parameters of loess as filling material

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(Received December 7, 2016, Revised May 12, 2017, Accepted April 2, 2018)

Abstract. Loess often causes problems when used as a filling material in the construction of foundations. Therefore, the compaction technique, shear behavior, and bearing capacity of a filled foundation should be carefully considered. A series of tests was performed in this study to obtain effective compaction techniques and construction parameters. The results indicated that loess is strongly sensitive to water. Thus, the soil moisture content should be kept within 12%-14% when it is used as a filling material. The vibrating-dynamic combination compaction technique is effective and has fewer limitations than other methods. In addition, the shear strength of the compacted loess was found to increase linearly with the degree of compaction, and the soil's compressibility decreased rapidly with an increase in the degree of compaction when the degree of compaction was less than 95%. Finally, the characteristic value of the bearing capacity increased with an increase in the degree of compaction in a ladder-type way when the degree of compaction was within 92%-95%. Based on the test data, this paper could be used as a reference in the selection of construction designs in similar engineering projects.

Keywords: loess; field filling test; compaction techniques; construction parameters

1. Introduction

Loess is widely distributed around the world and is famous for its fine behavior. Thus, it is widely used as a filling material in engineering projects (Daehyeon and Kang 2013). From a geotechnical point of view, the collapsibility, sensitivity to water, structural strength, and mural joints are the most significant characteristics of loess (Liang *et al.* 2015). However, loess often causes problems when used as a filling material in the construction of foundations. Therefore, the compaction technique, shear behavior, and bearing capacity of a filled foundation should be carefully considered. Loess is the predominant surface soil that has been used for the construction of foundations in Northwest China. However, because of the lack of systematic research data, the construction engineering of foundations in China is usually challenging when loess is used as a filling material.

Some scholars have carried out extensive research to solve the previously mentioned problems. Kozubal and Steshenko (2015) described a new complex soil compaction technique that could be applied to collapsing soils. In order to study the effect of dynamic compaction with a energy level of 12,000 kN·m, a field test was conducted to determine the optimum dynamic compaction operational parameters (Feng *et al.* 2015). Besides, the field load tests were carried out at the three collapsible loess sites under an arid environment on the Loess Plateau in Northwest China (Qian *et al.* 2016). The shear strength of loess is one of the most important mechanical properties of construction materials (Qian *et al.* 2014). Because of its distinctive physical and mechanical properties, the characteristics of the shear strength and deformation mechanism of loess have recently become a new focus of research (Zhang *et al.* 2013). In addition, the collapsible potential can be significantly improved by effectively compacting the loess when using it as a filling material (Daehyeon and Kang 2013).

Several fundamental achievements have been attained in the research on the deformation and strength of compacted soil (Luo *et al.* 2014). Chen and Sha (2010) analyzed the deformation property of compacted loess. A qualitative examination was performed to study the general trend of the variation of the cohesion and angle of internal friction of compacted loess-like silt with a change in the dry density and moisture content (Wang *et al.* 2010). In addition, it has been demonstrated that the cohesion and angle of internal friction of unsaturated soil decrease linearly with an increase in the moisture content. The influence of the dry density and moisture content on the strength parameters has been investigated (Cheng *et al.* 2008). A method for accurately determining the optimum water content of soil and the corresponding maximum dry density has been developed using a small number of loess samples (Ren and Lai 2015). Mona and Tarek (2016) studied the effect of applied pressure, void ratio, water content and silt content on the collapse potential, maximum shear modulus and damping ratio of loess. In addition, extensive research on important problems with loess has been conducted, and

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http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

(a) Disturbed loess (b) Undisturbed loess (c) Compacted loess

Fig. 1 Loess sample

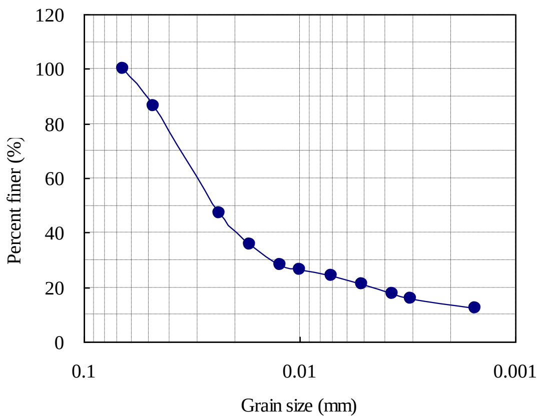


Fig. 2 Grain size distribution of loess sample

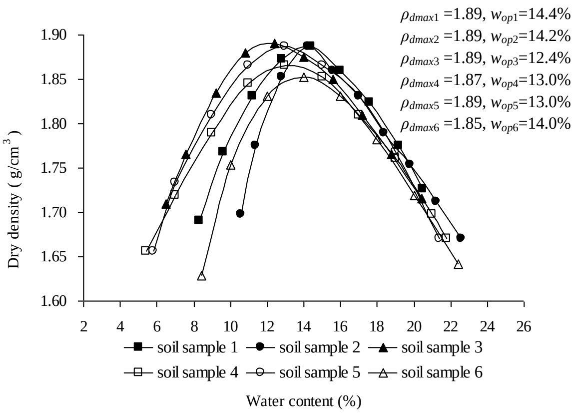


Fig. 3 Relationship curve between w and ρ

many important conclusions have been reached.

In this study, a series of experiments on the parameters for the compaction construction of loess was carried out. The efficiency of the compaction technique and reasonable compaction parameters for filling loess were analyzed. Additionally, the basic laws for the bearing capacity of a filling foundation, compression modulus, and shear strength index were also determined. The research results can provide a reference for the design and construction of similar projects, and can also provide a reliable basis for the establishment of relevant specifications and industry standards.

2. Materials

2.1 Loess sample

Loess is widely distributed around loess mountain areas. It is also the main stratum constituting the top of a loess hill. Its lithology is mainly silt with a little silty clay. This kind of soil has a loose structure, macroporosity, and a mural joint structure. The structure has a slight or mid-level density with a low tenacity and dry strength. The soil sample used in the test is shown in Fig. 1.

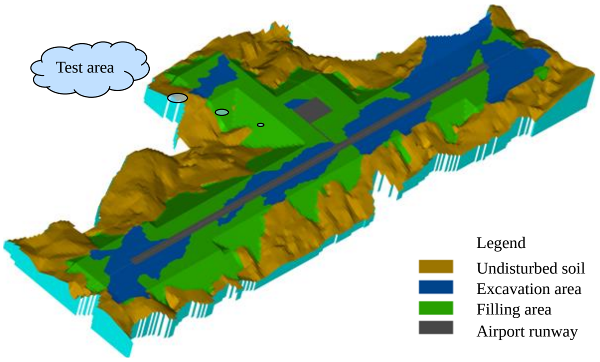
2.2 Grain size composition

Loess contains fine sand, silty sand, coarse grain silt, fine grain silt, and clay particles. The grain size composition of the loess sample is shown in Fig. 2.

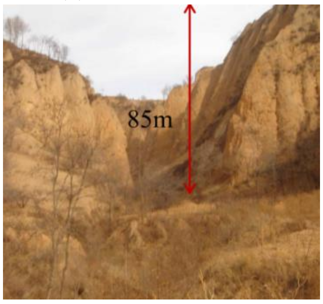
2.3 Optimum moisture content and maximum dry density

Heavy compaction tests were performed to determine the maximum dry density ($\rho_{d\max}$) and optimum moisture content (w_{op}) of the loess used in the test. Fig. 3 shows the curve of the relationship between the dry density (ρ) and moisture content (w) obtained from the tests. It shows that as the moisture content increases, the dry density initially increases and then decreases. When the moisture content increases to the optimum level and then continues to increase, the dry density rapidly decreases, which demonstrates that loess is sensitive to the moisture content. The optimum moisture content of the soil samples ranged from 12.3% to 14.2%, and the maximum dry density ranged from 1.85 g/cm^3 to 1.89 g/cm^3 (Mei *et al.* 2016).

For loess under a low moisture content, the friction between the soil particles is large, and the particles are dispersed. It is not easy to squeeze the adjacent soil particles under the same compaction mechanism, which leads to a loose soil surface when compacting. This phenomenon usually prevents the soil from being well compacted. In contrast, under a high moisture content, the voids between the soil particles are occupied by water, and the force of rolling compaction will be dissipated and born by this water. Because water is generally incompressible, it cannot be discharged out of the soil. During the process of rolling compaction, the soil will flow, which also prevents it



(a) Excavation area



(b) Topographic feature of the test area

(c) Completed Test area

Fig. 4 Engineering profile and filling test area

(a) Dynamic compactor

(b) Vibratory roller and impact roller

Fig. 5 Main compaction machine

from being compacted. Thus, the moisture content of the soil should be strictly controlled during the compaction. According to the experiment results, considering the loss of soil moisture under the compaction construction, the range of the soil moisture content should be controlled between 12% and 14%. At the same time, the uniformity of the soil also needs to be maintained. Silt has a characteristic wherein its moisture loss is relatively faster on the surface. Because of this, if the loose laying thickness is too large, the soil will be hard to dry under a high moisture content. Watering the soil after loose laying usually causes an uneven distribution of the water when compacted loess is under a low moisture content (Mei *et al*. 2016). Therefore, it is necessary to select the appropriate thickness of the loose laying during the construction.

3. Field filling test

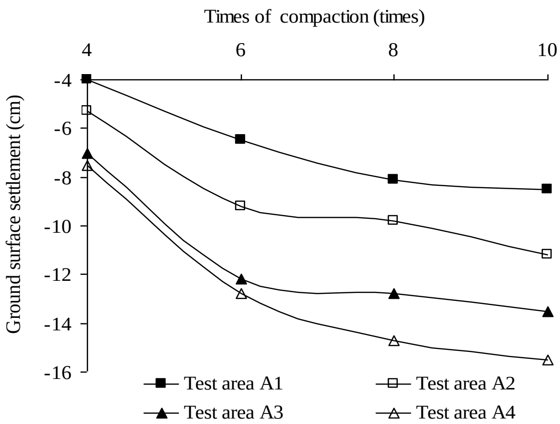
3.1 Engineering profile and general testing program

In order to obtain the compaction coefficients and construction parameters of different construction techniques when using loess as a filling material, a series of field compaction tests was performed, relying on the engineering of China's Lvliang Airport. Because of the filling material limitation, this engineering planned to use the loess distributed on top of the hills to fill up the gully area. The filling amount was about 1.9×10^7 m^3, and the evacuation amount was about 3.2×10^7 m^3. In addition, the maximal filling thickness of this engineering was 85 m (in the filling test area). This kind of high foundation filled with loess was the first case of this type in China, and is also rare around the world. The engineering profile, filling test area are shown in Fig. 4, and main compaction machine are shown in Fig. 5.

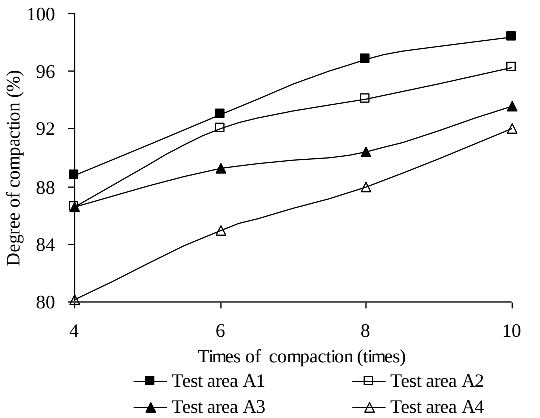
The field filling test contained four groups: the vibration compaction test (group A), impact compaction test (group B), vibrating-impact combination compaction test (group C), and vibrating-dynamic combination compaction test (group D). Each group was divided into several test sections, which utilized different compaction techniques. The soil moisture content should be kept within the optimal range (12%-14%) during the filling process. In the test, the degree of compaction of the compacted loess and ground surface settlement were measured.

3.2 Vibration compaction and impact compaction

The vibration compaction test consisted of four sections (A1, A2, A3, and A4). In each section, a vibratory road roller (with a speed of 3 km/h and weight of 50 t) was used to compact the reclamation soil. Among these sections, the

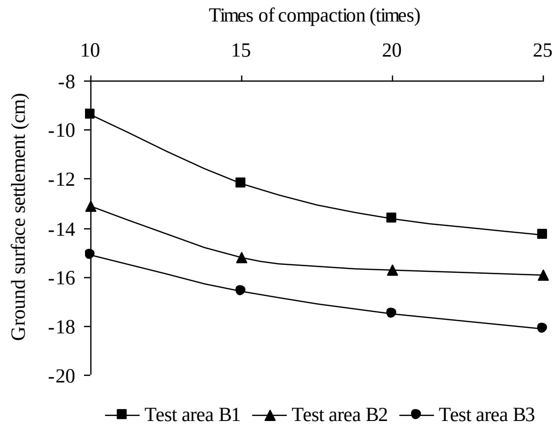


(a) Curve showing relation between compaction time and ground surface settlement

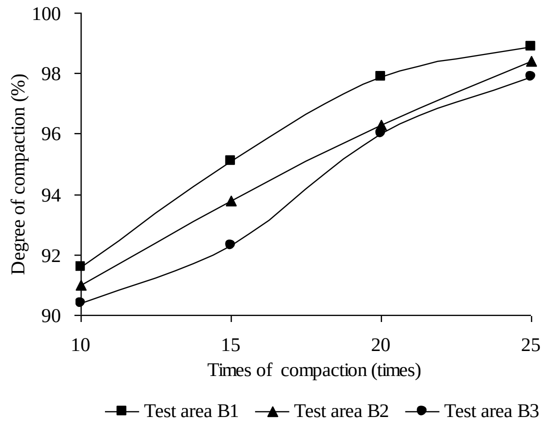


(b) Curve showing relation between compaction time and degree of compaction

Fig. 6 Test results for test group A



(a) Curve showing relation between compaction time and ground surface settlement



(b) Curve showing relation between compaction time and degree of compaction

Fig. 7 Test results for test group B

loose laying thickness of reclamation soil in section A1 was 30 cm, with values of 40, 50, and 60 cm in sections A2, A3, and A4, respectively. The degree of compaction of the compacted loess and ground surface settlement of each section were measured after being compacted by 4, 6, 8, and 10 times, respectively.

The impact compaction experiment consisted of three sections (B1, B2, and B3). In each section, an impact road roller (with a speed of 10 km/h and a weight of 28 t) was used to compact the reclamation soil. Among these sections, the loose laying thickness of the reclamation soil in section B1 was 70 cm, and the values for sections B2 and B3 were 80 and 90 cm, respectively. The degree of compaction of the compacted loess and the ground surface settlement of each section were measured after being compacted by 10, 15, 20 and 25 times, respectively.

Figs. 6 and 7 show curves for the relations between the compaction time and the ground surface settlement and degree of compaction.

It can be inferred from the above figures that under a certain loose laying thickness, the rate of ground settlement is faster at an early stage and slower at a later stage. Under certain compaction times, a larger loose laying thickness will result in a larger ground settlement. However, a relatively smaller settlement, which indicates a larger loose laying thickness, will result in a worse compaction effect. Under a certain loose laying thickness, the degree of compaction increases with the compaction time, whereas the relationship between the degree of compaction increase rate and compaction time shows the inverse trend. In addition, with a smaller thickness, the increase rate decays more rapidly. This phenomenon shows the process of the soil being gradually compacted. Under certain compaction times, a larger loose laying thickness will result in a smaller corresponding degree of compaction. Moreover, with a smaller thickness, the compaction will be completed more rapidly at an early stage, and the growth will be less obvious at a later stage.

A comparison of the results shows that even though impact compaction is more effective than vibrating compaction, this technique is not suitable for large-scale construction in a hilly gully area because of the space requirements. Therefore, the moisture content will be difficult to control during the construction process, which will lead to a poor working efficiency.

3.3. Vibrating-impact combination compaction

Using vibration compaction, it is difficult to obtain the proper degree of compaction that is suitable for the

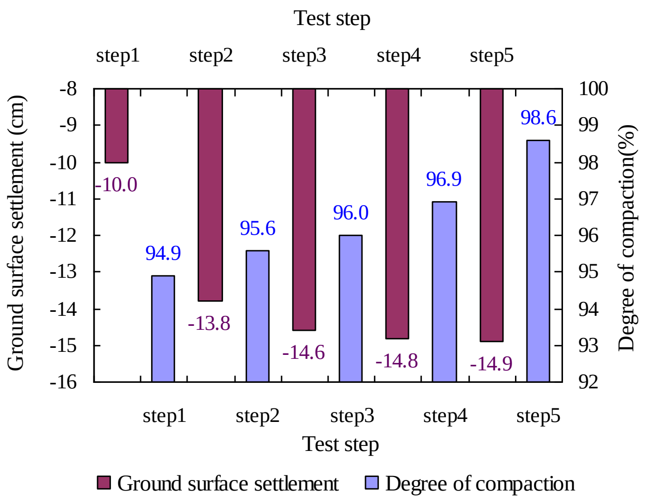


Fig. 8 Test results for group C

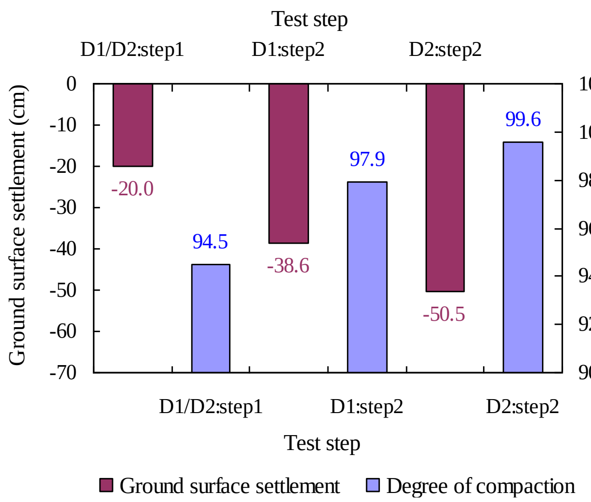


Fig. 9 Test results for group D

settlement control of filling foundations. Moreover, the construction speed of impact compaction cannot meet the requirements because of the limitation of each layer's thickness, but it can achieve an appropriate compaction coefficient. In order to improve the construction efficiency and meet the engineering requirements according to above tests results, a method that combined vibrating and impact compaction was designed. The construction process includes the following five steps.

Step 1: Use a vibratory road roller (with a speed of 3 km/h and weight of 50 t) to compact the reclamation soil. The loose laying thickness of the reclamation soil is 40 cm. Four layers are filled, and each layer is vibration-compacted 10 times. The degree of compaction should be more than 93% after filling.

Steps 2-5: Impact compaction should be conducted after the completion of the vibrating compaction. The thickness of the filling body and the compaction coefficient will be measured 10, 15, 20, and 25 times, respectively, after the impact compaction is finished. In the compaction process, the soil moisture content should be kept within the optimal range (12%-14%). The construction efficiency of this construction method was studied using test group C.

The test results for group C are shown in Fig. 8.

Because the moisture content was appropriately controlled in this test, the results of the vibration compaction were fairly good. The degree of compaction measured after the filling was 2% higher than the required value. After the impact compaction, the average ground surface settlement was 4.9 cm, which was equal to a 3.3% improvement in the degree of compaction. This was basically consistent with the test results for the degree of compaction, which indicated that the loess was uniformly compacted. The degree of compaction increased 0.7%, 1.1%, 2.0%, and 3.7% in steps 2-5, respectively, and could reach a value of more than 98% after the impact compaction was finished.

The results showed that the impact compaction was effective. This compound method is suitable for loess filling engineering, which has a relatively high requirement for the degree of compaction. However, the space requirements for impact compaction make this compound method unsuitable for large-scale construction in a hilly gully area.

3.4. Vibrating-dynamic combination compaction

The construction space in a gully region usually limits the efficiency of impact compaction. Thus, the vibrating-dynamic combination compaction method was considered. Similar to the vibration impact compaction, this method includes the following two steps.

Step 1: Use a vibratory road roller (with a speed of 3 km/h and a weight of 50 t) to compact the reclamation soil. The loose laying thickness of the reclamation soil is 40 cm. Twenty layers are filled, and each layer is vibration compacted 10 times. The degree of compaction should be more than 93% after filling.

Step 2: After the completion of the vibrating compaction, dynamic compaction will be carried out in two different sections (D1 and D2). In this step, the main ramming should be carried out before the full ramming starts. The energy level of the main ramming for section D1 is 2000 kN·m, and that for section D2 is 3000 kN·m, whereas the full ramming is 1000 kN·m. In addition, the times for the main ramming at each point are controlled within 10 to 12 times, while the full ramming is 3 to 5 times. In addition, the main ramming should stop when the average settlement of the last two ramming sessions is less than 5 cm, whereas that for the full ramming is 3 cm. The main ramming in each section is in accordance with a triangular distribution, where the center distance of the tamping point is 4 m. In addition, the lap length of the full ramming is a quarter of the rammer diameter. At the same time, the soil moisture content should be kept within the optimal range (12%-14%) in the compaction process.

The relationship between the compaction time, ground surface settlement, and degree of compaction in this group is shown in Fig. 9.

Similar to the vibrating-impact combination compaction test, because the moisture content was properly controlled, the compaction effect of the vibration compaction was good. The degree of compaction measured after the filling was about 1.5% higher than the required value. After the compaction with an energy level of 2000 kN·m, the ground surface settlement of section D1 was 18.6 cm, which was equal to a 3.1% improvement in the degree of compaction. This result was identical to the detection result for the degree of compaction (98%). After the compaction with an energy level of 3000 kN·m, the ground surface settlement of section D2 was 30.5 cm, which was equal to a 5.1% improvement in the degree of compaction. This result was also identical to the test result for the degree of compaction (99.6%), which showed that the compacted loess was uniform. It also demonstrated that a better loess compaction effect could be achieved by dynamic compaction.

The test results showed that the vibrating-dynamic combination compaction was effective for the compaction of loess. It has a fast construction speed and smaller space requirements. Thus, it is suitable for large-scale construction in hilly gully areas and could be the first choice for the compaction construction of loess.

4. Analysis of the test results

It can be seen from the results of the above 4 group of tests, degree of compaction of the filling foundation can reach design requirement with whichever compaction technique. However, the work efficiency differs greatly. Therefore, because of the cost limit, the ultimate aim of this test is to find a compaction technique suitable for similar engineering through comparison. Based on different compaction technique, test results were divided into the following 4 types.

(1) Type $A_{i(j)}$: Compaction technique is vibrating compaction. 'i' denotes the thickness of the loose laying soil, the value of which can be 30, 40, 50, and 60. 'j' denotes the number of times of the rolling compaction, the value of which can be 4,6,8, and 10.

(2) Type $B_{i(j)}$: Compaction technique is impact compaction. 'i' denotes the thickness of the loose laying soil, the value of which can be 70, 80, and 90. 'j' denotes the number of times of the rolling compaction, the value of which can be 10,15,20, and 25.

(3) Type C_m: Compaction technique is vibrating-impact compaction. 'm' denotes the number of times of the impact compaction after vibrating compaction, the value of which can be 10,15,20, and 25.

(4) Type D_n: Compaction technique is vibrating-dynamic combination compaction. 'n' denotes the energy level of dynamic compaction after vibrating compaction, the value of which can be 2000 and 3000.

Other construction parameters of the above compaction types were in accordance with the corresponding test area. Based on the different compaction requirement of loess filing foundation, compaction results of each type were shown in Table 1. According to the assessment of the practical construction, the compaction techniques which use shortest time for each degree of compaction were shown in Table 2.

Table 1 Compaction results of each type

Type	K		
	93%	95%	98%
$A_{30(4)}$	×	×	×
$A_{30(6)}$	▲	×	×
$A_{30(8)}$	▲	▲	×
$A_{30(10)}$	▲	▲	▲
$A_{40(4)}$	×	×	×
$A_{40(6)}$	×	×	×
$A_{40(8)}$	▲	×	×
$A_{40(10)}$	▲	▲	×
$A_{50(4)}$	×	×	×
$A_{50(6)}$	×	×	×
$A_{50(8)}$	×	×	×
$A_{50(10)}$	○	×	×
$A_{60(4)}$	×	×	×
$A_{60(6)}$	×	×	×
$A_{60(8)}$	×	×	×
$A_{60(10)}$	×	×	×
$B_{70(10)}$	×	×	×
$B_{70(15)}$	▲	▲	×
$B_{70(20)}$	▲	▲	○
$B_{70(25)}$	▲	▲	▲
$B_{80(10)}$	×	×	×
$B_{80(15)}$	▲	×	×
$B_{80(20)}$	▲	▲	○
$B_{80(25)}$	▲	▲	▲
$B_{90(10)}$	×	×	×
$B_{90(15)}$	○	×	×
$B_{90(20)}$	▲	▲	×
$B_{90(25)}$	▲	▲	○
C_{10}	▲	▲	×
C_{15}	▲	▲	×
C_{20}	▲	▲	×
C_{25}	▲	▲	▲
D_{2000}	▲	▲	○
D_{3000}	▲	▲	▲

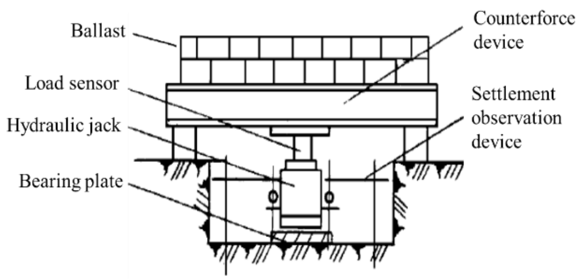
▲: Meet requirement;
○: Near requirement;
×: Below requirement

Practical construction shows that, water content is difficult to control when the vibrating compaction is used. Besides, the compaction is nonuniform, which often result in sludge cake. In the process of vibrating compaction technique, low frequency vibration should be adopted firstly until the soil is generally compacted. Then high-frequency vibration can be used. Finally, static pressure should be used to eliminate surface damage of the soil. When compacted by impact compaction technique, physical and mechanical properties of the filling soil will be evidently refined, compressibility of the soil will decrease sharply, and cohesion will greatly increase. Impact compaction technique has a fine compaction effect for shallow soil. Vibrating-dynamic combination compaction is the first choice for loess. Its fast construction speed and lower space requirements make it suitable for large-scale construction in a hilly gully area.

Moreover, when the water content of filling loess is too

Table 2 compaction techniques which use shortest time for each degree of compaction

K	Construction techniques using shortest time			
93%	$A_{40(8)}$	$B_{90(20)}$	C_{10}	D_{2000}
95%	$A_{40(10)}$	$B_{90(20)}$	C_{10}	D_{2000}
98%	$A_{30(10)}$	$B_{80(25)}$	C_{25}	D_{3000}



(a) Principle of the load test

(b) Load test

Fig. 10 Load test and the test procedure

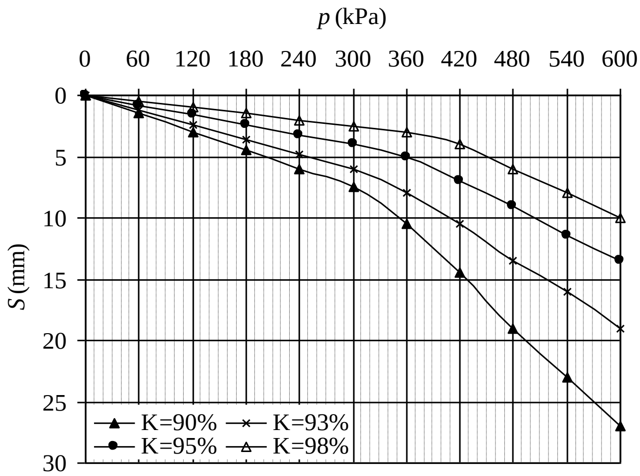


Fig. 11 Typical *p-S* curve of the load test

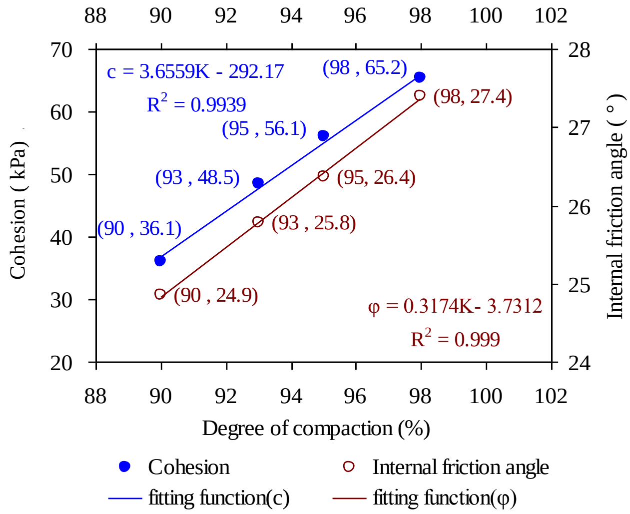


Fig. 12 Relationship between strength parameters (c, φ) and degree of compaction

low, friction between soil particles is big, and its ability to absorb water is low. Also, the soil particles are dispersed, causing the soil difficult to compress, and make the surface of the soil loose. Therefore, the soil cannot be compacted thoroughly. In contrast, when the water content is too high, void of the soil is filled by water. Rubbery soil often occurs during compaction process. The compaction quality is also low. Therefore, water content plays a key role in the compaction process of loess. When the water content is controlled ±2%within optimum water content, the soil is easy to compact and the compaction quality is high.

5. Main parameters for construction design

In order to provide the parameters for the construction design, with the goal of compacting loess with the optimal moisture content (13%) and maximum dry density (1.89 g/cm^3), statistical analyses of the strength parameters (c, φ), modulus of compression in a pressure range of 100-200 kPa ($E_{s1\text{-}2}$) and characteristic value of foundation bearing capacity (f_{ak}) under different degrees of compaction (K) were carried out using direct shear tests, confined compression tests, and static load tests, Load test is an in-situ test that obtain the relation between deformation and load of the foundation soil by gradually increase the load on a bearing plate with a certain area. Test results are commonly used to evaluate the bearing capacity of the foundation. A pressure-settlement (p-S) curve can be obtained from the test, in which the load corresponding to the break point of the curve is the characteristic value of bearing capacity of foundation. Foundation failure will occur when such value is reached. Figs. 10-11 shows the load test and the typical p-S curve. Some obvious facts can be seen in Fig. 12.

These curves present the relationships between the above values. They illustrate that the shear strength of the compacted loess increases linearly with an increase in the degree of compaction.

It is obvious that φ increases with increasing degree of compaction. This is attributed to the following three reasons. First, the degree of tightness between the soil particles increases with an increase in the degree of compaction, which, in turn, enhances the interaction between the soil particles and the water membrane. Second, the increase in the degree of compaction causes a decrease in the void ratio. The water molecules are in the form of a strongly bound water membrane and so they cannot move, which results in an increase in the soil intensity. Third, the

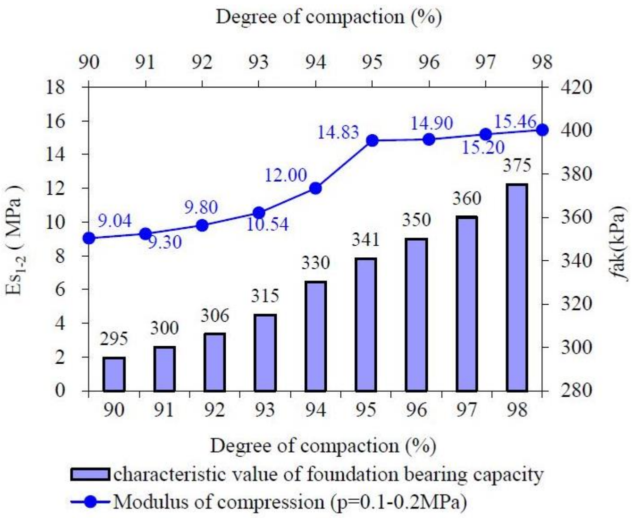


Fig. 13 Relationship between $E_{s1\text{-}2}$, f_{ak}, and degree of compaction

spaci ng between the soil particles decreases gradually with an increase in the degree of compaction. The thickness of the bound water membrane decreases and part of the water is converted into free water, which leads to a reduction in the lubrication effect and thus an increase in φ (Mei *et al.* 2016).

Furthermore, Fig. 13 shows that c increases with an increase in K. This is because the higher the K value, the tighter the soil grains become, which finally leads to a stronger occlusion effect between soil grains.

The soil's compressibility decreases rapidly with an increase in the degree of compaction when the degree of compaction is less than 95%. When the degree of compaction is greater than 95%, its effect on the soil's compressibility is not significant. The characteristic value of the bearing capacity increases with an increase in the degree of compaction in a ladder-type way when the degree of compaction is within 90%-98%. Moreover, increment speed of the characteristic value of bearing capacity of foundation get faster with an increase in the degree of compaction. A possible reason is that when the degree of compaction get higher, the modulus of compression is bigger, thus the soil will be harder to compress. When degree of compaction reaches a certain level, more compaction energy will be needed to increase the degree of compaction, bearing capacity of foundation will thus have a bigger increment. Construction designs for similar engineering projects could be selected based on the test data.

6. Conclusions

• Loess is sensitive to water when used as a filling material, and the maximum dry density can reach 1.89 g/cm^3 during compaction treatment if the condition of the soil moisture content is kept within 12%-14%.

• Impact compaction is more effective than vibration compaction for loess, whereas vibrating-impact combination compaction is much better. None of them are suitable for large-scale filling construction in a hilly gully area, although vibrating-impact combination compaction can be used for loess filling engineering, which has a high degree of compaction requirement.

• Vibrating-dynamic combination compaction is the first choice for loess. Its fast construction speed and lower space requirements make it suitable for large-scale construction in a hilly gully area.

• The shear strength of the compacted loess increases linearly with the degree of compaction, and the soil's compressibility decreases rapidly with an increase in the degree of compaction when the degree of compaction is less than 95%. In addition, the characteristic value of the bearing capacity increases with an increase in the degree of compaction in a ladder-type way when the degree of compaction is 92%-95%.

Acknowledgments

The research described in this paper was financially supported by the National Natural Science Foundation of China (No. 51408463), Natural Science Foundation Research Project of Shaanxi province (No. 2016JQ5091), Special Research Project of Education Department of Shaanxi Provincial Government (No. 17JK0424).

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